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From Origins to Impacts: A Comprehensive Review of Microplastics in Freshwater Environments

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ABSTRACT

Microplastics are plastic particles of dimensions less than 5mm, increasingly recognized as omnipresent contaminants in freshwater systems. These small particles are sourced from microbeads provided by personal care products, industrial abrasives, and other secondary sources formed by the degradation of larger plastic items. The microplastics are contaminated in freshwater environments through runoff, atmospheric deposition, and the discharge of water treatment processes. The presence of microplastics in freshwater has greater potential to cause harm to aquatic environments and human health. The primary objective of this paper is to identify the microplastic pollution in freshwater resources and classify the sources of this pollution in freshwater resources, including both primary and secondary microplastics, and to evaluate the ecological impact of microplastics and their potential health risks to humans through food chain transfer. This review synthesizes the most recent findings on sources, impacts, and potential mitigation measures of microplastic pollution in freshwater ecosystems to emphasize the attentive work needed urgently in our efforts to conquer the environmental challenge. The mitigation strategies in practice thus focus on policy implementation and correct technology in wastewater treatment, raising public awareness to minimize the use of plastics and encourage good waste management. However, studies with much detail are still required to develop systematic methodologies for microplastic analysis and go far enough to find long-term solutions

KEYWORDS: Microplastic, Water Pollution, Fresh Water Ecosystem, Bio-accumulation

1. INTRODUCTION

Microplastics are elucidated as plastic particles smaller than 5 millimeters in size and have been recorded in the recent past as being commonplace in ecosystems mainly in freshwater systems [1, 2 & 3]. They are threatening to the lives of organisms and human beings since they cause blockage in the digestive system, interference with the feeding process, and reduced reproductive capacity. These microplastics can become lodged in sediment layers, where they serve as a trap for these pollutants and may be transported through the ecosystems' food web [3 & 4]. The second half of the twentieth century brought the age that can be referred to as the "Age of Plastic" as the production and use of plastics accelerated. This indeed has beneficially impacted several areas including the medical sector, technology and in production of consumable goods. Thus, although the use of plastics is advantageous due to its wear resistance and susceptibility to degradation, the byproduct of this resilience becomes an ecological nuisance. When plastic is degraded, it produces what is referred to as microplastics, which are particles of less than 5mm in size, and that are present in the remotest parts of our planet [3]. These particles are found everywhere, from the sandy beaches of deserted islands to the deep and dark trenches of the oceans. Despite the remoteness of Arctic plastic pollution has been discovered in the glaciers of this region. The severe climate changes and the starting of new shipping routes shall cause the situation to be worsen in upcoming years [5]. In the middle of the twentieth century, the World witnessed a new stage also known as the “Age of Plastic,” as there was a noticeable tendency in the production and consumption of plastic goods. It is possible to note that this period was rather progressive in terms of several spheres including healthcare, technologies, and consumer goods. It can be inferred that although the qualities of plastics such as durability and degradation resistance are beneficial, the negative impact of this materialization is a prolific problem in today’s environment. The microplastics have reached the remotest parts of the earth. Such particles can be searched for all over the world, starting from oceans’ deserted seashores and up to the gigantic trenches of these depths. Research on microplastics states that the adsorption of persistent organic pollutants (POPs) can be occurred on the surface of microplastics and these POPs are transported to the aquatic organisms by the microplastics. After the investigation of microplastics found in the water resource of the Feilaixia Reservoir (Guangdong Province, China) the average counting of microplastics was 0.56 ± 0.45 items/m3 in the Feilaixia Reservoir water samples [6]. From 2016 to 2019, a stereo microscope study was carried out to analyse microplastics in Manhattan's Lower Hudson River Estuary using NOAA methodologies. In the Estuarine Sanctuary, they discovered microplastics in every sample and with constant yearly average surface concentrations. It was found that the year 2018 had the highest concentrations (830,762 microplastic particles/km^2). The average concentration for the year 2018 was three times higher than that of 2016 (243,772 particles/km^2) and 2019 (244,142 particles/km^2), and six times higher than 2017 (143,204particles/km^2) [7]. In a research on microplastics in Hiroshima Bay, Japan the testing of surface water along with bottom and beach sediments was done by Sagava N. et al. investigating the quantity, size, and kinds of microplastics as well as their polymer composition. Foamed polystyrene (FPS) accounted for 90% of the total polystyrene content in the beach sediments. It was followed by polyethylene (PE; 5%), polypropylene (PP; 3%), and others (2%) with no polystyrene detection (PS; 0%). In Hiroshima Bay, where it sunk to the bottom, FPS remained numerically dominant at 79%, PE (13%) at second position with PP at 6%, PS at 1%, and others at 2% following. Fascinatingly, the ratio of polymers generated by microplastics in Hiroshima Bay's surface water differed from that of the sediment samples taken from the beach and bottom; PE accounted for 43% of the total, with PP (23%), FPS (21%), other polymers with an abundance of 13% along with no detection of Polystyrene [8]. Research conducted by Pivokonsky M. et al. (2018) to investigate the quantity of microplastics found in freshwater and drinking water in the Czech Republic analysing the raw and treated water from three water treatment plants (WTPs) discovered Microplastics in all water samples. In raw water the average abundance of microplastics ranged from 1473±34 to 3605±497 particles/ L and in treated water it ranged from 338±76 to 628±28 particles/ L [9].

1.1 Types of Microplastics

Based on the origin the microplastics can be divided in two groups: primary and secondary microplastics [3]. Both types contribute to environmental pollution, but they differ in their sources and the processes through which they enter ecosystems.

1.1(a) Primary Microplastic

These include primary or engineered microplastic since they are produced small for particular applications and are released into the environment in small forms. Some of the most prevalent categories include microbeads, which are fine plastic particles (less than one millimeter) employed in cosmetic products, toothpaste, and face washes. These beads make their way into water bodies through the drainage systems [10]. Microplastics in the form of Nurdles used as primal matter in the production of plastics are also released into the environment during transportation and handling. Microscopic abrasive particulates typically applied in industrial applications like sandblasting and surface cleaning, can also be released into the ecosystem through sewage or inadequate waste management [3, 11 & 12].

1.1(b) Secondary Microplastic

Secondary microplastics come from the degradation processes of macro-plastics by physical, chemical, and biological action. Some of the major classifications of plastics are bottles, bags, and packaging materials which over time disintegrate into smaller fragments that can be easily dispersed by natural forces like sun, wind, water, or mechanical action. The synthetic textiles constitute micro and nano sized fibres of polyester, acrylic, and nylon; are released during washing of these synthetic textiles and are not removed during wastewater treatment. Finally they get released into our freshwater systems [13]. These also include tire wear particles which are small particles of plastic produced by abrasion of car tires on roads that are washed off the road by rain and accumulate in water bodies through the process of runoff [14]. Furthermore, there are paint particles which arise from the wear of paints and coatings applied on buildings, roads, and ships that add to the count of microplastics invading the environment [15].

1.2 Characteristics of Microplastics

Microplastics differ in the size and composition of their particles. Usually described as plastic debris with one or more dimensions of less than 5mm, microplastics may be as small as nano plastics and as large as several millimetres. It can also be observed in the forms of fibres, fragments, pellets, films, and foams depending on the source and degradation factors. Microplastics can be of any colour it emulates the colour of the larger plastic product and coloured microplastics are dangerous because they easily misidentify plastics as food. The most commonly used verities of Microplastics in our daily life among a large family of microplastics are polyethylene (PE), polyvinyl chloride (PVC), polypropylene (PP), Bakelite, polyethylene terephthalate (PET) and polystyrene (PS). They may also contain substances such as flame retardants, plasticizers, and stabilizers which may migrate out and contribute to further harm to the environment [3].

1.3 The Challenge of Measuring Microplastic Pollution Effects

It is quite challenging to determine the effects of microplastic pollution and this makes the work of researchers very difficult. Due to the many sources of microplastics and its spectrum of types, coupled with the diverse and massive nature of the aquatic environment and its inhabitants, it is challenging to define the potential of contamination, and its impact on living organisms and humans. The analytical techniques for microplastic analysis in environmental samples remain under development, and therefore the protocols should be consistent for comparison between different investigations. Furthermore, the comprehensive evaluation of the lasting impact of microplastic ingestion on ecosystems and human health requires research done by a multispecialty team encompassing environmental science, toxicology, and epidemiology.

2. Pathways for Microplastics

Knowing the mechanism by which microplastics mobilize within ecosystems is a crucial step towards source identification, prevention, and the health of both ecosystems and the people residing in them. The research by Carbery et al. (2018) emphasizes the need to investigate the pathways through which these pollutants affect human health and the urgency of further research on their long-term effects [16].

2.1 Primary Pathways for Microplastics

The microplastics can reach the ecosystem through several primary routes. It comes about when industries using or producing plastic materials discharge microplastics to effluent discharges, and cosmetics like exfoliants, toothpaste, etc. containing microbeads that discharge microplastics to the WWS systems. Small pieces of larger plastic debris wear down through physical and chemical actions, for example, through waves, rubbing and UV radiation, and biological processes. Microplastic pollution originates in the urban environment, with runoff carrying plastic from streets, sidewalks, and other spaces into water bodies; TWP (Tire Wear Particles) and plastic debris from road surfaces are also sources of microplastics in the runoff. Moreover, atmospheric transport enables microplastics to be picked up and relocated through airborne movements such as wind action and abrasion, as well as reconcentration through the resuspension of particles on surfaces- dry or wet deposition. Some of the factors included are that WWTPs release microplastics as not all particles are fully removed during the treatment process and are consequently released into the receiving water [17]. Tertiary treated sludge used for agriculture purposes as fertilizer releases microplastics into the soil where they can infiltrate the groundwater and be carried off by the runoffs. Some of the agricultural practices that contribute to the formation of microplastics include, for instance, plastic films used for mulching are fragmented into microplastics are generated by the fragmentation of plastic film used in process of mulching, or when water containing microplastic is used for irrigation, it deposits the microplastics in agricultural soils [18]. Marine input is characterized by the shedding or deterioration of fishing gear and accessories such as nets and lines, the release of plastics known as nurdles, and other solid materials from ships, recreational activities, and industries that discharge microplastics into the seas [3, 19 & 20].

2.2 Secondary Pathways for Microplastics

Microplastics follow various secondary routes in the environment. The microplastics are transported by the flowing water bodies from Inland sources to other sources such as lakes and oceans, and they are aggregated in estuaries and coastal environments with the help of Tidal and wave action. Leaching of microplastics from the soil to groundwater takes place in regions with heavy use of plastics, and groundwater can transport these particles to other parts also polluting drinking water [19]. Microplastics in sediments are mobilized by hydrodynamic forces, like currents and waves, to be transported in the water column before settling and accumulating on the seabed and affecting benthic species [8]. In the food chain, microplastic enters the organisms at various trophic levels and is accumulated /magnified; some organism expels microplastics while others internalize them, resulting in physical or chemical effects [16].

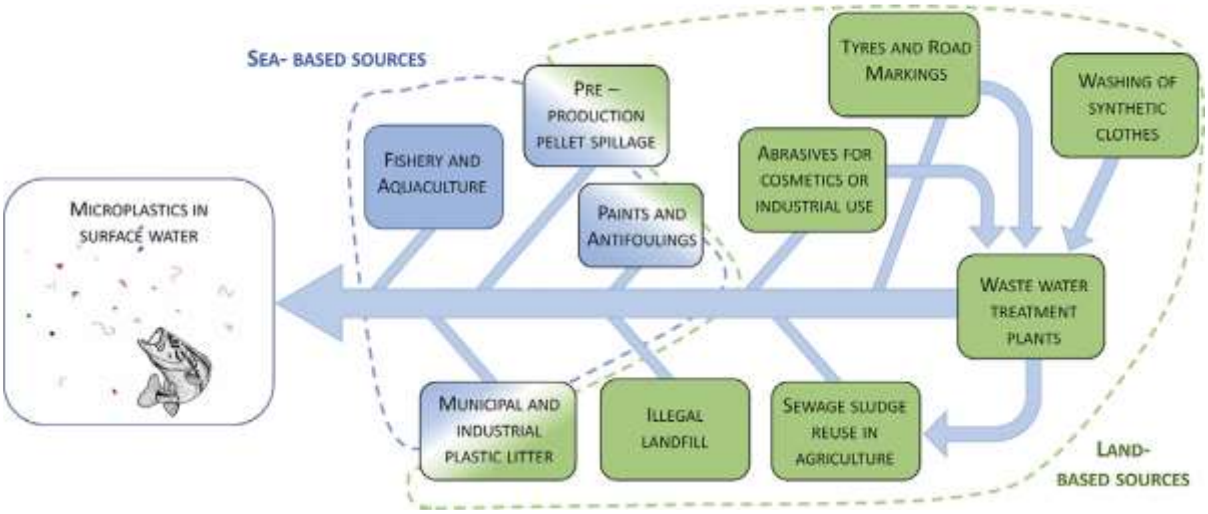

Figure 1. Representation of possible pathways of microplastic pollution in surface water. [21].

3. Ecological and Health Impacts

3.1 Ecological Impacts

3.1(a) Ingestion by Aquatic Life

When ingested by fish, invertebrates, and other organisms microplastics cause direct physical harm and reduce their fitness level. Microplastics have also been identified in different marine environments, proving how far and deep it go with plastic pollution. These particles are also immersed in the sediment layers of the deep sea as well as in the water column excluding them affecting a wide range of sea organisms. The issue of microplastics has been accentuated by Rochman et al. (2015) and others whereby they note the high rate at which these particles are accumulating in the marine environment. Thus, the microplastics' distribution is versatile, which means that both local measures for waste disposal, and global currents contribute to the distribution of pollutants [22]. Finding of microplastic pollution in species used by human as resources including the work identify by Fossi et al. (2016) on the fin whales prove that the pollution is universal. The identification of microplastics in such a premium marine species, there must be severe pollution and high biomagnification impact. Much like the fin whales, as the dominant species in the ecosystem they can serve as a barometer of the ecosystem's well-being and the detection of microplastic pollutants ranging in size from the tiniest plankton to gigantic whales [23].

3.1(b) Chemical Contamination

Microplastics are both physical pollutants and important vectors of chemical contamination in the environment; the risks associated with their presence can thus be very substantial. Microplastics may take up and leach harmful chemicals added to plastics during processing, as well as those adsorbed from the environment, and release them into marine, fresh, and terrestrial environments. These chemicals pose additional risks to aquatic life and ecosystems. These additives are incorporated to make plastics more flexible, or reinforced with heavy metals as stabilizers to increase durability, or flame retardants to make plastics less flammable. Because of the large surface area, microplastics act as vectors for persistent organic pollutants, which adhere to their surface and are transported into soils and various water bodies, aggravating environmental contamination. Moreover, the adsorption of heavy metals like lead, mercury, and cadmium on microplastics can further exert serious environmental and toxic health effects [3, 24].

3.1(c) Habitat Disruption

Accumulation of microplastics in sediments can change habitats and is, therefore, a major threat to benthic habitats and their benthic organisms. Microplastics ingress the aquatic environment through direct discharge, runoff, and atmospheric deposition. Because of their density and their interaction with other particles in water, such particles settle and accumulate in sediments over some time. The presence of microplastics could alter sediments significantly in benthic habitats [25, 26, 27].

3.1(d) Physical Modification of Sediment Structure

The addition of microplastics to sediments changes the native texture and influences its physical characteristics, such as porosity and permeability. Microplastics change the texture and surface features of sediments, thereby affecting organisms reliant on specific sediment structures for habitat. Microplastics can begin to leach additives and adsorbed pollutants into the sediment, thus contaminating the benthic environment. The presence of microplastics can change the sediments' chemical dynamics, which influence nutrient cycles and availability of many vital elements [26, 27, 28].

3.1(e) Biological Impacts

Microplastics are consumed by different and various types of benthic organisms, including worms, crustaceans, and bivalves, who mistake them for food. It can lead to physical blockages, reduced feeding efficiency, and poor growth. Leachates from microplastics can act as toxins to benthic organisms, whereby exposure leads to reduced reproduction, altered behavior, and increased mortality rates [3]. Benthic creatures play a very important role in the maintenance of health and functionality within aquatic ecosystems, where they are involved in nutrient cycling and stabilize sediments whose activities are linked with food web dynamics. This sensitivity of some species to habitat changes and chemical contaminants has a negative impact on biodiversity. Sometimes, pillars of altered habitats can be more suitable for invasive species that outcompete the native benthic organisms in space. Benthic organisms are responsible for processing organic matter and recycling nutrients. Population change will affect these critical services to ecosystems. Among a number of other organisms, which include polychaete worms and bivalves, some serve to hold or cement sediments in place. In that case, their loss can allow more erosion and habitat instability [30, 31,32]. There could, therefore, exist several trophic transfers of ingested microplastics by the benthic organisms upwards in the food web, impacting higher trophic levels like fish and birds and, finally, humans [3,15].

3.2 Human Health Risks

3.2(a) Drinking Water Contamination

Microplastics have been found in tap and bottled water. The presence of microplastics in drinking water raises concerns about potential health risks and the need for effective mitigation strategies [3]. Microplastics from urban, agricultural, and industrial runoff can enter rivers, lakes, and reservoirs, which are often sources of drinking water. Degradation of plastics disposed in landfills leaches microplastics into the groundwater sources. Ingestion of microplastics can cause physical damage through irritation and damage to the gastrointestinal tract. After ingestion, microplastics can leach harmful chemicals such as additives and absorbed pollutants into the body. Microplastics harbor pathogens and enhance infections. Koelmans et al. (2019) have extended the evaluation by warning of potential risk for microplastic contamination in drinking water, stating an even more direct route for human exposure [33]. This finding underlines the global dimension of the microplastic problem and calls for strict quality standards concerning water quality, which must include microplastic pollutants. One critical point brought about by probable widespread exposure via drinking water adds an urgent dimension to the conversation on the health implications of microplastic pollution [9].

3.2(b) Food Chain Transfer

Microplastics and associated toxins can be input into the human diet through seafood ingestion. One of the major concerns related to microplastics is their ability to absorb and transport dangerous chemical contaminants, such as persistent organic pollutants, heavy metals, and other classes of toxins. Some of these substances, including endocrine disruptors linked with cancer, could leach into the body from ingested microplastics upon degradation and may give rise to a variety of health complications. The research by Smith et al. (2018) calls for more detailed studies on the release of these chemicals from microplastics and their effects on human health [31].

3.2(c) Toxicological Effects

Therefore, when ingested, microplastics in marine life are in contact with not only physical particles but also with harmful chemicals. Exposure to these particles alters the health of marine species and unpublished food webs in the marine ecosystem. Evidence of contamination of microplastic in marine life may be used to explain the extent of the issue of these pollutants. For instance, Fossi et al. (2016) conducted a study on the stomach content of fin whales. The presence of microplastics in such top marine species suggests widespread contamination, which may exert high biomagnification effects [23]. As representatives of the apex predators, contamination in fin whales could portray the health situation of the marine environment, and the contamination depicts how far microplastic pollution can run, from the invisible plankton to the largest oceanic creatures (Barboza L.G.A. et al. 2018) [10].

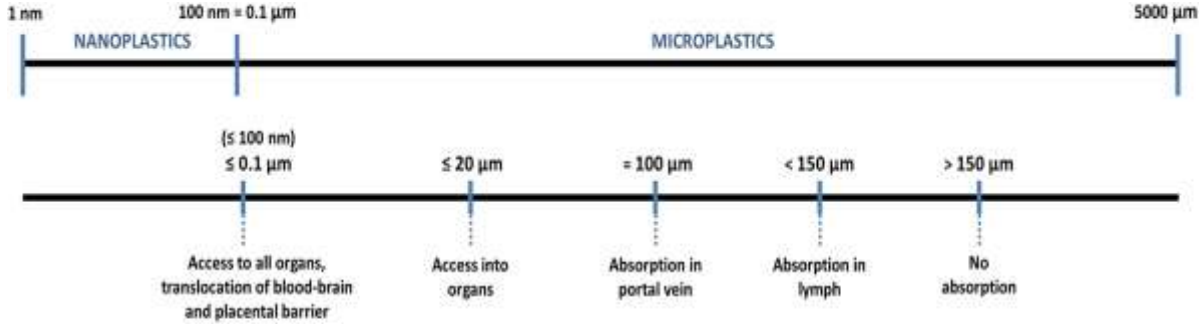

Figure 2. Possible Threats from Microplastics to Human Health [34].

Such micro-chemicals have been associated with inflammation, genotoxicity, and chemical toxicity effects on human health [34].

4. Identification and Quantification

The identification and quantification of microplastics in water samples consists a series of steps including sampling, separation, identification, and quantification, each requiring specific techniques and methodologies to accurately assess the presence and concentration of microplastics. The water sample for assessing the microplastics in surface can be collected using manta trawls and neuston nets with fine mesh (usually 300 micrometers) to capture particles, and grab sampling, which involves collecting water samples directly from the surface using containers. For subsurface water, the water is pumped from specific depths and filter it on-site. Ensuring consistent sampling procedures to avoid contamination and collecting replicate samples to account for variability are crucial protocols. Separation techniques include filtration, where water samples are passed through mesh filters with different pore sizes to retain microplastics, and membrane filters with pore sizes of 0.45 micrometers to 1.6 millimeters. Hydrogen peroxide (H2O2) is used as an oxidising agent for chemical digestion to digest organic matter, leaving behind microplastics. Identification techniques include optical microscopy for initial identification and counting of larger particles, fluorescence microscopy using fluorescent dyes to stain microplastics, Fourier-transform infrared spectroscopy (FTIR) to identify polymers based on their infrared absorption spectra. Near-infrared spectroscopy (NIR) can be used for identifying plastic types through near-infrared absorption properties. Quantification techniques include gravimetric analysis, where microplastic particles are collected, dried, and weighed to determine their mass; particle counting, which can be manual under a microscope or automated using image analysis software; and chemical analysis to quantify different types of polymers and measure concentrations of additives like plasticizers and flame retardants. Challenges and considerations include sampling bias due to differences in sampling techniques, the need for standardized protocols, preventing contamination during collection, processing, and analysis, sensitivity of identification techniques to detect smaller microplastics, and accurate identification methods to differentiate microplastics from other particles like natural fibers or organic matter [8, 11, 18, 34].

5. Mitigation Strategies

5.1 Policy and Regulation

Legislative measures should be taken at both country and international levels of cooperation in trying to mitigate microplastics in water resources. The USA has put in place a 2015 law, the Microbead-Free Waters Act, that bans the manufacture and sale of plastic microbead-containing rinse-off cosmetics. Proposals by the European Chemicals Agency restrict intentionally added microplastics in products like cosmetics, detergents, and plant protection products. EPR schemes of the EU and Canada require manufacturers to be responsible for the lifecycle of plastic products and pay for waste management. Plastic packaging regulations focus on plastic packaging reduction, reusable packaging, and recyclable materials, while the Single-Use Plastics Directive targeted single-use plastic items in the EU. These are policies on waste management that impose an upgrade in wastewater treatment plants by the inclusion of technologies such as advanced filtration and membrane bioreactors, as is the case in the EU Urban Waste Water Treatment Directive, and require the installation of filters and sedimentation basins in urban areas for the capture of microplastics emanating from stormwater runoff. At the international level, countries enter into agreements like the Basel Convention to try to manage plastic waste and collaborate with organizations like UNEP in the fight against plastic pollution. This fellowship across international borders is key to eradicating transboundary water pollution problems and sharing best practices and corresponding technologies for mitigating microplastics [19, 24].

5.2 Technological Solutions

Thus, opportunities for technological innovation are significant mitigants of microplastics in water resources. Funds should be committed to researching and developing new biodegradable plastics of natural origin as alternatives to traditional plastics that would help reduce plastic pollution. Further still, through pioneering filtration techniques such as nanofiltration and advanced oxidation processes, research can be used to arrest and subtract microplastics from the water systems. These developments are quite important in efforts geared toward establishing lasting solutions to mitigate the prevailing contamination of microplastic origin [15,19].

5.3 Public Awareness and Education

Consumer protection and awareness are very critical in this war against microplastics. Clear labelling of products containing microplastics will inform consumers and thus nudge them toward substitutes. Indeed, the EU has proposed making labeling, standardization, and certification of biodegradable and compostable plastics mandatory. Funding and supporting public education campaigns can attain many consumer behaviour changes by highlighting sources and impacts. The campaigns can encourage reducing the impact of single-use plastics and good waste disposal practices, hence microplastic pollution [15,19,24].

5.4 Economic Instruments

In this discourse, the scope of economic instruments cannot be left unexplored. Single-use plastics have a very active aspect that concerns the adoption of taxes or levies toward raising disincentives while creating revenue for the execution of policies aimed at managing plastic waste. One example is plastic bag levies, implemented with success in countries like Ireland and Denmark; usage came down considerably while reusables were ushered in through such a move. Subsidies and incentives that enable sustainable practices could grant such incentives to businesses that innovate and adopt alternatives to microplastics. Policies thus will catalyse the development of biodegradable materials and sustainable packaging solutions as a means to further reduce environmental microplastics and generally lead toward a more circular economy [15,19 & 24].

6. Future Research Directions

Some key areas that should be considered in future research in mitigating microplastics effectively in water resources include the following: more advanced and sensitive methods of detection and monitoring, investigation of cost-effective remote sensing and automation techniques in monitoring the distribution of microplastics in different environments and understanding the ecological impacts with possible transfers through food webs for comprehensive impact assessments. This will require the identification of primary sources like textiles and cosmetics, and understanding the pathways such as atmospheric deposition and urban runoff, to guide mitigation strategies effectively. It will be important to have innovations in technologies for filtration and remediation-related technologies that give biodegradable solutions for the removal of microplastics from wastewater and stormwater. There will be a need to examine the current policies and then come up with evidence-based recommendations geared at enhancing the existing regulatory framework besides stimulating global cooperation. Success in changing consumer behaviours with regard to the use and disposal habits of plastic products should also be evaluated in public awareness campaigns. Finally, international cooperation with the exchange of knowledge across institutions and governments all over the world will help in collective actions taken toward mitigation. These efforts are pertinent to protecting water resources both for aquatic ecosystems and human health for future generations [3, 15 & 19].

7. Conclusion

Microplastic pollution in freshwater ecosystems is likely to become one of the most important environmental and public health issues worldwide. Those tiny plastic particles range from primary microplastics like microbeads to secondary microplastics that come from the degradation of larger plastic items. They enter the aquatic environment through runoff, atmospheric deposition, and wastewater discharging. Their persistence and large distribution entail exposure to aquatic organisms and ecosystems while posing human health risks by way of their ingestion of drinking water and seafood intake.

Current mitigation strategies include legislation, technological innovation in filtration, wastewater treatment, raising public awareness, and international cooperation in the reduction of plastic use, improving waste management practices, and development of biodegradable alternatives. Difficulties still exist in efficient detection, monitoring, and assessment of the ecological impact of microplastics and their effective regulation under comprehensive frameworks.

Further dialogue must focus on the development of methods for both detection and monitoring, the demonstration of impacts on ecology across food webs, identification of major sources and pathways of microplastics, the invention of removal technologies in a functioning manner, optimization of policy performance, increasing public awareness, and improving global cooperation. What this will do is, therefore, greatly mitigate microplastic pollution and help set a safe paradigm for both freshwater ecosystems and human health in the future.

As microplastic pollution becomes a complex issue, it becomes consolidated with concerted efforts in scientific disciplines, government policies, industrial practices, and public awareness. Continuing to innovate, collaborate, and educate, we strive toward cleaner water resources and a sustainable environment.

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