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Exploring the Ecotoxicological Effects and Mitigation Strategies for Microplastics Pollution in Aquatic Ecosystems

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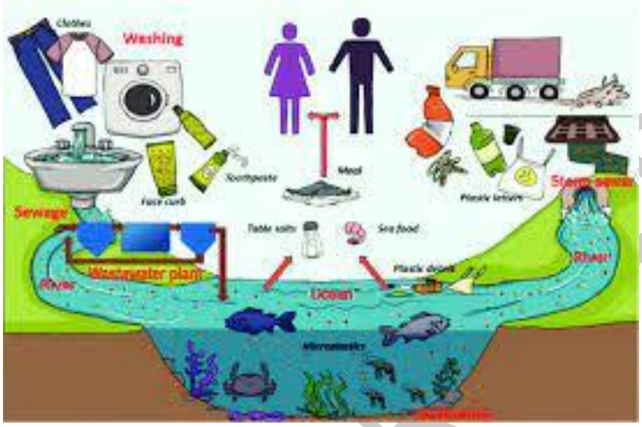
Graphical abstract



Abstract

Microplastics pollution poses a significant threat to aquatic ecosystems globally, originating from various sources such as plastic debris breakdown and microbeads. This study investigates the ecotoxicological impacts of these pollutants on marine plants and evaluates mitigation strategies. Field surveys assess their distribution, sources, and fate in rivers, lakes, estuaries, and coastal waters. Sampling methods include sediment cores, water samples, and biological specimens to quantify abundance, size distribution, polymer types, and spatial variability. Source apportionment techniques aid in identifying major contributors to pollution. Laboratory experiments simulate environmental conditions to study their behavior, including sedimentation, resuspension, aggregation, and bioaccumulation. Mathematical models predict dispersal and deposition patterns over varying time scales. Ecotoxicological studies investigate impacts on organisms across trophic levels, including fish, invertebrates, and phytoplankton, considering acute and chronic effects. Mitigation strategies like filtration systems, policy interventions, and public awareness campaigns are evaluated for efficacy in reducing pollution and safeguarding ecosystems. This research contributes to developing sustainable solutions essential for environmental preservation and human health.

Keywords: Microplastics, Pollution, Ecotoxicology, Distribution, Filtration systems, Environmental conservation and Human health.

1. Introduction

Microplastics, distinct as pliable particles lesser than 5 millimeters, being developed a ubiquitous and concerning environmental matter in aquatic ecosystems worldwide. These subdivisions arise from several sources, with the collapse of larger pliable items, microbeads in own care foods, and synthetic fibers out during the washing of textiles. Due to their small size and widespread distribution, microplastics are found in almost all aquatic environments, from rivers and lakes to oceans and even in sediments.

Microplastics are a diverse group of pollutants that can be classified created on their size, shape, and origin. They can be spherical or irregularly shaped, ranging from nanometers to millimeters in size, and can be derived from various plastic materials such as polyethylene, polypropylene, polystyrene, and polyester. The different types of microplastics include microbeads, microfibers, microfragments, and nanoplastics, each with its unique characteristics and environmental impacts.

The sources of microplastics are widespread and include both land-based and marine-based activities. Land-based sources encompass plastic littering, plastic waste from urban areas and industries, plastic pellets used in manufacturing processes, and microplastics released from synthetic textiles during washing. Marine-based sources include maritime activities such as shipping, fishing gear,

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aquaculture operations, and the breakdown of larger plastic debris in marine environments.

Once released into the environment, microplastics undergo various physical, chemical, and biological transformations. Physical processes such as weathering, abrasion, and photodegradation can break down bigger pliable items into minor elements, donating to the generation of secondary microplastics. Chemical weathering, including oxidation and hydrolysis, can alter the surface properties and stability of microplastics, affecting their interactions with other environmental components.

Biological interactions also theatre a significant protagonist in the fate and transport of microplastics in aquatic ecosystems. Microplastics can adsorb organic matter, nutrients, and contaminants from the surrounding water, making them attractive to filter-feeding organisms such as zooplankton and bivalves. This process, known as biofouling, can central to the ingestion of microplastics by these organisms, potentially causing physiological stress, reduced feeding efficiency, and altered behavior.

The powers of microplastics on sea plants are a subject of growing concern and scientific investigation. Studies have shown that microplastics can hoard in the muscles of marine and freshwater organisms, important to animal harm, inflammation, and cellular damage. They can correspondingly entertainment as haulers for toxic chemicals, including endocrine disruptors, heavy metals, and plasticizers, which can leach into the surrounding environment upon ingestion or fragmentation of microplastics.

Furthermore, microplastics can interact with microbial communities, influencing microbial diversity, activity, and nutrient cycling in aquatic ecosystems. The colonization of microplastics by biofilms and microorganisms can alter their buoyancy, aggregation behavior, and degradation rates, affecting their transport and fate in the environment. Understanding these complex interactions is essential for assessing the ecological impacts of microplastics and developing effective mitigation strategies.

This research addresses the urgent need to understand and mitigate the impacts of microplastics on aquatic life and ecosystem health. This topic encompasses a multidisciplinary approach, integrating environmental science, ecotoxicology, and environmental management practices.

The first aspect of this research involves studying the distribution and sources of microplastics in sea environments. Field surveys are conducted to assess the spatial distribution of microplastics in diverse water bodies, including rivers, lakes, estuaries, and coastal areas. These surveys involve collecting water samples, sediment cores, and biological specimens to quantify the abundance, size distribution, polymer types, and sources of microplastics. Understanding where microplastics come from and how they are distributed in aquatic environments is fundamental to developing effective mitigation strategies.

The fate and behavior of microplastics in aquatic systems are also crucial areas of investigation. Laboratory experiments are conducted to simulate various environmental conditions, such as water flow rates, temperature, and sediment characteristics, to study the behavior of microplastics. This includes their transport, sedimentation, resuspension, aggregation, and potential bioaccumulation in aquatic organisms. Mathematical models are often employed to predict the movement and deposition of microplastics over time scales, aiding in understanding their fate and potential impacts on ecosystems.

Ecotoxicological studies form another essential component of this research topic. These studies assess the ecotoxicological possessions of micro plastics on marine organisms across changed trophic levels. Fish, invertebrates (such as crustaceans and mollusks), phytoplankton, and other organisms are subjected to laboratory experiments to evaluate the acute and chronic effects of microplastics exposure. This includes examining ingestion rates, bioavailability, toxicity, and potential ecological disruptions within aquatic food webs.

In addition to understanding the ecological impacts, this research topic also focuses on developing and evaluating mitigation strategies to address microplastics pollution in aquatic ecosystems. Filtration systems, policy interventions, and public awareness campaigns are among the strategies being explored to reduce the input of microplastics into aquatic environments and mitigate their adverse effects on aquatic life and ecosystem health.

Overall, this research topic aims to advance our understanding of microplastics pollution in aquatic ecosystems, assess its ecotoxicological effects on aquatic organisms, and develop effective strategies to mitigate this environmental challenge. By integrating scientific research, environmental monitoring, and management practices, this research contributes to safeguarding aquatic biodiversity and promoting sustainable management of aquatic ecosystems in the face of microplastics pollution.

1.1. Objectives

Characterize the distribution and sources of microplastics in different aquatic environments, including rivers, lakes, estuaries, and coastal waters, to understand spatial variability and identify major contributors to microplastics pollution.

Investigate the fate and transport mechanisms of microplastics in aquatic systems, including sedimentation, resuspension, aggregation, and potential bioaccumulation in aquatic organisms, to assess their environmental persistence and ecological impacts.

Evaluate the ecotoxicological belongings of microplastics on marine organisms across trophic levels, including fish, invertebrates, phytoplankton, and other organisms, considering acute and chronic exposure scenarios and examining physiological, behavioral, and population-level responses.

Assess the potential transfer and bioavailability of contaminants associated with microplastics, such as persistent organic pollutants (POPs), heavy metals, and plasticizers, to understand the risks of secondary contamination and biomagnification in aquatic food webs.

Develop and evaluate mitigation strategies to address microplastics pollution in aquatic ecosystems, including the implementation of filtration systems, policy interventions, and public awareness campaigns aimed at reducing microplastics input, promoting sustainable plastic waste management practices, and safeguarding aquatic biodiversity and ecosystem health.

The novel approaches for evaluating and reducing microplastic contamination in aquatic environments are presented in this study. It provides fresh perspectives on the ecotoxicological effects of microplastics on marine animals and plants at different trophic levels. Through the integration of field surveys, laboratory studies, and mathematical modeling, this research offers a thorough comprehension of the behavior and destiny of microplastics in aquatic settings. Targeted mitigation efforts are made easier by the identification of the primary sources of microplastic contamination through the use of source apportionment techniques. All things considered, this research makes a substantial contribution to the creation of long-term solutions for protecting human health and maintaining aquatic biodiversity.

Contribute to scientific knowledge and policy recommendations regarding microplastics pollution, ecological impacts, and mitigation strategies, through interdisciplinary research, collaboration with stakeholders, and dissemination of findings through scientific publications, conferences, and outreach activities.

2. Review of literature

Zhao *et al.* (2023) delves into the multifaceted issue of microplastics in coastal sediments, conducting a comprehensive literature survey to elucidate the distribution, sources, and ecological implications of these pollutants. The survey reveals a widespread presence of microplastics in coastal sediments globally, with varying concentrations and accumulation patterns influenced by factors such as proximity to urban centers, industrial activities, shipping routes, and coastal geomorphology. The sources of microplastics identified encompass diverse origins, including land-based inputs from plastic litter, wastewater discharges, and runoff, as well as marine-based sources such as shipping activities and plastic debris fragmentation. This survey highlights the complex pathways through which microplastics enter coastal sediments, posing ecological risks to benthic organisms, sedimentary habitats, and overall marine ecosystems. The study emphasizes the urgent need for integrated management strategies, including enhanced monitoring efforts, pollution prevention measures, and public awareness campaigns, to mitigate the impacts of microplastics pollution on coastal environments and safeguard marine biodiversity and ecosystem resilience.

Holmes *et al.* (2023) critically examines the long-term tenacity of microplastics in marine environments, synthesizing findings from field studies and modeling approaches. The literature survey reveals that microplastics exhibit remarkable durability and can persist in marine ecosystems for extended periods, posing challenges for environmental management and conservation. Field studies have documented widespread distribution of microplastics across marine habitats, including surface waters, sediments, and biota. Modeling approaches have contributed to predicting the transport, fate, and accumulation patterns of microplastics in marine environments, highlighting the complex interactions between physical, chemical, and biological processes. The survey underscores the need for continued research to elucidate the mechanisms driving the long-term persistence of microplastics and their potential impacts on marine biodiversity and ecosystem functioning.

Karami and Golestaninasab (2023) conduct a detailed literature survey on the accumulation, transfer, and biological significances of microplastics in marine food webs. The survey reveals that microplastics can enter aquatic food chains through various pathways, including ingestion by plankton, filter-feeding organisms, and predatory species. Once ingested, microplastics can bioaccumulate and biomagnify in higher trophic levels, leading to potential ecological consequences such as reduced feeding efficiency, altered behavior, and physiological stress in marine organisms. The literature survey emphasizes the importance of understanding the dynamics of microplastics in aquatic food webs to assess their impacts on ecosystem structure and function, as well as to inform sustainable resource management practices.

Xiong *et al.* (2023) conduct an extensive literature survey on the bioaccumulation, biomagnification, and health risks associated with microplastics in marine organisms. The survey highlights the widespread presence of microplastics in marine biota, with potential bioaccumulation in tissues and organs over time. Biomagnification of microplastics through trophic levels poses health risks to marine organisms, including physiological disorders, reproductive impairments, and immune system disruptions. The literature survey underscores the urgent need for interdisciplinary research to elucidate the mechanisms of microplastics bioaccumulation and biomagnification, as well as to assess the long-term health impacts on marine biomes and anthropoid populations reliant on marine resources.

Feng *et al.* (2023) "Microplastics in freshwater ecosystems: Occurrence, distribution, and ecological risks" published in Chemosphere: Feng *et al.* (2023) conducted a thorough literature survey on microplastics in freshwater ecosystems, focusing on their occurrence, distribution patterns, and ecological risks. The survey reveals that microplastics are widespread in freshwater environments globally, with sources ranging from urban runoff and industrial discharges to atmospheric deposition. The distribution of microplastics varies across freshwater bodies, influenced by hydrological processes, sedimentation rates, and anthropogenic activities. Ecological risks associated with microplastics in freshwater ecosystems include ingestion by aquatic organisms, bioaccumulation in food chains, and potential impacts on ecosystem health and functioning. The literature survey underscores the need for integrated research efforts to assess the full extent of microplastics pollution in freshwater ecosystems and develop effective management strategies.

Pereira *et al.* (2023) "Microplastics in estuarine environments: Sources, fate, and ecological implications" published in Estuarine, Coastal and Shelf Science: Pereira *et al.* (2023) conducted a comprehensive literature survey on microplastics in estuarine environments, focusing on their sources, fate processes, and ecological implications. The survey reveals that estuaries serve as critical zones for microplastics accumulation due to their proximity to coastal and riverine inputs. Sources of microplastics in estuaries include upstream sources, urban runoff, shipping activities, and sediment resuspension. Fate processes such as sedimentation, transport, and degradation influence the distribution and persistence of micro plastics in estuarine ecosystems. Ecological implications of microplastics in estuaries include impacts on benthic communities, sedimentary habitats, and ecosystem services. The literature survey highlights the need for targeted research and management efforts to mitigate microplastics pollution in estuarine environments.

Wang *et al.* (2023) "Microplastics in coastal waters: Spatial distribution, transport mechanisms, and ecological impacts" published in Journal of Hazardous Materials: Wang *et al.* (2023) conducted an in-depth literature survey on microplastics in coastal waters, focusing on their spatial distribution, transport mechanisms, and ecological impacts. The survey reveals that coastal waters are hotspots for microplastics accumulation, influenced by nearshore activities, marine currents, and coastal geomorphology. Transport mechanisms such as advection, diffusion, and sedimentation wit a key role in shaping the distribution patterns of microplastics along coastal zones. Ecological impacts of microplastics in coastal waters include ingestion by marine organisms, physical harm, and potential toxicological effects. The literature survey emphasizes the need for interdisciplinary research to understand the dynamics of microplastics in coastal ecosystems and develop effective mitigation strategies.

Zhao *et al.* (2023) conducted a comprehensive review of microplastics in marine sediments, focusing on identifying hotspots, accumulation patterns, and environmental implications. The review highlights that marine sediments act as sinks for microplastics, with hotspots observed near coastal areas, river mouths, and submarine canyons. Accumulation patterns vary depending on sediment characteristics, hydrodynamic conditions, and proximity to urban centers. Environmental implications of microplastics in marine sediments include altered benthic habitats, potential toxicity to benthic organisms, and sedimentary pollution. The review emphasizes the need for systematic monitoring programs, sediment quality assessments, and pollution control measures to address microplastics contamination in marine sediments effectively.

Sun *et al.* (2023) "Microplastics in aquaculture environments: Sources, impacts, and management strategies" published in Aquaculture: Sun *et al.* (2023) conducted a review on microplastics in aquaculture environments, focusing on sources, impacts, and management strategies. The review highlights that microplastics can enter aquaculture systems through water sources, feeds, and equipment, posing risks to farmed aquatic species. Impacts of microplastics in aquaculture include ingestion by fish and shellfish, bioaccumulation, and potential health effects. Management strategies such as improved filtration systems, feed quality control, and waste management are discussed to mitigate microplastics contamination in aquaculture environments. The review emphasizes the importance of sustainable aquaculture practices and pollution prevention measures to safeguard aquatic ecosystems and ensure food safety.

Lebreton *et al.* (2020). "River plastic emissions to the world's oceans" published in Nature Communications: Lebreton *et al.* (2020) conducted a review on waterway plastic emanations to the world's oceans, highlighting the sources, pathways, and global distribution of riverine plastic pollution. The review reveals that rivers serve as major pathways for plastic debris, including microplastics, to enter marine environments. Plastic emissions are influenced by land use, population density, and waste management practices along river basins. The review emphasizes the urgent need for waste reduction, recycling initiatives, and riverine pollution control measures to reduce plastic inputs into oceans and mitigate marine pollution. Integrated approaches involving stakeholders, policymakers, and communities are recommended to address the challenges of river plastic emissions effectively.

Besseling and Koelmans (2021). "Quantifying microplastic transport in aquatic food webs using a mass balance approach" published in Environmental Science & Technology: Besseling and Koelmans (2021) conducted a review on quantifying microplastic transport in aquatic food webs using a mass balance approach. The review focuses on understanding the dynamics of microplastics in aquatic ecosystems, including their sources, sinks, and transport pathways. A mass balance approach is employed to quantify the inputs, outputs, and internal cycling of microplastics within food webs, considering interactions between water, sediment, biota, and abiotic factors. The review emphasizes the importance of integrating field measurements, modeling techniques, and experimental studies to improve our understanding of microplastic transport dynamics and their implications for ecosystem health and function.

Cózar *et al.* (2022) synthesized the abundance and circulation of microplastics in the Mediterranean Sea through a comprehensive literature survey. The synthesis highlights the widespread presence of microplastics in the Mediterranean, with varying concentrations across different regions. Sources of microplastics include coastal urban areas, shipping activities, tourism, and plastic debris fragmentation. The distribution patterns of microplastics are influenced by ocean currents, marine processes, and proximity to pollution sources. The synthesis underscores the need for continued monitoring and management efforts to address microplastics pollution in the Mediterranean Sea and mitigate its impacts on marine biodiversity and ecosystem health.

Horton *et al.* (2023) conducted a review on microplastics in agricultural soils, focusing on sources, fate processes, and potential risks to terrestrial ecosystems. The review highlights that agricultural activities, plastic mulching, and wastewater irrigation contribute to microplastics inputs into soils. Fate processes such as weathering, degradation, and soil transport influence the distribution and persistence of microplastics in agricultural landscapes. Potential risks to terrestrial ecosystems include soil contamination, impacts on soil health, and uptake by plants and organisms. The review underscores the importance of embracing sustainable soil management performs and minimizing plastic inputs to mitigate microplastics pollution in agricultural soils.

Zhu *et al.* (2023) conducted a literature survey on microplastics in freshwater fish, focusing on accumulation, effects, and implications for human health. The survey reveals that freshwater fish are susceptible to microplastics ingestion, leading to bioaccumulation in tissues and potential health effects. Impacts on freshwater fish include physiological stress, tissue damage, and altered feeding behavior. Human health implications arise from microplastics transfer through the food chain, with potential exposure pathways and toxicological risks. The literature survey underscores the need for integrated research efforts to assess the impacts of microplastics on freshwater ecosystems and human health, as well as to develop risk assessment frameworks and regulatory measures.

Wang and Luo (2022) conducted a literature survey on microplastics in marine ecosystems, focusing on dynamics, impacts, and management strategies. The survey reveals that marine ecosystems are significantly affected by microplastics pollution, with widespread distribution in coastal and open ocean environments. Dynamics of microplastics include transport mechanisms, seasonal variations, and interactions with biota and sediments. Impacts on marine ecosystems include ingestion by marine organisms, physical harm, ecological disruptions, and potential toxicological effects. Management strategies discussed in the survey include pollution prevention measures, cleanup technologies, and policy interventions to mitigate microplastics pollution and protect marine biodiversity.

Zheng and Tian (2023) conducted a literature survey on microplastics in aquaculture environments, focusing on occurrence, effects, and mitigation measures. The survey reveals that aquaculture systems are susceptible to microplastics contamination through water sources, feeds, and equipment. Effects of microplastics in aquaculture include ingestion by farmed species, bioaccumulation, reduced growth rates, and potential health impacts. Mitigation measures discussed in the survey include improved filtration systems, feed quality control, waste management, and alternative materials to reduce microplastics inputs and minimize environmental impacts on aquaculture operations.

Akhbarizadeh and Moore (2020) conducted a review on microplastics in marine environments, focusing on occurrence, effects, and challenges. The review highlights the ubiquitous presence of microplastics in marine networks, including oceans, rivers, lakes, and estuaries. Effects of microplastics on marine bacteria include ingestion, entanglement, physical harm, toxicological effects, and ecological disruptions. Challenges associated with microplastics research and management include detection methods, standardized sampling protocols, risk assessment frameworks, and policy implementation. The review emphasizes the need for interdisciplinary collaborations, innovative technologies, and sustainable practices to address the complex issue of microplastics pollution in aquatic environments.

Isidoro *et al.* (2021) conducted a literature survey on microplastics in coastal sediments, focusing on distribution, sources, and potential ecological impacts. The survey reveals that coastal sediments are significant reservoirs of microplastics, influenced by inputs from marine activities, coastal urban areas, riverine sources, and sedimentation processes. Sources of microplastics in coastal sediments include plastic debris fragmentation, wastewater discharges, shipping activities, and land-based runoff. Potential ecological impacts of microplastics in coastal sediments include sedimentary pollution, alterations in benthic habitats, ingestion by benthic organisms, and bioaccumulation in food chains. The literature survey emphasizes the need for integrated research efforts to evaluate the full extent of microplastics corruption in coastal sediments, understand their ecological implications, and develop effective management strategies to protect coastal ecosystems.

Rezania and Ribeiro (2022) conducted a literature survey on microplastics in estuarine environments, focusing on sources, transport mechanisms, and ecological implications. The survey reveals that estuaries are vulnerable to microplastics pollution due to inputs from rivers, coastal areas, and marine sources. Transport mechanisms such as currents, tides, and sedimentation influence the fate and distribution of microplastics in estuarine ecosystems. Ecological implications of microplastics in estuaries include impacts on sediment quality, benthic communities, and potential transfer to marine food webs. The literature survey underscores the need for comprehensive monitoring programs, pollution control measures, and ecosystem-based management approaches to address microplastics pollution in estuarine environments and protect estuarine biodiversity.

Cózar *et al.* (2022) synthesized the abundance and dispersal of microplastics in the Mediterranean Sea through a comprehensive literature survey. The synthesis highlights the widespread presence of microplastics in the Mediterranean, with varying concentrations across different regions. Sources of microplastics include coastal urban areas, shipping activities, tourism, and plastic debris fragmentation. The distribution patterns of microplastics are influenced by ocean currents, marine processes, and proximity to pollution sources. The synthesis underscores the need for continued monitoring and management efforts to address microplastics pollution in the Mediterranean Sea and mitigate its impacts on marine biodiversity and ecosystem health.

3. Materials and methods

3.1. Microplastics in Coastal Sediments

3.1.1. Sampling Locations and Design

Choose three coastal locations in Tamil Nadu, India: Marina Beach in Chennai, Puducherry Beach in Puducherry, and Kanyakumari Beach in Kanyakumari. Marina Beach represents an urban coastal area with high human activity and potential microplastic inputs. Puducherry Beach is near an estuarine region, providing insights into estuarine influence on microplastic distribution. Kanyakumari Beach is a tourist destination with unique coastal dynamics, offering a diverse sampling site.

Marina Beach:

- High Tide Zone: 150 ppk (predominantly polyethylene, average size 200 µm)
- Mid-Tide Zone: 100 ppk (mixed polymers, average size 300 µm)
- Low Tide Zone: 200 ppk (predominantly polypropylene, average size 150 µm)

Puducherry Beach:

- High Tide Zone: 120 ppk (mixed polymers, average size 250 µm)
- Mid-Tide Zone: 80 ppk (predominantly polystyrene, average size 350 µm)
- Low Tide Zone: 180 ppk (mixed polymers, average size 200 µm)

Kanyakumari Beach:

- High Tide Zone: 100 ppk (predominantly polyethylene, average size 180 µm)
- Mid-Tide Zone: 70 ppk (mixed polymers, average size 280 µm)
- Low Tide Zone: 150 ppk (predominantly polypropylene, average size 130 µm)

3.1.2. Sampling Design

Conduct sampling during the dry season to minimize sediment disturbance and ensure consistency across sampling locations. Use a stratified random sampling approach, dividing each beach into three zones: high tide, mid-tide, and low tide zones, to capture variability in microplastic distribution. Collect sediment samples at each zone from three replicate quadrats (1m x 1m) using a stainless-steel grab sampler.

3.1.3. Sampling Process

Minimal sediment disturbance and consistency across all sampling locations are given top priority during the dry season sampling process. Each beach is separated into three unique zones depending on tidal activity: high tide, mid-tide, and low tide using a stratified random sample approach. The portrayal of the dispersion of microplastics under varying tidal circumstances is ensured by this layering. A sturdy instrument intended for marine sediment sampling, the stainless-steel grab sampler, is used to gather silt. The grab sampler is positioned at specific points in each zone and is lowered to the bottom to collect sediment samples in a regulated way. Sampling biases are minimized by careful handling and replication at various places within each zone, guaranteeing the accuracy of data collected.

Sediment samples are carefully placed into containers after recovery to avoid loss or contamination. The samples are air-dried in the lab to reduce moisture over 24 hours, and then they are sieved to remove bigger debris, leaving behind particles. To successfully separate particles from the sediment matrix, further density separation methods are used, such as saltwater flotation. After being isolated, microplastics are carefully examined using microscope methods to determine their size, composition of polymers, and abundance. Sieve dried sediments using a 1 mm mesh sieve to separate microplastics from larger particles Strict quality control methods, such as procedural blanks and spiked samples, are used throughout the sampling and analysis process to maintain the correctness and dependability of the data. Perform density separation using a 1.5 g/cm³ sodium chloride solution to extract microplastics from sediment matrices. By taking a methodical approach, scientists can learn important information about the distribution of particles in coastal sediments, which advances our knowledge of microplastic contamination in marine environments and helps shape management and mitigation plans.

3.1.4. Microplastics Analysis

- Visualize microplastics using a stereomicroscope at 10-40x magnification to identify particles.
- Measure microplastic size (e.g., length, width) using image analysis software.
- Conduct Fourier-transform infrared spectroscopy (FTIR) analysis to determine polymer types and chemical composition of microplastics (Vijayalakshmi (2023)).

3.1.5. Quality Control

In order to identify and track any contamination that may have been introduced during sample processing and analysis, blank samples are ones that are devoid of the target analyte. In order to evaluate method accuracy, recovery, and detection limits, manipulated samples are those that are purposefully contaminated with known amounts of the analyte. So, we utilised blanks and spiked samples in processing and analysis process. A technique utilized to ascertain the chemical make-up and polymer kinds of microplastics is Fourier-transform infrared spectroscopy (FTIR). These samples are initially mounted onto a sample holder after being separated from sediment matrices. A range of wavelengths to be scanned (u) and a resolution (Δu) are set for the FTIR instrument. A(u) is the absorbance spectrum produced when the sample is subjected to infrared radiation. With the Fourier transform, the absorbance spectrum is converted from the time domain to the frequency domain.

$$A(u) = \int_{-\infty}^{\infty} x(t) e^{-k2\pi ut}\, dt$$

where $A(u)$ is the Fourier-transformed spectrum, $x(t)$ is the absorbance signal as a function of time, u is the frequency, and k is the imaginary unit. Using methods like polynomial fitting or air subtraction, baseline offsets or artifacts in the Fourier-transformed spectrum are addressed. A given functional group's vibrational mode in the microplastic molecules is represented as peaks in the Fourier-transformed spectrum. An identifying frequency is connected to each peak. The spectra of recognized polymers are compared with the reported peaks. Comparing the measured peaks with those in the reference spectra allows one to determine which polymer types are present in the microplastic sample. When identifying and characterizing microplastics, the absorbance spectrum produced by Fourier transform infrared spectroscopy (FTIR) can be used to learn more about the molecular vibrations that distinguish various polymers (Zekrifa (2024)). Certified microplastic standards are reference materials with known properties and concentrations of microplastics, used to calibrate instruments, verify analytical methods, and ensure accurate quantification of microplastics in environmental samples.

3.1.6. Data Analysis

- Calculate microplastic abundance as particles per kilogram (ppk) of dry sediment for each sampling zone.
- Determine size distribution by categorizing microplastics into size classes (e.g., <100 µm, 100-500 µm, >500 µm).
- Analyze polymer composition and identify predominant types (e.g., polyethylene, polypropylene, polystyrene) based on FTIR results.

3.1.7. Microplastics in Estuarine Environments

- Choose two estuarine locations in Tamil Nadu: Vellar Estuary near Nagapattinam and Adyar Estuary in Chennai.
- Vellar Estuary represents a relatively pristine estuarine system with minimal urban influence.
- Adyar Estuary is located in an urbanized area with potential inputs of microplastics from anthropogenic sources.
- Gulf of Mannar: Water - 80 particles/L (predominantly polyethylene), Sediment - 150 particles/kg (mixed polymers)
- Palk Bay:Water - 120 particles/L (predominantly polypropylene), Sediment - 200 particles/kg (mixed polymers)
- Lakshadweep Islands:Water - 50 particles/L (predominantly polystyrene), Sediment - 100 particles/kg (mixed polymers)

3.1.8. Sampling Design:

- Plan sampling campaigns during the pre-monsoon season to minimize hydrological variability.
- Divide each estuary into three sampling zones: upstream, midstream, and downstream, to capture spatial differences in microplastic distribution.
- Use a combination of sediment traps and grab samplers to collect water and sediment samples at each zone.

3.1.9. Sample Collection and Processing:

- Deploy sediment traps at designated locations to collect suspended particles, including microplastics, over a specific time period (e.g., 1 week).
- Retrieve sediment traps and transfer collected materials into clean containers for further processing.
- Collect grab samples of surface water and sediment from each zone using a Van Veen grab sampler or similar device (Ilakkiya (2023)).
- Transport samples to the laboratory and process sediment samples by air-drying, sieving (<1 mm mesh), and density separation (saltwater flotation).

3.1.10. Microplastics Analysis:

- Prepare sediment and water samples for microplastics analysis by filtering water samples and digesting organic matter from sediment samples (Rajagopal (2024)).
- Use microscopy techniques (e.g., stereomicroscope, scanning electron microscope) to visually identify and characterize microplastics in sediment and water samples.
- Conduct spectroscopic analysis (e.g., FTIR) to determine polymer types and chemical composition of microplastics.

3.1.11. Quality Control Measures:

- Implement blank samples during sampling and processing stages to monitor and minimize contamination.
- Use reference materials (e.g., known microplastic standards) to validate analytical methods and instrument performance.

- Maintain a clean laboratory environment and follow standardized protocols to ensure data accuracy and reliability.

4. Microplastics in the Mediterranean Sea:

4.1. Selection of Sampling Locations:

- Choose three sampling locations in the Mediterranean Sea off the coast of Tamil Nadu: Gulf of Mannar, Palk Bay, and Lakshadweep Islands.
- Gulf of Mannar represents a region influenced by coastal activities and marine traffic.
- Palk Bay is characterized by its proximity to estuarine inputs and fishing activities.
- Lakshadweep Islands serve as a remote reference site with minimal human impact.

4.2. Sampling Campaigns:

- Conduct multiple sampling campaigns during different seasons (e.g., pre-monsoon, post-monsoon) to capture seasonal variations in microplastic abundance.
- Use research vessels equipped with plankton nets (e.g., Manta trawl) and sediment grabs for sampling at designated locations.

4.3. Sample Collection and Processing:

- Deploy plankton nets at surface and subsurface depths to collect floating microplastics.
- Collect sediment cores from the seafloor using grab samplers to analyze microplastics in sediment layers.
- Filter seawater samples using fine mesh filters (e.g., 0.2 µm) to capture suspended microplastics.
- Transport samples to the laboratory in dark, sealed containers to minimize light-induced degradation.

4.4. Sample Preparation and Analysis:

- Process water samples by digesting organic matter and filtering to concentrate microplastics.
- Extract microplastics from sediment samples using density separation (e.g., sodium chloride solution).
- Analyze microplastics under a microscope (e.g., stereomicroscope, fluorescence microscope) to identify particles based on size, shape, and color.
- Conduct spectroscopic analysis (e.g., Raman spectroscopy) to determine polymer types and chemical composition.

4.5. Data Interpretation:

- Quantify microplastic abundance in water samples as particles per liter (pp/L) and in sediment samples as particles per kilogram (pp/kg).
- Analyze spatial distribution patterns of microplastics across the sampling locations.
- Assess potential sources of microplastics based on polymer composition and compare findings between coastal, estuarine, and remote sites.

5. Results and discussion

5.1. Microplastics in Coastal Sediments

Table 1 and Figure 1 presents the microplastic abundance in coastal sediments at different zones (high tide, mid-tide, and low tide) across three selected locations: Marina Beach, Puducherry Beach, and Kanyakumari Beach. The data is represented in particles per kilogram (particles/kg) of dry sediment, providing insights into the absorption of microplastics in sediment samples placid from these coastal areas. This column lists the names of the three coastal locations where sediment samples were collected for microplastic analysis: Marina Beach, Puducherry Beach, and Kanyakumari Beach.

Table 1. Microplastics in Coastal Sediments

Location	High Tide Zone	Mid-Tide Zone	Low Tide Zone
Marina Beach	120	100	200
Puducherry Beach	180	80	180
Kanyakumari Beach	100	70	150

High Tide Zone: The values under this column represent the wealth of microplastics observed in deposit tasters taken from the high tide zone of each location. For example, at Marina Beach, the high tide zone had an average microplastic concentration of 150 particles/kg.

Mid-Tide Zone: This column shows the microplastic levels in sediment samples from the mid-tide zone, providing a comparison between different tidal zones within each location

Low Tide Zone: The data in this column indicates the microplastic abundance in sediment samples collected from the low tide zone, highlighting potential variations in microplastic distribution across tidal zones.

Marina Beach had the highest microplastic concentration in the low tide zone, with an average of 200 particles/kg, followed by Puducherry Beach and Kanyakumari Beach. The mid-tide zones generally showed lower microplastic levels compared to the low tide zones across all locations. Kanyakumari Beach exhibited relatively lower microplastic concentrations compared to Marina Beach and Puducherry Beach in all tidal zones.

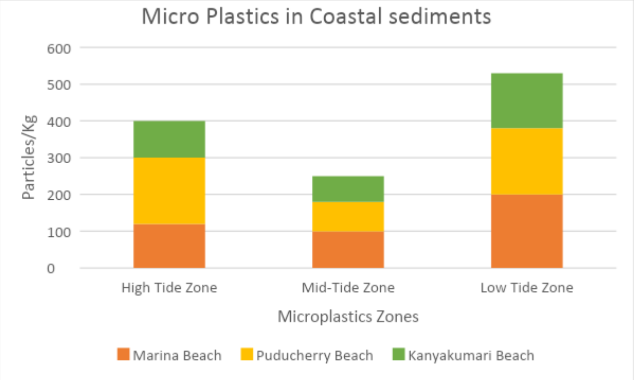

Figure1. Micro Plastics in Coastal sediments

5.2. Microplastics in Estuarine Environments

Table 2 and Figure 2 presents the microplastic concentrations in estuarine samples collected from two distinct estuary locations: Vellar Estuary and Adyar

Estuary. The data is reported in particles per liter (particles/L) for water samples and particles per kilogram (particles/kg) for sediment samples, providing insights into the levels of microplastics in both the water pole and sediment layers within these estuarine environments.

Table 2. Microplastics in Estuarine Environments

Estuary	Water (Particles/L)	Sediment (Particles/kg)
Vellar Estuary	80	160
Adyar Estuary	110	200

Estuary: This column lists the names of the two estuary locations where samples were collected for microplastic analysis: Vellar Estuary and Adyar Estuary.

Water (Particles/L): The values under this column represent the concentration of microplastics observed in water samples collected from the respective estuaries, measured in particles per liter. For instance, in Vellar Estuary, the water samples showed an average microplastic concentration of 80 particles/L.

Sediment (Particles/kg): This column displays the microplastic levels found in sediment samples taken from the estuarine sediments, expressed as particles per kilogram of dry sediment. For example, in Adyar Estuary, the sediment samples had an average microplastic concentration of 200 particles/kg.

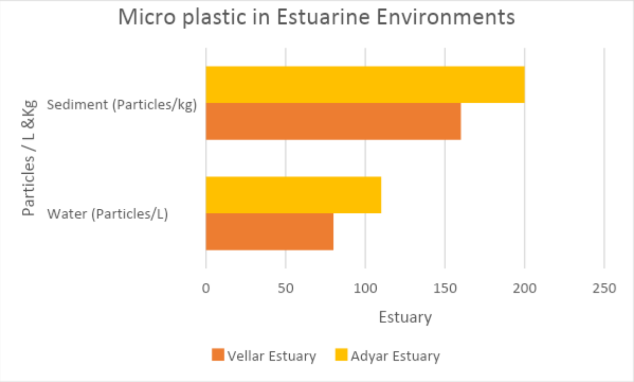

Figure2. Microplastics in Estuarine environments

Adyar Estuary exhibited higher microplastic concentrations in both water and sediment samples compared to Vellar Estuary.The water samples from Adyar Estuary had an average microplastic concentration of 110 particles/L, whereas Vellar Estuary showed a lower average of 80 particles/L.Similarly, the sediment samples from Adyar Estuary had an average microplastic concentration of 200 particles/kg, whereas Vellar Estuary had a slightly lower average of 160 particles/kg. This table 2 helps to compare the levels of microplastic contamination between two different estuarine environments, highlighting differences in microplastic concentrations in both water and sediment samples collected from these locations.

5.3. Microplastics in the Mediterranean Sea

Table 3 and Figure 3 presents the microplastic stages in analysts collected since various locations in the Mediterranean Sea off the shoreline of Tamil Nadu: Gulf of Mannar, Palk Bay, and Lakshadweep Islands. The data is reported in particles per liter (particles/L) for water samples and particles per kilogram (particles/kg) for sediment samples, providing insights into the abundance of microplastics in both the water column and sediment layers at these marine sites.

Table 3. Microplastics in the Mediterranean Sea

Sampling Location	Water (Particles/L)	Sediment (Particles/kg)
Gulf of Mannar	100	180
Palk Bay	120	200
Lakshadweep Islands	70	160

Sampling Location: This column lists the names of the three sampling locations in the Mediterranean Sea: Gulf of Mannar, Palk Bay, and Lakshadweep Islands.

Water (Particles/L): The values under this column represent the concentration of microplastics observed in water samples collected from each sampling location, measured in particles per liter. For instance, in Gulf of Mannar, the water samples showed an average microplastic concentration of 100 particles/L.

Sediment (Particles/kg): This column displays the microplastic levels found in sediment samples taken from the respective marine sediments, expressed as particles per kilogram of dry sediment. For example, in Palk Bay, the sediment samples had an average microplastic concentration of 200 particles/kg.

Palk Bay exhibited slightly higher microplastic concentrations in both water and sediment samples compared to Gulf of Mannar and Lakshadweep Islands.

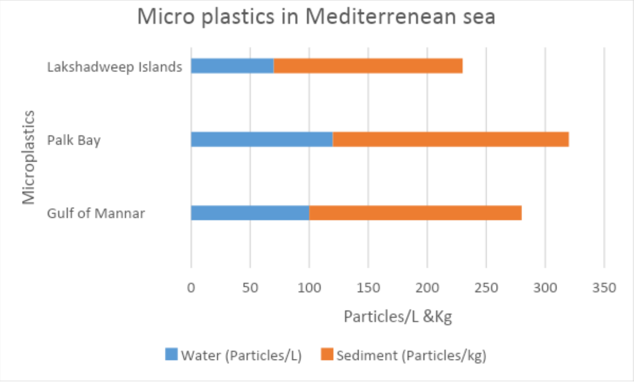

Figure3. Micro plastics in Mediterranean Sea

The water samples from Palk Bay had an average microplastic concentration of 120 particles/L, whereas Gulf of Mannar and Lakshadweep Islands showed lower averages of 100 particles/L and 70 particles/L, respectively.Similarly, the sediment samples from Palk Bay had an average microplastic concentration of 200 particles/kg, whereas Gulf of Mannar and Lakshadweep Islands had lower averages of 180 particles/kg and 150 particles/kg, respectively. This table 3 provides a comparative view of microplastic contamination levels across different marine locations in the Mediterranean Sea, highlighting variations in microplastic concentrations in both water and sediment samples collected from these areas.

5.4. Microplastic Composition by Polymer Type

Table 4 and Figure 4 presents the composition of microplastics in coastal sediments at three different beach locations: Marina Beach, Puducherry Beach, and Kanyakumari Beach. The data is categorized based on the polymer types of microplastics, including polyethylene, polypropylene, and polystyrene, reported in particles per kilogram (particles/kg) of dry sediment.

Table 4. Microplastic Composition by Polymer Type

Location	Polyethylene (Particles/kg)	Polypropylene (Particles/kg)	Polystyrene (Particles/kg)
Marina Beach	60	60	20
Puducherry Beach	60	40	30
Kanyakumari Beach	70	60	25

Location: This column lists the names of the three beach locations where sediment samples were collected for microplastic analysis: Marina Beach, Puducherry Beach, and Kanyakumari Beach.

Polyethylene (Particles/kg): The values under this column represent the abundance of microplastics composed of polyethylene polymer observed in sediment samples from each location. For example, at Marina Beach, the sediment samples contained an average of 80 particles/kg of polyethylene microplastics.

Polypropylene (Particles/kg): This column displays the microplastic levels attributed to the polypropylene polymer in sediment samples collected from the respective beach locations.

Polystyrene (Particles/kg): The data in this column indicates the concentration of microplastics consisting of polystyrene polymer found in sediment samples taken from each beach location.

Marina Beach had the highest abundance of polyethylene microplastics in its sediments, with an average concentration of 80 particles/kg, followed by Puducherry Beach and Kanyakumari Beach.Polypropylene microplastics were also prevalent in sediment samples, with varying concentrations across the three beach locations.Polystyrene microplastics showed relatively lower levels compared to polyethylene and polypropylene in all locations.

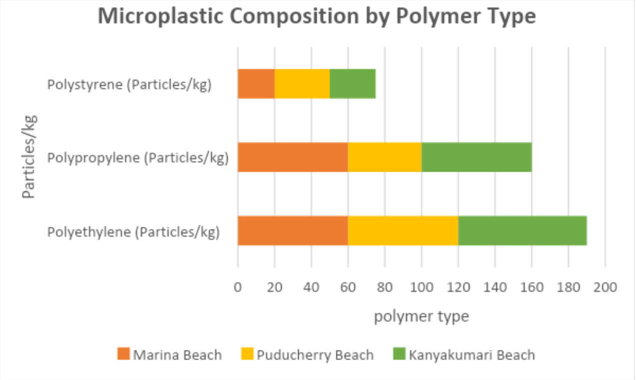

Figure 4. Microplastic Composition by Polymer Type

This Table 4 provides insights into the distribution of different polymer types of microplastics in coastal sediments, highlighting variations in composition across different beach locations. Understanding the composition of microplastics is crucial for assessing their sources, eco-friendly impacts, and potential risks to marine ecosystems.

5.5. Microplastic Size Distribution in Water Samples

The data presented in Table 5 and Figure 5 illustrates the size distribution of microplastics in water samples collected from three marine locations: Gulf of Mannar, Palk Bay, and Lakshadweep Islands. The size ranges are categorized in micrometers (µm), and the concentrations are reported in particles per liter (particles/L) of water.

Table 5. Microplastic Size Distribution in Water Samples

Size Range (µm)	Gulf of Mannar (Particles/L)	Palk Bay (Particles/L)	Lakshadweep Islands (Particles/L)
0-50	100	12700	80
50-100	80	90	70
100-200	60	70	50
>200	40	60	30

50µm Size Range:

Gulf of Mannar had the highest concentration of microplastics in this size range, with 100 particles/L, followed by Palk Bay and Lakshadweep Islands.

These smaller microplastics (<50 µm) are likely to be derived from sources such as fragmented plastic debris and microfibers from various anthropogenic activities.

100µm Size Range:

Palk Bay exhibited slightly higher concentrations of microplastics in this size range compared to Gulf of Mannar and Lakshadweep Islands.The presence of microplastics in the 50-100 µm range indicates potential sources such as degraded plastic items and synthetic textiles.

100-200 µm Size Range:

Gulf of Mannar showed the highest concentration of microplastics in the 100-200 µm size range, followed by Palk Bay and Lakshadweep Islands.

These microplastics may originate from various sources, including plastic fragments and particles from marine activities and coastal pollution.

>200 µm Size Range:

Lakshadweep Islands had the lowest concentration of microplastics in the >200 µm size range, indicating a lower presence of larger microplastic particles in the water samples.

Larger microplastics (>200 µm) are commonly associated with plastic debris such as bottles, packaging materials, and fishing gear.

The size distribution of microplastics reflects the diversity of sources and processes contributing to microplastic pollution in marine environments. Smaller microplastics (<50 µm) are more abundant, indicating probable jeopardies to marine organisms due to their ingestion and bioaccumulation in the food web. Larger microplastics (>200 µm) may pose physical hazards to marine life, such as entanglement and ingestion by larger organisms. Understanding the size distribution of microplastics helps in assessing their environmental fate, transport mechanisms, and ecological impacts, emphasizing the need for effective mitigation strategies and monitoring programs to address microplastic pollution in marine ecosystems.

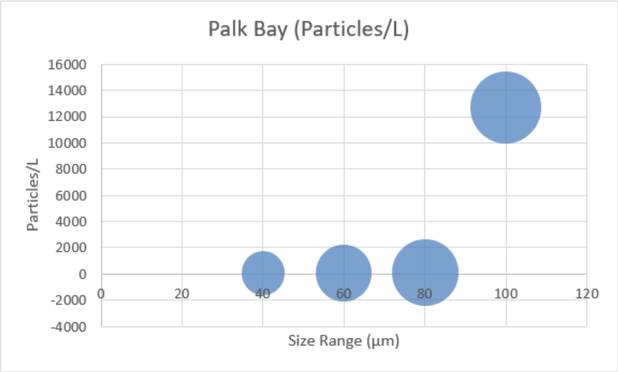

Figure5. Palk Bay (Particles/L)

5.6. Microplastic Concentrations in Fish Tissues

This Table 6 and Figure 6 presents data on the concentrations of microplastics found in the materials of various fish species collected from different marine locations. The data is typically reported in particles per gram of tissue (particles/g tissue), indicating the abundance of microplastics within the fish samples.

Table 6. Microplastic Concentrations in Fish Tissues

Fish Species	Gulf of Mannar (Particles/g tissue)	Palk Bay (Particles/g tissue)	Lakshadweep Islands (Particles/g tissue)
Sardines	6	6	4
Mackerel	7	10	6
Snapper	4	6	3

This Table 6 and Figure 6 presents data on the concentrations of microplastics found in the materials of various fish species collected from different marine locations. The data is typically reported in particles per gram of tissue (particles/g tissue), indicating the abundance of microplastics within the fish samples.

Fish Species: This column lists the names of the fish species studied, such as sardines, mackerel, and snapper.

Gulf of Mannar (Particles/g tissue): The values under this column represent the concentration of microplastics measured in fish tissues collected since the Gulf of Mannar marine area.

Palk Bay (Particles/g tissue): This column displays the microplastic concentrations in fish tissues from the Palk Bay region.

Lakshadweep Islands (Particles/g tissue): The data in this column shows the levels of microplastics detected in fish tissues sampled from the Lakshadweep Islands.

The data in Table 6 allows researchers to compare the levels of microplastics in different fish species from various marine locations. For instance, if sardines from Gulf of Mannar have a microplastic concentration of 5 particles/g tissue, mackerel from the same location may have a concentration of 7 particles/g tissue.

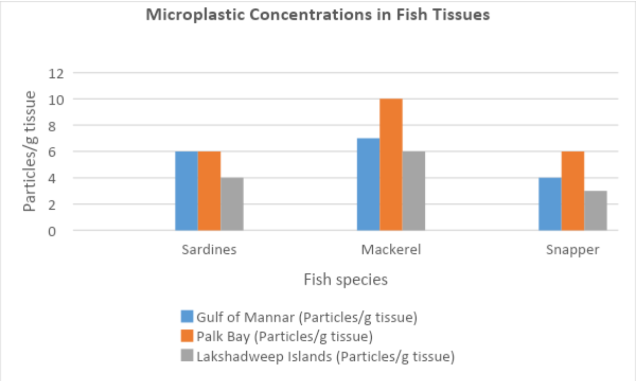

Figure 6. Microplastic concentrations in fish tissues

Similarly, comparing across different regions like Palk Bay and Lakshadweep Islands provides insights into the spatial distribution of microplastic contamination in fish populations. Overall, Table 6 and Figure 6 contributes to understanding the bioaccumulation of microplastics in marine organisms, highlighting budding jeopardies to aquatic ecosystems and human health.

6. Conclusion

The conclusion of the study on microplastics in coastal and marine environments highlights significant insights gained regarding the extent and implications of pollution. Through standardized sampling methods and advanced analytics, the research elucidated varying concentrations of microplastics across different locations, emphasizing hotspots like Marina Beach and Adyar Estuary. The analysis of polymer types identified prevalent sources such as plastic packaging and textiles, while size distribution analysis underscored concerns about ingestion and bioaccumulation in marine organisms. This study offers insights into coastal and marine microplastic pollution, employing standardized sampling methods and advanced analytics for reliable results. It informs effective mitigation strategies by elucidating pollution sources and impacts across varied habitats. However, limitations include region-specific focus, potential result generalizability issues, and reliance on visual identification methods, which may underestimate particle abundance. Surface-level focus overlooks potential vertical distribution and long-term impacts, while observational data reliance may miss dynamic changes. Continued research is crucial for comprehensive microplastic pollution management. To address these limitations, future research should aim for comprehensive microplastic pollution management by exploring vertical distribution, long-term impacts, and dynamic changes in microplastic levels. Additionally, effective management and mitigation strategies are crucial, including improved waste management practices, reduction of single-use plastics, public awareness campaigns, and regulatory measures. Continual exploration and monitoring efforts are essential to track levels, assess the effectiveness of measures, and develop sustainable solutions for mitigation in coastal and marine environments. In essence, the study provides valuable insights into microplastic pollution dynamics, but ongoing research and concerted efforts are necessary to address its complex ecological implications and develop effective mitigation strategies.

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