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Recent Advances in Research from Plastic Materials to Microplastics

ABSTRACT

Plastics have become ubiquitous in our lives. Due to the ever-increasing population, rapid urbanization, and industrial advancement, the use of plastics has increased manifold. These plastic materials often disintegrate into microplastics (MPs) which are less than 5mm in size. MPs mostly enter aquatic habitats through improper waste management, illegal dumping, and unavoidable and unintentional discharges that take place during construction, manufacturing, farming, domestic consumption, and recreational activities. This review centers on exploring the origin, occurrence, and possible adverse effects of MPs on human well-being. Of the 485 literature reviewed for the study between 2014-2023, 105 were found to be related to the MPs which were spread over 10 themes. The maximum number of papers were on sources of MPs, followed by MPs in freshwater ecosystems and waste management. The least number of literature was from the themes, transport of MPs and MPs in the soil environment. The literature was published mostly in China, India, Europe, and the Americas. Other countries like Australia, Latin America, Africa, and the Middle East contribute very little. The literature scan reveals that only 9% of all the generated plastic waste material is recycled, 12% is burned, and 79% of plastic litter is dumped in landfills and oceans. The dumped plastic settles and pollutes a variety of environmental matrices. MPs are intentionally manufactured to be added to personal care products that are washed down the drains through sewage or industrial wastewater. These MPs vary in density and colour, subject to the polymer type, and are present in varying sizes and concentrations in aquatic environments. The characterization of MPs originating from different types of polymer materials, in the reviewed literature, was performed based on the data obtained from Scanning Electron Microscopy Energy Dispersive Spectroscopy (SEM-EDS), Attenuated Total Reflection Fourier Transform Infra-Red spectroscopy (ATR-FTIR), Raman spectroscopy, and Atomic Force Microscopy (AFM). MPs have the potential to absorb harmful hydrophobic pollutants from the surroundings resulting in an indirect transfer of contaminants into the food web. Such MPs enter and affect humans, causing problems with the reproductive system, body weight, sex ratio, and live births. MPs pose a serious threat to organisms when ingested since they can obstruct the digestive tract, leading to oxidative and pathological stress, slowing down growth, and interfering with reproduction. Apart from the above, a comprehensive analysis of MP pollution, as well as its effect on human beings and the environment, has been discussed in terms of source identification and abundance. Also, has been discussed is a detailed review of the existing waste material recycled into new materials or reused without alteration or degradation to produce new energy sources. In the end, integrated strategies have been proposed to prevent the input of plastic waste material into the environment, by source control, improved plastic waste management, and techniques for degradation and conversion of MPs.

Keywords: *Microplastics; landfill; health impacts; aquatic environment; management; eco-friendly*

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1. INTRODUCTION

Plastics are an important part of human daily life activities. They are flexible, lightweight, portable, and easy to transport and hence are omnipresent in our daily lives. Plastic materials have made significant contributions to food packaging, drug delivery, protection against infectious illness, roads, and pavements [1]. The increase in global plastic production is evident, with the output reaching 390 million tons in 2021 but is estimated to double in the next 20 years [2]. Only 9% of the produced plastic waste material is recycled, 12% is incinerated, and 79% of plastic litter is dumped in landfills and oceans. The dumped plastic settles and pollutes a variety of environmental matrices [3]. According to the United Nations Environment Programme, an estimated 9-14 million tons of plastic waste material found its way to the aquatic environment in 2016 which is expected to increase and may reach between 23 and 37 million tons per year by 2040 unless corrective actions are taken [4]. This is due to improper management, illegal dumping, and unavoidable and unintentional discharges of plastic waste causing severe ecological problems [5]. It is almost impossible to remove plastic from the environment, as the burning of plastics causes air pollution by emitting nitrogen oxides, dioxins, and dioxin-related chemicals into the atmosphere [6]. Once in the environment, plastic undergoes mechanical (erosion, abrasion), chemical (photo-oxidation, temperature), and biological (degradation by micro-organisms) actions [7]. All these degradation processes lead to their breakdown into microplastics (MPs) [8].

The term "microplastics' was introduced in 2004 by Richard Thompson [9]. The International Organization for Standardization (2020) has Technical Committee 61 (ISO/TC 61) focused on plastics and a Sub-committee 14 (SC 14) that deals with environmental aspect and defines MPs as solid plastic particles of a specific size range (1 μm to 1000 μm) [10]. Recently, researchers defined MPs as particles that are less than 5 mm in size [8]. MPs have been recognized as emerging pollutants (EPs) with potentially detrimental effects on river health and freshwater ecosystems. Harmful chemicals, including phthalates or polybrominated diphenyl ethers, have been found in MPs [11]. MPs are ubiquitous and have been detected in different sizes, concentrations, and chemical compositions in diverse environments, including marine environments [12] rivers and lakes [13], air [14], and soil [15].

There are various routes through which MPs enter freshwater environments [16]. These pathways highlight the pervasive nature of MP pollution and the diverse sources contributing to its presence in rivers and other water bodies. It includes run-off from various sources based on land, such as sewage sludge, agricultural plastic, garbage, road marking paint, tyre-wear debris, household dust, and artificial turf [17]. It is also released through wastewater such as washing synthetic clothes [18]; cosmetic microbeads [16]; and fragments of sanitary pads and wet wipes when flushed down the toilet. Sadia et al. [19] listed different types of MPs detected in wastewater treatment plants (WWTPs) viz., polypropylene (PP), polyethylene (PE), polycarbonate (PC), polyurethane (PU), polystyrene (PS), polyethylene terephthalate (PET), polyester (PES), and polyvinyl chloride (PVC). These MPs originate every day, enter WWTPs primarily through domestic wastewater, and make it a challenge to effectively capture and completely remove them due to their small size. The effluents from WWTP are transported from land via rivers to the oceans, contributing to MP pollution in marine ecosystems [20]. It is estimated that the global input of plastic debris being carried by rivers into the sea ranges between 0.41 to 4 x 10^6 t/y [21]. The aquatic organisms ingest these MPs which can lead to various health issues, including internal blockages and damage to the gastrointestinal tract in fish, resulting in decreased appetite and mortality. These MPs have the potential to contaminate the sources of drinking water, migrate up the food chain, and emit toxic compounds that may be hazardous to human health and cause cancer. Furthermore, exposure to MPs can cause oxidative stress, metabolic dysfunction, immunological responses, neurotoxicity, and impacts on developing and reproductive systems [22].

Due to the rising level of demand for plastic products, there is an increase in production rates, which poses a significant challenge in the fight against MP pollution. As plastic production continues to grow, likely, MPs pollution will also increase, unless significant measures are taken to address its sources and impacts. Therefore, policies and laws are required to be implemented for plastic use, management, and disposal. Governments around the world have taken steps to address this issue by implementing measures to curb the usage of disposable plastic products in India [23], cosmetic products containing plastic microbeads in the U.K., U.S. and Canada, plastic bags in India, Australia, Bangladesh, Rwanda, South Africa and China [24], and non-biodegradable tableware in France [25]. Besides banning and limiting the use of plastics, Sweden has initiated the concept of home garbage collection and attained zero waste and sustainable energy by recycling 99% of household waste [26]. These regulations and bans are significant steps toward reducing the environmental impact of plastic pollution [25]. It will not only reduce the use of plastics but may also lead to the development of an alternative eco-friendly material to encourage a shift towards more sustainable practices. Considering the severity of the effects of MPs on humans, the environment, land, and aquatic animals, this study is a comprehensive review to assess the present state of the art about the characterization of MPs, the origin and abundance of MPs in rivers and identify toxicological effects on the environment and the human health. Additionally, it aims to identify the awareness gaps and take note of policy initiatives to minimize MPs in rivers and their management.

2. SCIENTOMETRIC ANALYSIS

2.1 Literature Search

For a better understanding of subject areas of interest related to MPs, the published papers were analyzed from 2004, when the term microplastics was first introduced by Thompson et al., [9] in 2004 to 2023. As per the Google Scholar database, the number of articles published on MPs vis-à-vis year is as,

2004-2008: 1520

2009-2013: 2880

2014-2018: 14,300 and

2019-2023: 31,500

Since most of the articles were published after 2014, this paper focuses on the articles for the period between 2014 and 2023.

The online databases used to search for the papers were, Web of Science (https://www.webofscience.com/), Scopus (https://www.scopus.com/), and Science Direct (http://www.sciencedirect.com). "Microplastics", "aquatic environment", "rivers", "environmental impacts", "human health" and "management" are the search keywords used resulting in 485 articles. After eliminating irrelevant literature and then removing duplication of literature in databases, 105 articles, related to the topic, were selected for the study. The selected articles were classified according to the publication year, publication area, and the characterization techniques used in the study.

2.2 Overview of selected literature

The literature obtained from keyword search is shown in Table 1 as the initial number of articles indexed in different databases. After filtering the articles related to the title and removing the duplicates, the final number of articles viz., 105 were finalized for study.

Table 1. Literature search results

Database journal	Initial number of articles	Final number of articles
Web of Science (ESCI)	60	26
SCI	36	19
SCIE	70	40
Scopus	155	89
Pubmed	63	38
Pubmed Central	31	11
Medline	46	29
Others (Book chapter/conferences/facts /thesis)	24	13
Total	485	105 (excluding duplication)

The selected literature was ***classified into 10 themes*** viz., plastic waste and its additives, MPs pollution and its challenges, sources, and transport of MPs, MPs in soil environment, freshwater ecosystem, and aquatic system, toxicity of MPs in environment, impacts on human health, waste management and removal/treatment of plastics and MPs as depicted in Figure 1, where the numbers in parentheses are the number of articles found under the respective class, out of the total 105.

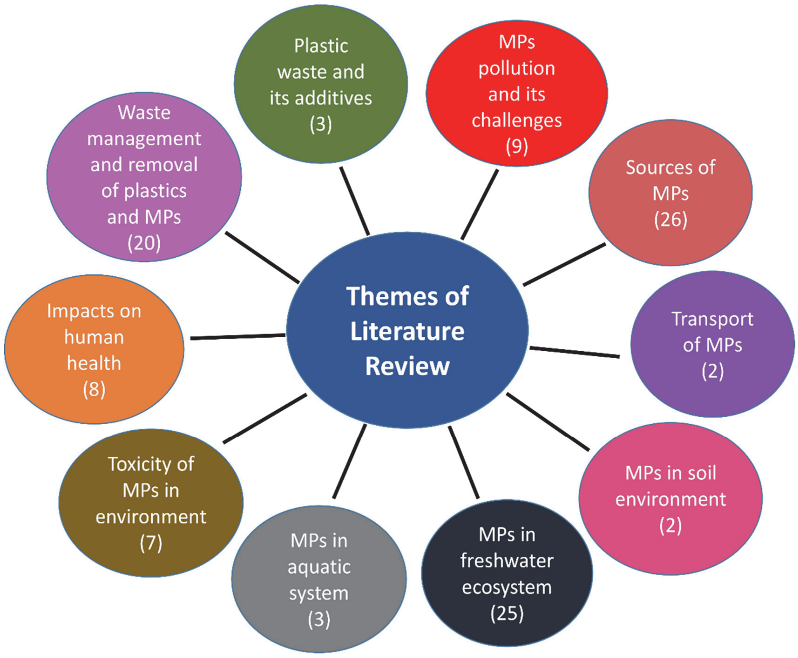

Figure 1. Themes of literature review

The ***year-wise distribution*** of the articles (Figure 2) shows an increase in the number of publications with each passing year since 2014, however, in the initial years, till 2016 the numbers were very less. Since 2017, the numbers started increasing and most of the publications came out after 2018, which peaked at 21 in 2021 and since then it has decreased to 19 in 2023. The changing trend in the number of publications shows that MP distribution has become a highly researched topic, attracting a significant number of academic research. The number of publications slightly dropped in 2022, as the focus is more on developing more innovative and efficient methods for controlling MPs.

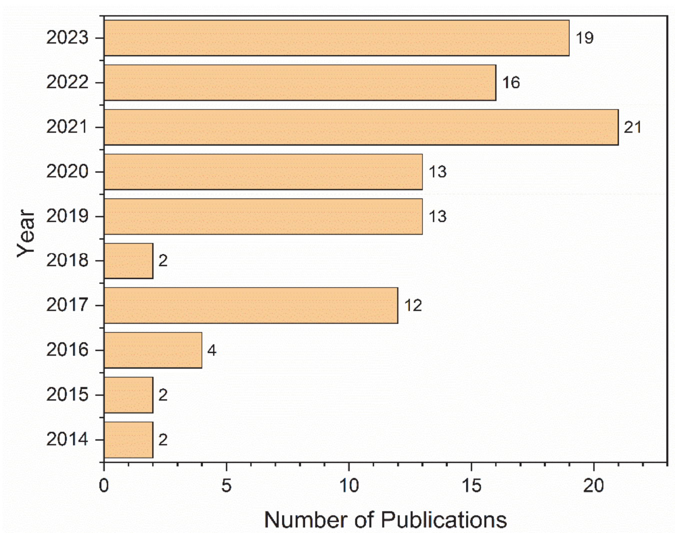

Figure 2. Number of papers published over the last 10 years

The ***spatial spread*** of the publications revealed that most of the research was carried out in countries such as China, India, the UK, and North America, as depicted in Figure 3. Latin American, African, and Middle Eastern countries conducted very limited studies. The least number of publications (only one) is from Turkey, Finland, Sri Lanka, and Brazil.

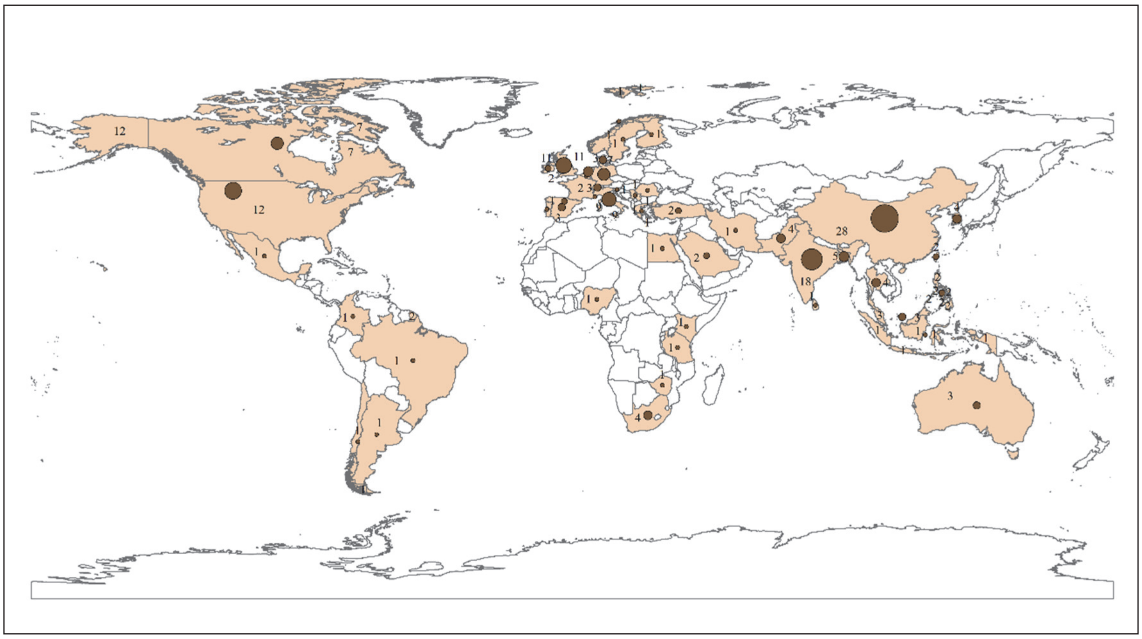

Figure 3. Publications' country distribution

The ***main characterization factors*** of the MPs were also studied and five factors were considered, viz., Size, Shape, Colour, Surface, and polymetric composition (Figure 4). Further, how these factors were determined using which methodology(ies) were also studied.

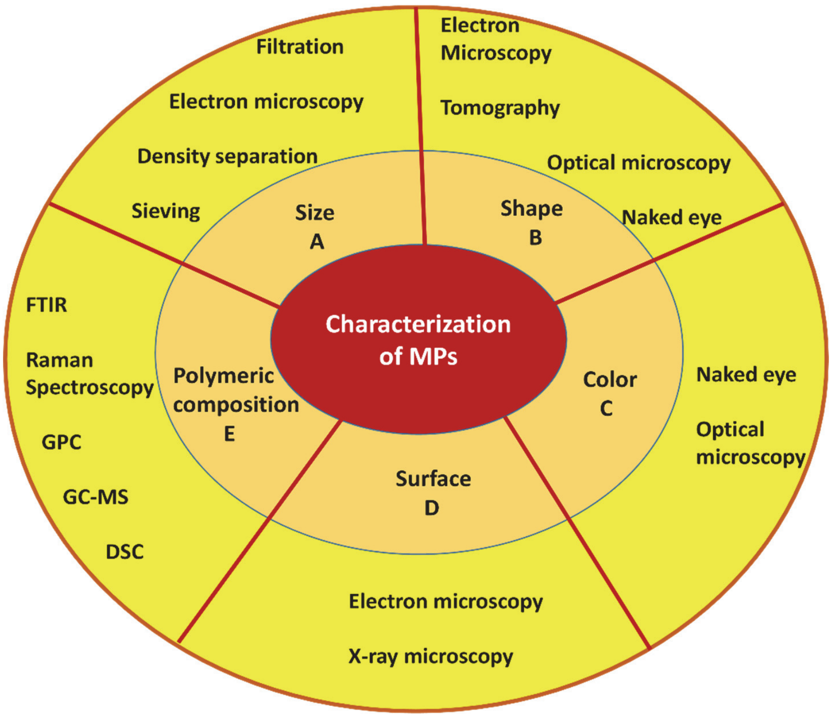

Figure 4. Summary of the characterization of MPs with the analytical methods

The current research on the characterization techniques of MPs includes ATR-FTIR, SEM-EDS, Raman spectroscopy, and AFM (Table S1).

To summarise, this paper is an attempt to present an up-to-date assessment of recent and advanced research about microplastics, their origin and occurrence, identification and removal methods, and proposes integrated strategies to prevent the input of plastic waste material into the environment, by source control, improved plastic waste management and techniques for degradation and conversion of MPs.

3. ORIGIN OF MPS

The origin of MPs in aquatic systems is multifaceted, with various sources contributing to their presence. MPs are found to exhibit a broad range of characteristics, including variations in size (> 1 μm to <5 mm) [8], shape (fibers, films, foams, and fragments) [15], colour (blue, white, green, black, brown, pink, and grey) [27], chemical composition (varying with the type of polymer) [28], and specific density (ranging from *0.89 g/cm³ to 1.58 g/cm³*) [29]. These differences are the result of its diverse sources and processes. MPs are commonly categorized as primary and secondary sources. Primary MPs are designed for commercial use to be added intentionally to personal care products such as cleansers, shampoos, toothpaste, and cosmetics. Although primary MPs constitute just a fraction of the total MPs discovered (from 1μm to 5mm) [30], sewage and wastewater are recognized as significant sources of MP pollution because these can easily pass through the filtration units and end up in aquatic environments [19]. Secondary MPs originate after large plastics breakdown on exposure to UV radiation, thermal degradation, biodegradation, hydrolysis, and mechanical abrasion [30]. Various materials, such as plastic shopping bags, containers, sewage and industrial waste, textiles, fishing gear, and tyres, might act as secondary pollutants.

The land-based point source of MPs is the direct inflow of wastewater effluents from coastal cities into the nearby coastal waters. In past studies, MPs have been detected in drinking groundwater [31], bottled water [32], and commercial food-grade sea salt [33]. Table S2 in supplementary information enumerates the different sources with their concentration such as PCPs, textiles, food packaging containers, etc that discharge MPs into the environment.

Among the various sources of MP pollution, a significant contribution is from textiles and single-use plastics. Fabrics made of polymers like nylon, polyester, and acrylic shed millions of microfibers with every wash. The composition of the textile, cleaning conditions, and detergent types all influence the release of these microfibers [18]. A study in Sweden provides insights into the staggering volume of MPs released from household laundry (8–950 tonnes of MP production per year) [34]. In a study [35], the quantities of fiber fragments released were 137,951 (65% polyester/35% cotton) and 728,789 (100% polyacrylonitrile (PAN)) while washing 6 kg of clothing. Direct washing of clothes in rivers, especially in underdeveloped and developing countries is another practice that directly introduces MPs into aquatic ecosystems [36]. Apart from textiles and single-use plastics, food packaging, straws, and cups are other significant contributors to plastic pollution. Plastic-coated paper cups, which contain polymers like PE, PP, and PS on the inside of the cup, can release 675-5984, 781-4951, and 838-5215 MPs/L respectively into beverages [37], consumed by humans. These MPs have harmful effects on human beings and after passing through the wastewater treatment plant (WWTP), end up in rivers and oceans.

4. OCCURRENCE OF MPS

Microplastic pollution varies significantly based on geographical locations. Different regions experience varying levels of pollution. Its distribution, quantity, and movement are influenced by complex factors including human activities (such as plastic usage and disposal), population density (which correlates with plastic consumption and waste generation), meteorological conditions (dispersion of plastic), and hydrological processes (which influence movement within water bodies) [38]. Studies conducted globally [39,40, 41], highlight the existence of MPs in riverine environments worldwide. MPs can enter rivers through surface runoff from roads and urban areas, wind dispersal, atmospheric deposition, and WWTP effluents [13]. Rivers are sources of MPs as it is consumed by the biota that inhabits river systems and wastewater sinks for untreated water discharged from the industry [39]. The sources of MPs have been identified by Horton et al. [42] in the river Thames basin (UK), which includes MPs from markings on the road surface from sewage and discharged input.

MPs of different sizes (50 μm to 5 mm) have been reported in rivers globally viz., the Ergene, Turkey [40]; Karnafull, Bangladesh [43]; Ganga, India [44]; Haihe, China [13]; Lawaye, Philippines [45] among many others. Table 2 lists the rivers across the diverse regions with the data on the concentration and particle size of the MPs.

Table 2. Abundance of MPs in rivers around the world

River	Country	Concentration (MPs/ m^3)	Particle size (mm)	References
Haihe River	China	0.69 to 74.95	0.333-5	[13]
Netravathi River	India	288	0.3-5	[39]
Ergene River	Turkey	(4.65 ± 2.06) x 10^3 (May)	> 0.045	[40]
		(6.90 ± 5.16) x 10^3 (Sept)		
Kosasthalaiyar River	India	(4.94 ± 8.98) x 10^3	> 0.5	[41]
Karnafull River	Bangladesh	(0.57 ± 0.07 - 6.63 ± 0.52) x 10^3		[43]
Ganga River	India	0.38–0.684	2.5–5	[44]
Lawaye River	Philippines	3333	0.363-5	[45]
Chao Phraya River	Thailand	21 ± 16	0.335- 5.15	[47]
Adyar River	India	0.33 x 10^3	0.335 - 5	[48]
Kosasthalaiyar River	India	0.67 x 10^3	0.335- 5	[48]
Multhirappuzhayar River	India	0.20 x 10^3	0.335-5	[48]
Tapi-Phumduang River	Thailand	(0.136–0.562) x 10^3	-	[49]
Rivers in Sungai Dungun	Malaysia	22.8–300.8	-	[50]
Nakdong River	South Korea	293 ± 83 (upstream)	0.050–0.150	[46]
		4760 ± 5242 (downstream)		
		210-15,560 (rainy season)	0.05-0.33	[51]
		260-1410 (dry season)		

For instance, the Ergene River in Turkey exhibits seasonal concentrations varying from (4.65 ± 2.06) x 10^3 in May to (6.90 ± 5.16) x 10^3 MPs/m^3 in September, with particles exceeding 45 μm [40]. The Ganga River in India reported a concentration between 0.38 and 0.684 MPs/m^3, with particle sizes ranging from 2.5 to 5 mm [44]. Other rivers in India including Netravathi, Kosasthalaiyar, Adyar, and Multhirappuzhayar also present varying concentrations and particle sizes [39, 41, 48]. The MP concentration of rivers from different countries including Bangladesh, Thailand, China, Malaysia, Philippines, and South Korea [13, 43, 45, 46, 47, 50] have varying concentrations with different sizes.

In South Korea, MPs abundance in the Nakdong River shows seasonal variations, with higher quantities observed during the rainy season (210 to 15,560 items/m^3) as compared to the dry season (260 to 1410 items/m^3). This variation may be influenced by factors such as increased surface runoff during heavy rainfall, carrying more MPs into the river [51]. Lebreton et al. [52] reported that 1.05 × 10^5 tons of plastic waste materials are dumped into the Indian Ocean annually by the Ganges in India, one of the rivers that carry millions of tons of plastic waste to the seas. According to Napper et al. [53], the Ganges, along with the Brahmaputra and Meghna (GBM), release up to 1–3 billion MPs into the Indian Ocean daily. These inputs have severe implications for marine ecosystems and organisms, emphasizing the urgency of addressing plastic pollution at its source.

5. MPS EXPOSURE ROUTES AND THEIR EFFECTS ON THE ENVIRONMENT AND HUMAN

MPs have hydrophobic surfaces with a high surface area-to-volume ratio to adsorb organic chemicals from the surrounding environment thus increasing the toxicity [54]. The toxicity is influenced by factors such as size, shape, weathering process, surface charge, adsorption, etc. [55]. The type and concentrations of additives contained in plastics are the crucial factors, some of which may be toxic. When these plastics break down into MPs, their additives are released into the environment and subsequently absorbed and accumulated by living organisms. Phthalate plasticizers, bisphenol A (BPA), brominated flame retardants, triclosan, nonylphenol, and organotin chemicals are among the additives in plastics [56]. Therefore, interactions between MP and phytoplankton, zooplankton, and algae disrupt the marine carbon cycle and have an impact on carbon fixation, which in turn affects climate change and global warming [57]. MPs pose a potential threat to human health due to their common existence in the environment. It has also been reported that these compounds may accumulate in humans because of biological processes. The risk of human exposure increases with the movement of MPs. According to Cimmino et al. [58], BPA inhibits thyroid hormone, reduces pancreatic beta cell function, and worsens obesity and cardiovascular issues. Also, the usage of phthalates, a different addition, has been linked to cancer, abnormal sexual behavior, and birth defects [59].

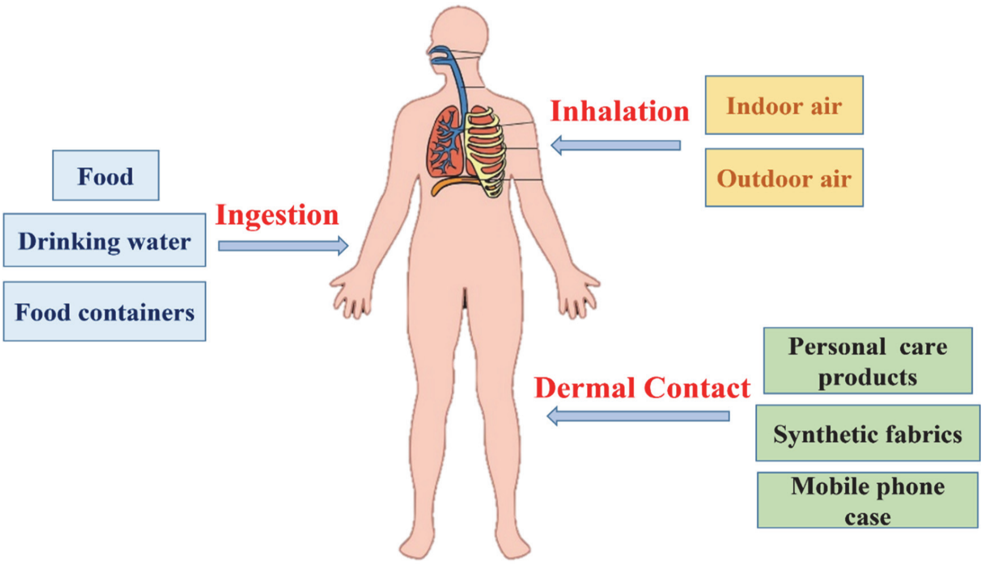

Figure 5. Pathways of human exposure to MPs

Humans are exposed to MPs through different routes: the ingestion of water or food, the inhalation of both indoor and outdoor air, and dermal contact through personal care products, clothing, and objects like cell phone cases (Figure 5). MPs are readily ingested by a variety of marine organisms, entering the food chain at its lowest levels. When these contaminated organisms, in the form of seafood, are consumed by humans, the MPs are transferred to the human body. These MPs affect humans causing problems with the reproductive system, body weight, sex ratio, and live births [60]. Common takeaway food containers are typically made of polypropylene (PP), polystyrene (PS), polyethylene (PE), and polyethylene terephthalate (PET) which become MPs contaminated on exposure to plastic products and goods that leach BPA [61]. A person who eats in takeaway containers 4–7 times a week consumes 12-203 pieces of MPs [62].

MPs act as vectors for pollutants in the environment, harmful diseases, and chemical parasites. MPs remain suspended in the atmosphere because of their small size and low density, making them inhalable. This ability of MPs to enter the respiratory system raises concerns about their potential health effects on human beings [63]. When MPs are inhaled, they can potentially damage the human lungs and the gastrointestinal tract (GIT) followed by endocytosis [64]. Once MPs are inhaled, these particles can interact in various ways with the pulmonary epithelium, through active cellular uptake, direct cellular penetration, or diffusion. In Paris, MP contamination is not only limited to outdoor air (5.4 fibers/m^3) but also to indoor air (0.9 fibers/m^3) [65]. The average concentration of MPs reported in Shanghai is 1.42 particles/m^3 in the outdoor air within the size range of 23 to 5000 μm [66]. According to Tursi et al. [67] the main sources of MPs in the air, both indoors and outdoors, include landfills, synthetic textiles, building materials, waste, and the degradation processes of plastic.

The application of cosmetics such as face creams or facial cleansers to the skin, increases the exposure risk of MPs. This damage causes localized inflammation and cytotoxicity which harm the skin [68]. The MPs are also transferred to human hands during the use of protective mobile phone cases (PMPCs) [69]. Table 3 indicates plastic components and their associated health and environmental effects.

Table 3. Health effects associated with the type of plastic polymer

Type of polymer	Health effects	Environmental effects	References
Polyethylene terephthalate (PETE)	Necrosis, erythema, pulmonary edema and coughing	Precursors of ozone in atmospheric environments	[70]
Poly Vinyl Chloride (PVC)	Liver damage, anemia, weakness, kidney and brain damage, carcinogenic, and effects on the central nervous system	Deteriorate air and drinking water quality	[71]
Polycarbonate (PC)	liver function alternation, insulin resistance changes, brain damage	Impacts the emission of greenhouse gases	[72]
Low-Density Polyethylene (LDPE)	Irritated throat, eyes, breathing shortness, mood swings, blurred vision, memory loss, nausea, headache and vomiting	Greenhouse gas emissions that contribute to climate change	[73]
High-Density Polyethylene (HDPE)	Brain function is limited by irritation to the eyes, skin, and respiratory system	Upon exposure to room temperature air, undergoes autoxidation to generate benzoic acid	[74]

It has also been reported in Table 3 that there are varying health and environmental effects for different polymers. For instance, exposure to PETE may result in necrosis and pulmonary complications, in addition to its involvement in the generation of ozone [70]. The utilization of PVC carries the potential of inducing liver injury and central nervous system impacts, while simultaneously contributing to the degradation of air and water quality [71]. PC and LDPE instigate a range of health issues and the emission of greenhouse gases [72,73]. Furthermore, HDPE can irritate the eyes and respiratory tract, and it undergoes autoxidation leading to the production of benzoic acid [74].

6. MANAGEMENT OF MPS

Although plastics have become ubiquitous in our lives, to minimize the effect of MPs on our health, a sustainable approach to the production and consumption of plastic products is highly desirable to protect the environment, human health, and the global economy. The marine pollution reduces the economic opportunities by damaging the marine industries (fishing and tourism) which will ultimately result in income loss among the fishermen [75]. Effective management strategies could involve a combination of research, policy-making, public engagement, and international collaboration. Authors recommend government reduce the problem of MPs through environmental awareness campaigns to educate localities [76]. The fundamental strategies to address MP pollution should concentrate on (i) source control, through the implementation and enforcement of laws and regulations, and (ii) remediation and clean up, including removing MPs that are already present in water bodies [77].

6.1 MPs control at source

Controlling the sources of MP pollution is crucial in mitigating its impact on the environment. This can be achieved through the regulations that restrict the amount, and use of MPs, particularly in personal care and cosmetic products, thus, reducing the amount of MPs entering the aquatic environment. Additionally, the efforts to reduce disposable plastic materials by prohibiting water bottles, shopping bags, straws, and cutlery [78]. The Ministry of Environment, Forests, and Climate Change in India has made significant efforts to lessen the pollution caused by disposable plastic waste materials. Items prohibited under the Plastic Waste Management (Amendment) Rules, 2021 include stirrers, earbuds with plastic sticks, balloons with plastic sticks, plastic flags, candy sticks, ice-cream sticks, and decorative polystyrene (Thermocol) [79]. The strategies recommended for consumers, producers, and government to control MPs at source are mentioned in Table 4.

Table 4. Control strategies for MPs at the source

Sources	Responsibility	Strategies
Laundry	Consumer	Changing washing habits
		Buy textiles that release less fiber
	Producer	Setting filter in the washing machine
PCPs	Consumer	Buy plastic-free cosmetics
	Producer	Stop using plastic microbeads
	Government	Ban on plastic microbeads in PCCPs
Plastics bags	Consumer	Bringing a reusable carry bag for shopping (preferably a paper bag)
	Producer	Reduce unnecessary packaging
	Government	Ban, tax, or levy heavy fees on plastic bags/ heavy fines on usage
Bottled water	Consumer	Use of boiling water
		Use of reverse osmosis filters
	Producer	Reusable water bottle material
	Government	Ban on Single-use plastics
Tyre wear	Consumer	Change in way of operating vehicle (driving habits)
Wastewater	WWTP facility	Advanced treatment technologies

Clothes are one of the main causes of MP pollution in the world. Polyester or other types of MPs are undoubtedly present in the majority of clothing. These articles of clothing contain MP fiber that is released into the water while washing. The release of MPs can be reduced by adding a filter to washing machines which can trap these fibers [80]. Another way to reduce MPs is the use of public transit or carpooling which shall reduce tyre wear and, consequently, the release of MPs from degraded rubber [81]. It is advisable to avoid the use of products that contain MP beads including toothpaste and face washes by checking the ingredients label (It should be made mandatory for the producers to indicate the amount of MPs present/added to the product). These beads can get through filtration systems, travel long distances, and even get into the water supply. Choosing to avoid single-use plastics such as straws, glasses, plates, and takeaway containers can have a significant positive impact on reducing the plastic waste entering the environment hence reducing the production and release of MPs. Further, initiatives such as promoting the use of biodegradable alternatives, implementing recycling programs, raising public awareness about plastic pollution, encouraging businesses to adopt sustainable practices, and supporting research into innovative solutions are some of the other solutions that when implemented may result in less production of MPs and its release in the environment.

6.2 Remediation and clean-up

The removal of MPs that are already present in water bodies is essential to prevent further contamination and minimize their impact on aquatic life. Authors have suggested that governments need to improve garbage collection systems and enhance recycling rates to prevent waste from leaking into the ecosystem between the trash can and the landfill. Additionally, strategies and initiatives to encourage businesses and users to promote the Refuse-Reduce-Reuse-Repair-Recycle circular economy would lessen the flow of MPs that end up in the environment [82]. There is a need for innovative technologies such as robotic devices to clean up MPs in aquatic environments. Moreover, designing and employing drones or autonomous vehicles equipped with sensors to find and remove MPs. The removal of MPs becomes challenging due to their small size and potential for increased ecological toxicity. Therefore, plastics can be collected and recycled into new materials, mixed with other materials, and reused by incorporating them into specific products or processes without alteration or degradation to produce new energy sources [83]. Table 5 provides details of different recycling practices for plastic waste into valuable products across different countries [84-88].

Table 5. Plastic waste into useful products

Plastic waste	Recycled product	Country	References
PET	Used to modify bitumen production which turns out to be durable and long-lasting	India	[84]
PET	Electrocatalytic upcycling into valuable commodity chemicals, potassium formate terephthalic acid, and H2 fuel.	China	[85]
PET powder and expanded polystyrene (EPS)	Incorporating waste foam into a bio-matrix Open-cell material for use as both acoustic and thermal insulation for industrial, civil, and maritime applications.	Italy	[86]
PVC	Used in pavement construction increases resistance to permanent deformation in terms of rutting	India	[87]
PP	Converted into oil (olefins, paraffins, cyclists, and aromatics) using supercritical water	US	[83]
PET	Used as a modifier in asphalt mixtures, tends to reduce the penetration and increase the softening point of the modified asphalt binder.	Egypt	[88]

India modifies bitumen production by adding up to 12% PET waste to achieve stronger binding between binder and aggregate for sustainable infrastructure production [84]. In China, PET is used for electrocatalytic upcycling, demonstrating the strategy for plastic waste management [85]. In Egypt, the addition of 12% PET waste material to asphalt binder upgraded the pavement service life by 2.81 times and saved around 20% of asphalt layer thickness [88]. The innovative use of PET and EPS in Italy for creating bio-matrix open-cell material capable of acting as an acoustic and thermal insulator signifies a sustainable and eco-friendly approach to recycling marine MP waste [86].

In another study, MP waste found in the ocean and soil is used as a source of liquid fuel. Here, Ni–Pd/TNPs nanocatalyst catalyst is designed for two specific reactions: catalytic cracking of MPs-phenol and steam reforming. These reactions result in the generation of valuable liquid products such as trimethyl-(2-trimethylsilylphenyl)silane, cyclohexane-1,3-dione, 2-allylaminomethylene-5,5-dimethyl-, bis(2-ethylhexyl)phthalate (BEHP), etc. and hydrogen fuel. It indicates the potential for converting MP pollution into value-added fuels and reducing threats to marine life. This approach promotes the management of MP waste through the use of sustainable materials in various industries [89].

7. CONCLUSIONS

MPs are abundant, ubiquitous, and persistent. These tiny plastic particles, often invisible to the naked eye, have permeated various ecosystems, from the depths of oceans to the air we breathe. MPs represent a global environmental challenge with far-reaching implications. Comprehending the origins, occurrence, and health effects of MPs is vital for addressing this complex issue. The management of MPs is not only an environmental imperative but also a concern for public health and long-term sustainability. As the global community continues to address the sources, occurrence, and health effects of MPs, a multi-faceted approach involving research, regulation, education, and innovation is essential to mitigate this growing threat to our planet. It is also important to raise awareness of the impacts of MP and plastic waste mismanagement on the environment. Strict policies are required at local, national, regional, and international levels to reduce the use and consumption of plastics.

REFERENCES

[1] R.Kumar, A.Verma, A.Shome, R.Sinha, S.Sinha, P.K. Jha, R.Kumar, P.Kumar, Shubham, S.Das, P.Sharma, P.V.Vara Prasad (2021) Impacts of plastic pollution on ecosystem services, sustainable development goals, and need to focus on circular economy and policy interventions. *Sustainability*, 13, 9963, https://doi.org/10.3390/su13179963

[2] Plastics Europe Plastics – The Facts 2022 an analysis of European plastics production, demand and waste data. *Plastics Europe, Plastics the Fact 2022, Belgium*. https://plasticseurope.org/wp-content/uploads/2022/10/PE-PLASTICS-THE-FACTS_V7-Tue_19-10-1.pdf.

[3] 3. A.A.Okunola, O.A.Kehinde, A.E.Olufiropo (2019) Public and environmental health effects of

plastic wastes disposal: A review. *Journal of Toxicology and Risk Assessment*, 5, 76-86. https://doi.org/10.23937/2572-4061.1510021

[4] UNEP (2021). *From Pollution to Solution*, p. 10.1016, https://doi.org/S0262-4079(18)30486-X,

[5] A.Ashrafy, A.A.Liza, M.N.Islam, M.M.Billah, S.T.Arafat, M.M.Rahman, S.M.Rahman (2023) Microplastics pollution: A brief review of its source and abundance in different aquatic ecosystems. *Journal of Hazardous Materials Advances*, *9*, 100215. https://doi.org/10.1016/j.hazadv.2022.100215

[6] J.Ru, Y.Huo, Y.Yang (2020) Microbial degradation and valorization of plastic wastes. *Frontiers in Microbiology*, 11, 442, https://doi.org/10.3389/FMICB.2020.00442

[7] F.Julienne, N.Delorme, F.Lagarde (2019) From macroplastics to microplastics: Role of water in the fragmentation of polyethylene. *Chemosphere*, 236, 124409, http://doi.org/10.1016/j.chemosphere.2019.124409

[8] A.I.Osman, M.Hosny, A.S.Eltaweil, S.Omar, A.M.Elgarahy, M.Farghali, P.S.Yap, Y.S.Wu, S.Nagandran, K.Batumalaie, S.C.B.Gopinath, O.D.John, M.Sekar, T.Saikia, P.Karunanithi, M.H.M.Hatta, K.A.Akinyede (2023) Microplastic sources, formation, toxicity and remediation: A review. *Environmental Chemistry Letters*, 21, 1–41, http://doi.org/10.1007/s10311-023-01593-3

[9] R.C. Thompson, Y.Olsen, R.P.Mitchell, A.Davis, S. J.Rowland, A.W.G. John, D.McGonigle, A.E.Russell (2004) Lost at sea: Where is all the plastic? *Science*, 304, 838, https://doi.org/10.1126/science.1094559

[10] ISO (2020). *Plastics-Environmental Aspects – State of Knowledge and Methodologies*, p. 41.

[11] A.Parsaeimehr, C.M.Miller, G.Ozbay (2023) Microplastics and their interactions with microbiota. *Heliyon*, 9, e15104, https://doi.org/10.1016/j.heliyon.2023.e15104

[12] J.Wang, Z.Tan, J.Peng, Q.Qiu, M.Li (2016) The behaviors of microplastics in the marine environment. *Marine Environmental Research*, 113, 7–17, https://doi.org/10.1016/j.marenvres.2015.10.014

[13] Y.Liu, J.Zhang, C.Cai, Y.He, L.Chen, X.Xiong, H.Huang, S.Tao, W.Liu (2020) Occurrence and characteristics of microplastics in the Haihe River: An investigation of a seagoing river flowing through a megacity in northern China. *Environmental Pollution*, 262, 114261, https://doi.org/10.1016/j.envpol.2020.114261

[14] J.C.Prata (2018) Airborne microplastics: Consequences to human health? *Environmental Pollution*, 234, 115–126, https://doi.org/10.1016/j.envpol.2017.11.043

[15] Y.M.Lozano, T.Lehnert, L.T.Linck, A.Lehmann, M.C.Rillig (2021) Microplastic shape, polymer type, and concentration affect soil properties and plant biomass. *Frontiers in Plant Science*, 12, 616645, http://doi.org/10.3389/fpls.2021.616645

[16] G. Kalčíková, B. Alič, T. Skalar, M. Bundschuh, and A. Ž. Gotvajn (2017) Wastewater treatment plant effluents as source of cosmetic polyethylene microbeads to freshwater. *Chemosphere*, 188, 25–31, https://doi.org/10.1016/j.chemosphere.2017.08.131

[17] J.Boucher, D.Friot (2017) Primary microplastics in the oceans: A global evaluation of sources. In: *Primary Microplastics in the Oceans: A Global Evaluation of Sources*, https://doi.org/10.2305/iucn.ch.2017.01.en

[18] A.P.Periyasamy, A.Tehrani-Bagha (2022) A review on microplastic emission from textile materials and its reduction techniques. *Polymer Degradation and Stability*, 199, 109901, https://doi.org/10.1016/j.polymdegradstab.2022.109901

[19] M.Sadia, A.Mahmood, M.Ibrahim, M.K.Irshad, A.H.A.Quddusi, A.Bokhari, M.Mubashir, L.F.Chuah, P.L.Show (2022) Microplastics pollution from wastewater treatment plants: A critical review on challenges, detection, sustainable removal techniques and circular economy. *Environmental Technology and Innovation*, 28, 102946, https://doi.org/10.1016/j.eti.2022.102946

[20] [7]I.E.Napper, A.Bakir, S.J.Rowland, R.C.Thompson (2015) Characterisation, quantity and sorptive properties of microplastics extracted from cosmetics. *Marine Pollution Bulletin*, 99, 178–185, https://doi.org/10.1016/j.marpolbul.2015.07.029

[21] C.Schmidt, T.Krauth, S.Wagner (2017) Export of plastic debris by rivers into the sea. *Environmental Science and Technology*, 51, 12246–12253, https://doi.org/10.1021/acs.est.7b02368

[22] Z.Yuan, R.Nag, E.Cummins (2022) Human health concerns regarding microplastics in the aquatic environment – From marine to food systems. *Science of the Total Environment*, 823, 153730, https://doi.org/10.1016/j.scitotenv.2022.153730

[23] The gazette of India, extraordinary, Part II, Section 3; Ii. *Extraordinary. Ministry of the Environment, Forest and Climate Change*. https://cpcb.nic.in/uploads/plasticwaste/Notification-12-08-2021.pdf, Subsection (I).

[24] D.Xanthos T.R.Walker (2017) International policies to reduce plastic marine pollution from single-use plastics (plastic bags and microbeads): A review. *Marine Pollution Bulletin*, 118, 17–26, https://doi.org/10.1016/j.marpolbul.2017.02.048

[25] J.P.McDevitt, C.S.Criddle, M.Morse, R.C.Hale, C.B.Bott, C.M.Rochman (2017) Addressing the issue of microplastics in the wake of the microbead-free waters act—A new standard can facilitate improved policy. *Environmental Science and Technology*, 51, 6611–6617, https://doi.org/10.1021/acs.est.6b05812

[26] G.Bakshi H.Does (2016) Sweden recycle 99% of its household waste? *Global Citizen*. Melbourne.

[27] D.Saad, M.Ndlovu, G.Ramaremisa, H.Tutu, M.Sillanpää (2023) Characteristics of microplastics in sediment of the Vaal River, South Africa: Implications on bioavailability and toxicity. *International Journal of Environmental Science and Technology (Tehran)*, http://doi.org/10.1007/s13762-023-05168-1

[28] S.Sarkar, H.Diab, J.Thompson (2023) Microplastic pollution: Chemical characterization and impact on wildlife. *International Journal of Environmental Research and Public Health*, 20, 1745, http://doi.org/10.3390/ijerph20031745

[29] T.Dalu, T.Banda, T.Mutshekwa, L.F.Munyai, R.N.Cuthbert (2021) Effects of urbanisation and a wastewater treatment plant on microplastic densities along a subtropical river system. *Environmental Science and Pollution Research*, 28, 36102–36111, https://doi.org/10.1007/s11356-021-13185-1

[30] M.N.Issac, B.Kandasubramanian (2021) Effect of microplastics in water and aquatic systems. *Environmental Science and Pollution Research*, 28, 19544–19562, https://doi.org/10.1007/s11356-021-13184-2

[31] A.A.Koelmans, N.H.Mohamed Nor, E.Hermsen, M.Kooi, S.M.Mintenig, J.DeFrance (2019) Microplastics in freshwaters and drinking water: Critical review and assessment of data quality. *Water Research*, 155, 410–422, https://doi.org/10.1016/j.watres.2019.02.054

[32] I.Gambino, F.Bagordo, T.Grassi, A.Panico, A.DeDonno (2022) Occurrence of microplastics in tap and bottled water: Current knowledge. *International Journal of Environmental Research and Public Health*, 19, 5283, https://doi.org/10.3390/ijerph19095283

[33] F.Parvin, J.Nath, T.Hannan, S.M.Tareq (2022) Proliferation of microplastics in commercial sea salts from the world longest sea beach of Bangladesh. *Environmental Advances*, 7, 100173, https://doi.org/10.1016/j.envadv.2022.100173

[34] K.Magnusson, K.Eliasson, A.Fråne, K.Haikonen, J.Hultén, M.Mikael Olshammar, J.Stadmark, A.Voisin, I.V.L.Svenska (2016) *Swedish Sources and Pathways for Microplastics to the Marine Environment. Report*- C183 Swedish Environmental Research Institute, Stockholm.

[35] I.E.Napper, R.C.Thompson (2016) Release of synthetic microplastic plastic fibres from domestic washing machines: Effects of fabric type and washing conditions. *Marine Pollution Bulletin*, 112, 39–45, https://doi.org/10.1016/j.marpolbul.2016.09.025

[36] F.C.Alam, E.Sembiring, B.S.Muntalif, V.Suendo (2019) Microplastic distribution in surface water and sediment river around slum and industrial area (case study: Ciwalengke River, Majalaya district, Indonesia). *Chemosphere*, 224, 637–645, http://doi.org/10.1016/j.chemosphere.2019.02.188

[37] H.Chen, L.Xu, K.Yu, F.Wei, M.Zhang (2023) Release of microplastics from disposable cups in daily use. *Science of the Total Environment*, 854, 158606, https://doi.org/10.1016/j.scitotenv.2022.158606

[38] R.A.Rojas-Luna, L.Oquendo-Ruiz, C.A.García-Alzate, V.A.Arana, R.García-Alzate, J.Trilleras (2023) Identification, abundance, and distribution of microplastics in surface water collected from Luruaco Lake, low basin Magdalena River, Colombia. *Water*, 15, 344, https://doi.org/10.3390/w15020344

[39] K.Amrutha, A.K.Warrier (2020) The first report on the source-to-sink characterization of microplastic pollution from a riverine environment in tropical India. *Science of the Total Environment*, 739, 140377, https://doi.org/10.1016/j.scitotenv.2020.140377

[40] Z.Akdogan, B.Guven, A.E.Kideys (2023) Microplastic distribution in the surface water and sediment of the Ergene River. *Environmental Research*, 234, (116500, https://doi.org/10.1016/j.envres.2023.116500

[41] G.B.Priyanka, B.Govindarajulu (2023) Transportation of microplastics from the rural area into the urban area of the Kosasthalaiyar River in the metropolitan city of Chennai. *Regional Studies in Marine Science*, 66, (103151, https://doi.org/10.1016/j.rsma.2023.103151.

[42] A.A.Horton, C.Svendsen, R.J.Williams, D.J.Spurgeon, E.Lahive (2017) Large microplastic particles in sediments of tributaries of the River Thames, UK – Abundance, sources and methods for effective quantification. *Marine Pollution Bulletin*, 114, 218–226, http://doi.org/10.1016/j.marpolbul.2016.09.004.

[43] M.J.Hossain, S.AftabUddin, F.Akhter, N.Nusrat, A.Rahaman, M.N.A.Sikder, M.M.Monwar, M.S.N.Chowdhury, S.Jiang, H.Shi, J.Zhang (2022) Surface water, sediment, and biota: The first multi-compartment analysis of microplastics in the Karnafully river, Bangladesh. *Marine Pollution Bulletin*, 180, 113820, https://doi.org/10.1016/j.marpolbul.2022.113820

[44] R.SingH, G.S.Singh (2020) Integrated management of the Ganga River: An ecohydrological approach. *Ecohydrology and Hydrobiology*, 20, 153–174, https://doi.org/10.1016/j.ecohyd.2019.10.007

[45] E.Q.Espiritu, S.A.S.Dayrit, A.S.O.Coronel, N.S.C. Paz, P.I.L.Ronquillo, V.C.G.Castillo, E.P.Enriquez (2019) Assessment of quantity and quality of microplastics in the sediments, Waters, Oysters and Selected Fish Species in Key Sites Along the Bombong Estuary and the Coastal Waters of Ticalan in San Juan, Batangas. *Philippine Journal of Science*, 148 (4), 789–801.

[46] S.Eo, S.H.Hong, Y.K.Song, G.M.Han, W.J.Shim (2019) Spatiotemporal distribution and annual load of microplastics in the Nakdong River, South Korea. *Water Research*, 160, 228–237, https://doi.org/10.1016/j.watres.2019.05.053

[47] K.Ounjai, S.K.Boontanon, P.Piyaviriyakul, S.Tanaka, S.Fujii (2022) Assessment of microplastic contamination in the urban lower Chao Phraya River of Bangkok city, Thailand. *Journal of Water and Health*, 20, 1243–1254, https://doi.org/10.2166/wh.2022.130

[48] S.Lechthaler, K.Waldschläger, C.G.Sandhani, S.A.Sannasiraj, V.Sundar, J.Schwarzbauer, H.Schüttrumpf (2021) Baseline study on microplastics in Indian rivers under different anthropogenic influences. *Water*, 13, 1648, https://doi.org/10.3390/w13121648

[49] N.Chinfak, P.Sompongchaiyakul, C.Charoenpong, H.Shi, T.Yeemin, J.Zhang (2021) Abundance, composition, and fate of microplastics in water, sediment,

and shellfish in the Tapi-Phumduang River system and Bandon Bay, Thailand. *Science of the Total Environment*, 781, 146700, https://doi.org/10.1016/j.scitotenv.2021.146700

[50] Y.H.Tee, Y.S.Ibrahim, W.M.A.WanMohdKhalik (2020) Microplastic abundance, distribution, and composition in sungai dungun, Terengganu, Malaysia. *Sains Malaysiana*, 49, 1479–1490, https://doi.org/10.17576/jsm-2020-4907-01

[51] J.H.Kang, O.Y.Kwon, K.W.Lee, Y.K.Song, W.J.Shim (2015) Marine neustonic microplastics around the southeastern coast of Korea. *Marine Pollution Bulletin*, 96, 304–312, https://doi.org/10.1016/j.marpolbul.2015.04.054

[52] L. C. M. Lebreton, J. Van Der Zwet, J. W. Damsteeg, B. Slat, A. Andrady, and J. Reisser (2017) River plastic emissions to the world's oceans. *Nature Communications*, 8, 15611, https://doi.org/10.1038/ncomms15611

[53] I.E. Napper, A. Baroth, A. C. Barrett, S. Bhola, G. W. Chowdhury, B. F. R. Davies, E.M.Duncan, S.Kumar, S.E.Nelms, M.N.HasanNiloy, B.Nishat, T.Maddalene, R.C.Thompson, H.Koldewey, H. (2021) The abundance and characteristics of mi-croplastics in surface water in the trans-boundary Ganges River. *Environmental Pollution*, 274, 116348, https://doi.org/10.1016/j.envpol.2020.116348

[54] T. Pelamatti, L. R. Cardelli, and L. M. Rios-Mendoza (2022) The role of microplastics in bioaccumulation of pollutants. In: *Handbook of Microplastics in the Environment*. Springer International Publishing: Cham, Germany, pp. 667–696.

[55] X.Shi, Z.Chen, W.Wei, J.Chen, B.-J.Ni (2023) Toxicity of micro/nanoplastics in the environment: Roles of plastisphere and eco-corona. *Soil and Environmental Health*, 1, 100002, http://doi.org/10.1016/j.seh.2023.100002

[56] P.J.Landrigan, H.Raps, M.Cropper, C.Bald, M.Brunner, E.M.Canonizado, D.Charles, T.C.Chiles, M.J. Donohue, J.Enck, P.Fenichel, L.E.Fleming, C.Ferrier-Pages, R.Fordham, A.Gozt, C.Griffin, M.E.Hahn, B.Haryanto, R.Hixson, H.Ianelli, B.D.James, P.Kumar, A.Laborde, K.L.Law, K.Martin, J.Mu, Y.Mulders, A.Mustapha, J. Niu, S.Pahl, Y.Park, M.Pedrotti, J.A.Pitt, M.Ruchirawat, B.J.Seewoo, M.Spring, J.J.Stegeman, W.Suk, C.Symeonides, H.Takada, R.C.Thompson, A.Vicini, Z.Wang, E.Whitman, D.Wirth, M.Wolff, A.K.Yousuf, S.Dunlop (2023) The minderoo-Monaco commission on plastics and human health. *Annals of Global Health*, 89, https://doi.org/10.5334/aogh.4056

[57] M.Shen, S.Ye, G.Zeng, Y.Zhang, L.Xing, W.Tang, X.Wen, S.Liu (2020) Can microplastics pose a threat to ocean carbon sequestration? *Marine Pollution Bulletin*, 150, 110712, https://doi.org/10.1016/j.marpolbul.2019.110712

[58] I.Cimmino, F.Fiory, G.Perruolo, C.Miele, F.Beguinot, P.Formisano, F.Oriente (2020) Potential mechanisms of bisphenol A (BPA) contributing to human disease. *International Journal of Molecular Sciences*, 21, 5761 https://doi.org/10.3390/ijms21165761

[59] Y.Wang, H.Qian (2021) Phthalates and their impacts on human health. *Healthcare*, 9, 603, https://doi.org/10.3390/healthcare9050603

[60] I.Dubey, S.Khan, S.Kushwaha (2022) Developmental and reproductive toxic effects of exposure to microplastics: A review of associated signaling pathways. *Frontiers in Toxicology*, 4, 901798, https://doi.org/10.3389/ftox.2022.901798

[61] M.F.Manzoor, T.Tariq, B.Fatima, A.Sahar, F.Tariq, S.Munir, S.Khan, M.M.A.NawazRanjha, A.Sameen, X.A.Zeng, S.A.Ibrahim (2022) An insight into bisphenol A, food exposure and its adverse effects on health: A review. *Frontiers in Nutrition*, 9, 1047827, https://doi.org/10.3389/fnut.2022.1047827

[62] F.Du, H.Cai, Q.Zhang, Q.Chen, H.Shi (2020) Microplastics in take-out food containers. *Journal of Hazardous Materials*, 399, 122969, https://doi.org/10.1016/j.jhazmat.2020.122969,

[63] C. Pironti, M. Ricciardi, O. Motta, Y. Miele, A. Proto, and L. Montano (2021) Microplastics in the environment: Intake through the food web, human exposure and toxicological effects. *Toxics*, 9, 224, https://doi.org/10.3390/toxics9090224

[64] T.K.Dey, M.E.Uddin, M.Jamal (2021) Detection and removal of microplastics in wastewater: Evolution and impact. *Environmental Science and Pollution Research*, 28, 16925–16947, https://doi.org/10.1007/s11356-021-12943-5,

[65] R.Dris, J.Gasperi, C.Mirande, C.Mandin, M.Guerrouache, V.Langlois, B.Tassin (2017) A first overview of textile fibers, including microplastics, in indoor and outdoor environments. *Environmental Pollution*, 221, 453–458, https://doi.org/10.1016/j.envpol.2016.12.013

[66] K.Liu, X.Wang, T.Fang, P.Xu, L.Zhu, D.Li (2019) Source and potential risk assessment of suspended atmospheric microplastics in shanghai. *Science of the Total Environment*, 675, 462–471, https://doi.org/10.1016/j.scitotenv.2019.04.110

[67] A.Tursi, M.Baratta, T.Easton, E.Chatzisymeon, F.Chidichimo, M.De Biase, G.De Filpo (2022) Microplastics in aquatic systems, a comprehensive review: Origination, accumulation, impact, and removal technologies. *RSC Advances*, 12, 28318–28340, https://doi.org/10.1039/d2ra04713f

[68] L.M.Hernandez, N.Yousefi, N.Tufenkji, A.T.Nanoplastics (2017) Are There Nanoplastics in Your personal care products? *Environmental Science and Technology Letters*, 4, 280–285, https://doi.org/10.1021/acs.estlett.7b00187.

[69] Q.L.Li, M.Yuan, Y. Chen, X.J.Jin, J.F.Shangguan, J.L.Cui, S.Chang, M.Guo, Y.Wang (2023) The neglected potential source of microplastics from daily necessities: A study on protective mobile phone cases. *Journal of Hazardous Materials*, 441, 129911, https://doi.org/10.1016/j.jhazmat.2022.129911

[70] H.Zhang, Y.Xu, L.Jia, M.Xu (2021) Smog chamber study on the ozone formation potential of acetaldehyde. *Advances in Atmospheric Sciences*, 38, 1238–1251, https://doi.org/10.1007/s00376-021-0407-5

[71] D.Boyle, A.I.Catarino, N.J.Clark, T.B.Henry (2020) Polyvinyl chloride (PVC) plastic fragments release Pb additives that are bioavailable in zebrafish. *Environmental Pollution*, 263, 114422, https://doi.org/10.1016/j.envpol.2020.114422

[72] M.Shen, W.Huang, M.Chen, B.Song, G.Zeng, Y.Zhang (2020) plastic crisis: Un- ignorable contribution to global greenhouse gas emissions and climate change. *Journal of Cleaner Production*, 254, 120138, https://doi.org/10.1016/J.JCLEPRO.2020.120138

[73] T.Lomonaco, E.Manco, A.Corti, J.LaNasa, S.Ghimenti, D.Biagini, F.DiFrancesco, F.Modugno, A.Ceccarini, R.Fuoco, V.Castelvetro (2020) Release of harmful volatile organic compounds (VOCs) from photo-degraded plastic debris: A neglected source of environmental pollution. *Journal of Hazardous Materials*, 394, 122596, https://doi.org/10.1016/j.jhazmat.2020.122596

[74] M.Sankar, E.Nowicka, E.Carter, D.M.Murphy, D.W.Knight, D.Bethell, G.J.Hutchings (2014) The benzaldehyde oxidation paradox explained by the interception of peroxy radical by benzyl alcohol. *Nature Communications*, 5, 3332, https://doi.org/10.1038/ncomms4332

[75] J.Kramm, C.Völker (2018) Understanding the risks of microplastics: A social-ecological risk perspective. In: *Handbook of Environmental Chemistry*. Springer International Publishing: Cham, Germany, 223–237.

[76] A.Jakovcevic, L.Steg, N.Mazzeo, R.Caballero, P. Franco, N.Putrino, J.Favara (2014) Charges for plastic bags: Motivational and behavioral effects. *Journal of Environmental Psychology*, 40, 372–380, http://doi.org/10.1016/j.jenvp.2014.09.004

[77] A.O.C.Iroegbu, S.S.Ray, V.Mbarane, J.C.Bordado, J.P.Sardinha (2021) Plastic pollution: A perspective on matters arising: Challenges and opportunities. *ACS Omega*, 6, 19343–19355, https://doi.org/10.1021/acsomega.1c02760

[78] R.Geyer, J.R.Jambeck, K.L.Law (2017) Production, use, and fate of all plastics ever made. *Science Advances*, 3, e1700782, https://doi.org/10.1126/sciadv.1700782

[79] E.Nøklebye, H.N.Adam, A.Roy-Basu, G.K.Bharat, E.H.Steindal (2023) Plastic bans in India – Addressing the socio-economic and environmental complexities. *Environmental Science and Policy*, 139, 219–227, https://doi.org/10.1016/j.envsci.2022.11.005

[80] L.M.Erdle, D.NouriParto, D.Sweetnam, C.M.Rochman (2021) Washing machine filters reduce microfiber emissions: Evidence from a community-scale pilot in Parry Sound, Ontario. *Frontiers in Marine Science*, 8, https://doi.org/10.3389/fmars.2021.777865

[81] I.SkumlienFuruseth, E.StøhleRødland (2020) *Reducing the Release of Microplastic from Tire Wear: Nordic Efforts*. Nordic Council of Ministers.

[82] C.F.Chien, K.Aviso, M.L.Tseng, M.Fujii, M.K.Lim (2023) Solid waste management in emerging economies: Opportunities and challenges for reuse and recycling. *Resources, Conservation and Recycling*, 188, 106635, https://doi.org/10.1016/j.resconrec.2022.106635

[83] W.-T.Chen, K.Jin, N.-H.Linda Wang (2019) Use of supercritical water for the liquefaction of polypropylene into oil. *ACS Sustainable Chemistry and Engineering*, 7, 3749–3758, http://doi.org/10.1021/acssuschemeng.8b03841.

[84] M.S.Ahmad, S.A.Ahmad (2022) The impact of polyethylene terephthalate waste on different bituminous designs. *Journal of Engineering and Applied Science*, 69, http://doi.org/10.1186/s44147-022-00104-5

[85] H.Zhou, Y.Ren, Z.Li, M.Xu, Y.Wang, R.Ge, X. Kong, L.Zheng, H.Duan (2021) Electrocatalytic upcycling of polyethylene terephthalate to commodity chemicals and H2 fuel. *Nature Communications*, 12, 4679, https://doi.org/10.1038/s41467-021-25048-x,

[86] M.Caniato, L.Cozzarini, C.Schmid, A. Gasparella (2021) Acoustic and thermal characterization of a novel sustainable material incorporating recycled microplastic waste. *Sustainable Materials and Technologies*, 28, (e00274, https://doi.org/10.1016/j.susmat.2021.e00274

[87] P.Chandrasekaran, K.Nirmalkumar, R.Uthra, K.S.VihashKumar, R.Vishnu (2021) Study on construction of roads using PVC wastes-review. *IOP Conference Series: Materials Science and Engineering*, 1145, 012105, http://doi.org/10.1088/1757-899X/1145/1/012105

[88] I.A.El-Naga, M.Ragab (2019) Benefits of utilization the Recycle polyethylene terephthalate waste plastic materials as a modifier to asphalt mixtures. *Construction and Building Materials*, 219, 81–90, https://doi.org/10.1016/j.conbuildmat.2019.05.172

[89] W. Nabgan, B. Nabgan, T. A. Tuan Abdullah, M. Ikram, A. H. Jadhav, M. W. Ali, A. A. Jalil (2022) Hydrogen and value-added liquid fuel generation from pyrolysis-catalytic steam reforming conditions of microplastics waste dissolved in phenol over bifunctional Ni-Pt supported on Ti-Al nanocatalysts. *Catalysis Today*, 400–401, 35–48, https://doi.org/10.1016/j.cattod.2021.11.026

IZVOD

NEDAVNI NAPREDAK U ISTRAŽIVANJU OD PLASTIČNIH MATERIJALA DO MIKROPLASTIKE

Plastika je postala sve prisutnija u našim životima. Zbog sve većeg broja stanovnika, brze urbanizacije i industrijskog napretka, upotreba plastike se višestruko povećala. Ovi plastični materijali se često raspadaju u mikroplastiku (MP) koja je manja od 5 mm. Mikroplastika uglavnom ulazi u vodena staništa nepravilnim upravljanjem otpadom, nelegalnim odlaganjem i neizbežnim i nenamernim ispuštanjima koja se dešavaju tokom izgradnje, proizvodnje, poljoprivrede, potrošnje i rekreativnih aktivnosti. Ovaj pregled se fokusira na istraživanje porekla, pojave i mogućih štetnih efekata mikroplastike na ljudsko blagostanje. Od 485 literature pregledane za studiju između 2014-2023, utvrđeno je da je 105 povezano sa mikroplastikom koji su bili raspoređeni na 10 tema. Najveći broj radova bio je o izvorima MP, zatim o mikroplastici iz slatkovodnih ekosistema i upravljanja otpadom. Najmanje literature je bilo iz tematike transporta mikroplastike i mikroplastike u zemljištu. Literatura je objavljena uglavnom u Kini, Indiji, Evropi i Americi. Druge zemlje poput Australije, Latinske Amerike, Afrike i Bliskog istoka doprinose vrlo malo. Skeniranje literature otkriva da se samo 9% celokupnog proizvedenog plastičnog otpada reciklira, 12% se spaljuje, a 79% plastičnog otpada se baca na deponije i okeane. Bačena plastika se taloži i zagađuje različite matrice životne sredine. MP su namerno proizvedeni da se dodaju proizvodima za ličnu negu koji se ispiru u kanalizaciju kroz kanalizacijske ili industrijske otpadne vode. Ovi MP se razlikuju po gustini i boji, zavisno od vrste polimera, i prisutni su u različitim veličinama i koncentracijama u vodenim sredinama. Karakterizacija MPs koji potiču od različitih tipova polimernih materijala, u recenziranoj literaturi, izvršena je na osnovu podataka dobijenih iz Skenirajuće elektronske mikroskopije, Energi Dispersive Spectroscopi (SEM-EDS), Attenuated Total Reflection, Fourier Transform Infra-Red spektroskopije (ATR-FTIR).), Ramanova spektroskopija i mikroskopija atomske sile (AFM). Mikroplastike imaju potencijal da apsorbuju štetne hidrofobne zagađivače iz okoline što dovodi do indirektnog prenosa zagađivača u mrežu hrane. Takvi MP ulaze i utiču na ljude, uzrokujući probleme sa reproduktivnim sistemom, telesnom težinom, odnosom polova i živorođenim. MP predstavljaju ozbiljnu pretnju organizmima kada se progutaju jer mogu da opstruiraju digestivni trakt, što dovodi do oksidativnog i patološkog stresa, usporavanja rasta i ometanja reprodukcije. Pored navedenog, razmatrana je i sveobuhvatna analiza zagađenja MP, kao i njegovog uticaja na ljude i životnu sredinu u smislu identifikacije izvora i rasprostranjenosti. Takođe, razmatran je detaljan pregled postojećeg otpadnog materijala koji se reciklira u nove materijale ili se ponovo koristi bez izmena ili degradacije za proizvodnju novih izvora energije. Na kraju, predložene su integrisane strategije za sprečavanje unošenja plastičnog otpadnog materijala u životnu sredinu, kontrolom izvora, poboljšanim upravljanjem plastičnim otpadom i tehnikama za degradaciju i konverziju MP.

Ključne reči: mikroplastika; deponija; uticaji na zdravlje; vodena sredina; menadžment; ekološki

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