Microplastic Contamination in Freshwater Ecosystems: Sources, Impacts, Detection Methods and Future Perspectives

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Abstract
Microplastic contamination has emerged as a major environmental challenge affecting freshwater ecosystems worldwide. Microplastics are plastic particles smaller than 5 mm that enter rivers, lakes, reservoirs and wetlands through domestic wastewater, industrial discharge, agricultural runoff and degradation of larger plastic materials. Due to their persistence, small size and ability to adsorb toxic pollutants, microplastics can affect aquatic organisms and may enter food webs. This paper reviews sources, distribution, ecological impacts, detection methods and management strategies related to freshwater microplastic pollution. Microplastic pollution has emerged as a critical environmental challenge affecting freshwater ecosystems worldwide. Microplastics (MPs), generally defined as plastic particles smaller than 5 mm, originate from the fragmentation of larger plastic debris and from direct release of small plastic particles from various human activities. Rivers, lakes, reservoirs, and wetlands act as important pathways and accumulation zones for microplastics before they reach marine environments. These pollutants interact with aquatic organisms, alter ecosystem functions, and may transfer toxic chemicals and microorganisms through food webs. This review discusses the major sources of microplastic contamination in freshwater ecosystems, their ecological and human health impacts, advanced detection and characterization techniques, and future strategies for monitoring and mitigation. Understanding microplastic behaviour and developing effective management approaches are essential for protecting freshwater resources and achieving sustainable environmental health.

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Introduction

Plastic production and consumption have increased rapidly, resulting in accumulation of plastic waste in natural environments. Freshwater ecosystems act as important pathways for transporting plastic particles from land to oceans. Microplastics are now detected in surface water, sediments and aquatic organisms. Plastic production has increased dramatically due to its versatility, durability, and low cost. However, improper disposal and poor waste management have resulted in widespread plastic contamination in terrestrial and aquatic environments. Freshwater ecosystems are particularly vulnerable because rivers and lakes receive plastic waste from urban, industrial, agricultural, and atmospheric sources.

Microplastics are small plastic particles that originate either from the breakdown of larger plastics (**secondary microplastics**) or are intentionally manufactured at microscopic sizes (**primary microplastics**). Due to their small size, persistence, and ability to adsorb harmful pollutants, microplastics have become a major concern for environmental scientists.

Freshwater systems provide drinking water, food resources, and habitats for diverse organisms. The presence of microplastics threatens biodiversity, ecosystem stability, and potentially human health

Sources of Microplastics

Major sources include domestic sewage, synthetic textile fibres, industrial activities, agricultural plastics, tyre wear particles and weathering of larger plastic debris.

Transport and Fate

Microplastics are transported by water currents and can settle in sediments. Their movement depends on particle size, density, shape and environmental conditions.

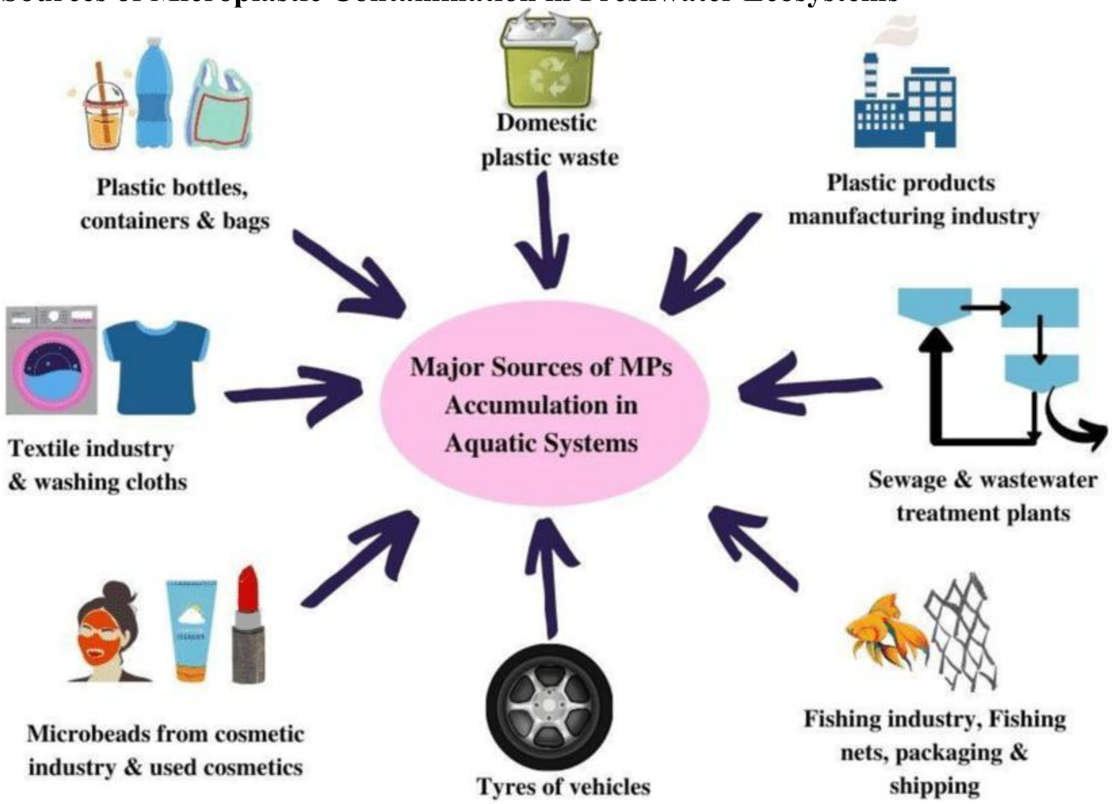
Ecological Impacts

Microplastics may be ingested by plankton, insects, fish and other aquatic organisms. Effects include physical damage, reduced feeding efficiency, oxidative stress and possible transfer of contaminants through food chains.

Detection Methods
Common analytical approaches include visual microscopy, Fourier Transform Infrared Spectroscopy (FTIR), Raman spectroscopy, Scanning Electron Microscopy (SEM), and pyrolysis gas chromatography–mass spectrometry (Py-GC/MS).

Mitigation Strategies
Reducing plastic use, improving wastewater treatment, monitoring freshwater systems and promoting circular economy approaches are essential for reducing microplastic pollution.

2. Sources of Microplastic Contamination in Freshwater Ecosystems



2.1 Domestic Wastewater
Household activities contribute significantly to microplastic pollution. Synthetic textile fibres released during washing, cosmetic products containing plastic particles, and plastic-based household materials enter wastewater systems.
Wastewater treatment plants can remove a large proportion of microplastics; however, smaller particles often pass through and enter rivers and lakes through treated effluents.

2.2 Industrial Activities
Industries such as plastic manufacturing, packaging, textiles, and chemical industries release microplastic particles through industrial discharge and accidental losses of plastic pellets.
Industrial areas near freshwater bodies often show higher microplastic concentrations.

2.3 Agricultural Runoff
Plastic materials are widely used in agriculture, including

2.3.1 Plastic mulching films
Plastic mulch farming is an agricultural practice where a plastic mulch film typically made from polyethylene is laid over well-prepared soil beds, with pre-punched holes to allow crop growth. The mulch film acts as a protective barrier between the soil and the external environment, helping farmers better control growing conditions.
Unlike organic mulches such as straw or crop residues, agricultural plastic mulch does not decompose during the crop cycle. Instead, it creates a stable and controlled microclimate by reducing moisture loss, suppressing

weeds, and regulating soil temperature. This makes plastic mulching in agriculture especially effective for vegetables, fruits, and commercial horticulture crops.

Benefits of Mulching for Modern Farmers

1. Water Conservation (Evaporation Control)

In open-field farming, a significant portion of irrigation water is lost through surface evaporation before it reaches plant roots. **Plastic mulch film acts as an impermeable barrier**, sealing moisture within the root zone. This allows farmers to **reduce irrigation frequency**, improve water-use efficiency, and sustain crops in water-scarce regions.

2. Weed Management: The "Zero Light" Rule

Effective weed control depends on the **opacity of the mulch film**. High-quality plastic mulch films are engineered for **zero light transmission**, preventing sunlight from reaching the soil. Without light, weed seeds cannot photosynthesize or germinate, eliminating weed pressure without herbicides.

3. Soil Structure & Root Health

Plastic mulching protects the soil surface from erosion, compaction, and crusting caused by heavy rainfall. By maintaining a **loose, aerated soil structure**, it promotes strong **white root development** near the surface — the most nutrient-rich zone. Healthy white roots enhance water and nutrient uptake, forming the foundation of vigorous plant growth.

4. Improved Yield and Output

Plastic mulching directly improves crop yield by creating **consistent growing conditions** throughout the field. With stable soil moisture, controlled root-zone temperature, and zero competition from weeds, plants experience less stress and utilise water and nutrients more efficiently. This leads to **uniform plant growth, earlier maturity, and higher marketable yields**, especially in drip-irrigated systems.

Plastic mulching films contaminate aquatic systems through microplastic pollution mainly through the following pathways:

1. Weathering and Fragmentation in Agricultural Fields

Plastic mulch films (commonly polyethylene films) are spread over soil to conserve moisture and control weeds. During field use, they are exposed to:

- **UV radiation from sunlight**
- Temperature changes
- Wind and mechanical stress
- Farming activities (ploughing, harvesting)

These processes make the plastic brittle and cause it to break into smaller pieces called **secondary microplastics (<5 mm)**.

2. Soil Transport by Rainfall Runoff

After fragmentation, microplastic particles remain in agricultural soil. During heavy rainfall:

- Surface runoff carries plastic fragments into nearby:
  - streams
  - rivers
  - ponds
  - reservoirs

Thus, agricultural landscapes become important sources of freshwater microplastic contamination.

3. Incomplete Removal After Crop Harvest

Farmers often remove mulch films after cultivation, but complete removal is difficult because:

- Thin plastic pieces tear easily
- Small fragments remain mixed with soil
- Machinery can break films into tiny particles

These remaining plastics accumulate in soil and gradually migrate to water bodies.

4. Soil Erosion and Leaching

Microplastics present in soil can move through:

- Soil erosion
- Irrigation return flows
- Drainage channels

They may enter groundwater and surface water systems.

5. Transport of Toxic Chemicals

Plastic mulch fragments can adsorb pollutants such as:

- Heavy metals (lead, cadmium)
- Pesticide residues
- Organic pollutants

When these microplastics enter aquatic environments, they may transfer contaminants to aquatic organisms.

6. Effects on Aquatic Organisms

Once in freshwater ecosystems, microplastics from mulch films can be ingested by:

- Zooplankton
- Insects
- Fish
- Molluscs

Possible effects include:

- Reduced feeding
- Gut blockage
- Oxidative stress
- Reduced growth and reproduction

Flow pathway:

Plastic mulch films → UV degradation & farming activities → microplastic formation → soil accumulation → rainfall runoff/erosion → rivers & lakes → aquatic organisms → food web contamination

2.3.2 Greenhouse materials

Greenhouse materials are an important agricultural source of microplastic contamination in freshwater ecosystems. The contamination occurs through the degradation and transport of plastic materials used in protected cultivation.

Microplastic Contamination Due to Greenhouse Materials

Greenhouses commonly use plastic-based materials such as polyethylene (PE) films, polypropylene (PP) nets, plastic sheets, irrigation pipes, clips, trays, and containers. Continuous exposure to environmental conditions leads to the formation of microplastics.

1. Degradation of Greenhouse Cover Films

Greenhouse roofs and side covers are often made of polyethylene films. Over time, they undergo:

- UV radiation damage
- Heat fluctuations
- Wind abrasion
- Mechanical stress during installation and maintenance

These processes cause cracks and fragmentation, releasing small plastic particles (microplastics) into the surrounding environment.

2. Release Through Weathering and Aging

Aged greenhouse plastics become brittle and lose their structural strength. Tiny fragments can detach and mix with:

- Greenhouse soil
- Irrigation water
- Drainage water

These particles can later be transported into nearby freshwater systems.

3. Irrigation and Runoff Pathways

Microplastics generated from greenhouse materials can enter aquatic environments through:

- Rainwater washing plastic surfaces
- Irrigation water discharge
- Drainage channels
- Agricultural runoff

They may reach:

- Streams
- Rivers
- Lakes
- Groundwater

4. Plastic Irrigation Systems as Sources

Greenhouses frequently use plastic pipes and drip irrigation systems. Aging of these materials can release microplastic particles due to:

- Friction from water flow
- Chemical degradation
- Sunlight exposure

These particles may directly enter irrigation effluents.

5. Accumulation in Agricultural Soil

Fragments from greenhouse films, nursery bags, and plastic trays can remain in soil. Repeated cultivation cycles may increase microplastic accumulation, which can later be transported by erosion and runoff.

6. Ecological Impacts

Greenhouse-derived microplastics may:

- Be ingested by aquatic organisms
- Reduce feeding efficiency in zooplankton and fish
- Carry pesticides and heavy metals
- Affect aquatic microbial communities

Flow pathway for your review paper:

Greenhouse plastic materials → UV/weathering & mechanical degradation → microplastic generation → soil/water contamination → runoff and drainage → freshwater ecosystems → aquatic organisms

2.3.3 Irrigation pipes

Irrigation Pipes as a Source of Microplastic Contamination

Plastic irrigation systems are widely used in modern agriculture for efficient water delivery, especially **drip irrigation and sprinkler systems**. Most irrigation pipes are manufactured from plastic polymers such as **polyvinyl chloride (PVC), polyethylene (PE), and polypropylene (PP)**. Over prolonged use, these materials can become significant sources of microplastic contamination in agricultural environments and freshwater ecosystems.

1. Weathering and Degradation of Irrigation Pipes

Irrigation pipes installed in agricultural fields are exposed to:

- **Ultraviolet (UV) radiation**
- High temperatures
- Moisture fluctuations
- Chemical fertilizers and pesticides

These factors weaken the polymer structure, causing surface cracking, brittleness, and gradual fragmentation into microplastic particles.

2. Mechanical Abrasion and Physical Wear

During agricultural operations, irrigation pipes experience:

- Pressure fluctuations
- Bending and movement during field activities
- Friction from soil particles
- Damage during installation and removal

Continuous mechanical stress causes small plastic fragments to detach from pipe surfaces and enter the surrounding soil and water.

3. Release into Irrigation Water

Aging plastic pipes can release microplastic particles directly into irrigation water. These particles may be transported through:

- Drip emitters
- Drainage channels
- Agricultural runoff

Eventually, they may reach nearby:

- Rivers
- Lakes
- Reservoirs
- Groundwater systems

4. Interaction with Agricultural Chemicals

Microplastics released from irrigation pipes can adsorb and transport:

- Pesticide residues
- Fertilizers
- Heavy metals

This increases their potential impact on aquatic organisms when they enter freshwater environments.

5. Ecological Impacts

Irrigation pipe-derived microplastics may:

- Be ingested by aquatic organisms

- Affect microbial communities
- Cause oxidative stress and physiological changes in aquatic animals
- Act as carriers of toxic pollutants

Contamination Pathway
Plastic irrigation pipes → Aging/weathering → Microplastic formation → Irrigation water & soil contamination → Runoff/drainage → Freshwater ecosystems → Aquatic food web

2.3.4 Fertilizer coatings

Fertilizer Coatings as a Source of Microplastic Contamination
Modern agriculture increasingly uses controlled-release fertilizers (CRFs) and slow-release fertilizers (SRFs), where nutrient granules are coated with plastic-based materials to regulate the release of nutrients. These coatings commonly contain polymers such as polyethylene (PE), polypropylene (PP), polyurethane (PU), and other synthetic resins. After application to agricultural fields, these coatings can contribute to microplastic contamination in soils and freshwater ecosystems.

1. Degradation of Plastic-Coated Fertilizers
After fertilizer application, the polymer coatings remain in the soil after nutrient release. Environmental factors such as:

- UV radiation
- Temperature variations
- Soil microbial activity
- Mechanical disturbance during cultivation
- Moisture changes

cause the coatings to crack and fragment, generating secondary microplastics.

2. Transport Through Agricultural Runoff
During rainfall events or excessive irrigation, fragmented coating materials can be mobilized from agricultural soils and transported through:

- Surface runoff
- Drainage systems
- Irrigation return flows

These microplastic particles may enter nearby:

- Streams
- Rivers
- Lakes
- Reservoirs

and contribute to freshwater contamination.

3. Accumulation in Agricultural Soil
Incomplete degradation of polymer coatings results in the accumulation of plastic residues in soil. Repeated use of coated fertilizers can increase microplastic concentrations, leading to long-term contamination.

4. Interaction with Pollutants
Microplastics originating from fertilizer coatings can act as carriers for various contaminants by adsorbing:

- Heavy metals (e.g., cadmium, lead)
- Pesticide residues
- Persistent organic pollutants

These pollutants may be transferred to aquatic organisms after microplastics enter freshwater environments.

5. Effects on Aquatic Ecosystems
Fertilizer coating-derived microplastics may:

- Be ingested by plankton and fish
- Affect feeding and growth
- Alter microbial communities
- Cause oxidative stress and physiological changes
- Influence nutrient cycling in aquatic systems

Contamination Pathway
Plastic-coated fertilizers → Polymer coating degradation → Microplastic formation → Soil accumulation → Runoff/erosion → Freshwater ecosystems → Aquatic organisms
Weathering and degradation of these materials release microplastics into agricultural soils and nearby water systems.

2.4 Atmospheric Deposition
Microplastics can travel through the atmosphere as airborne particles. Fibres from synthetic clothes, vehicle emissions, and urban dust may settle into freshwater ecosystems through rainfall and dry deposition.

2.5 Degradation of Plastic Waste
Large plastic items such as bottles, bags, fishing materials, and packaging waste gradually degrade due to:

- Sunlight exposure
- Mechanical abrasion
- Temperature changes
- Microbial activity

This produces smaller plastic fragments that accumulate in aquatic environments.

3. Types and Characteristics of Microplastics
Microplastics are classified based on:
Size

- Large microplastics: 1–5 mm
- Small microplastics: <1 mm
- Nanoplastics: <1 µm

Shape

- Fibres
- Fragments
- Films
- Pellets
- Foams

Common Polymer Types

Polymer	**Common Sources**
Polyethylene (PE)	Bags, packaging
Polypropylene (PP)	Containers, textiles
Polystyrene (PS)	Food packaging
Polyvinyl chloride (PVC)	Pipes, construction materials
Polyethylene terephthalate (PET)	Bottles, fabrics

4. Fate and Transport in Freshwater Ecosystems
Microplastics undergo various environmental processes:

- **Floating:** Low-density plastics remain on water surfaces.
- **Sedimentation:** High-density plastics accumulate in sediments.
- **Bioaccumulation:** Organisms ingest microplastics.
- **Long-distance transport:** Rivers carry microplastics across regions.

Factors influencing their movement include:

- Water flow
- Particle size
- Polymer density
- Biofilm formation
- Sediment properties

5. Ecological Impacts

5.1 Effects on Aquatic Organisms
Microplastics are consumed by various organisms including:

- Plankton
- Fish
- Molluscs
- Aquatic insects

Ingestion may cause:

- Reduced feeding ability

- Internal injuries
- Reduced growth
- Reproductive problems
- Energy loss

5.2 Food Chain Transfer

Microplastics can move through aquatic food chains:

Plankton → Small fish → Large fish → Humans

This raises concerns regarding seafood safety and ecosystem health.

5.3 Chemical Toxicity

Microplastics can absorb pollutants such as:

- Heavy metals
- Pesticides
- Persistent organic pollutants (POPs)

They may act as carriers of harmful chemicals in aquatic environments.

6. Human Health Concerns

Human exposure may occur through:

- Drinking water
- Food
- Aquatic products
- Airborne particles

Possible effects under investigation include:

- Inflammation
- Oxidative stress
- Cellular damage
- Chemical exposure from absorbed pollutants

Further research is needed to understand long-term health consequences.

7. Detection and Characterization Methods

7.1 Visual Microscopy

Simple and inexpensive method for preliminary identification.

7.2 Fourier Transform Infrared Spectroscopy (FTIR)

FTIR identifies chemical composition by detecting polymer-specific infrared absorption patterns.

Advantages:

- Accurate polymer identification
- Widely used method

7.3 Raman Spectroscopy

Uses laser-based analysis to identify small plastic particles.

Advantages:

- Detects very small particles
- High chemical specificity

7.4 Pyrolysis Gas Chromatography–Mass Spectrometry (Py-GC/MS)

A destructive technique that identifies polymer composition through thermal breakdown products.

Advantages:

- High accuracy
- Quantitative analysis

7.5 Advanced Imaging Techniques

Techniques such as scanning electron microscopy (SEM) provide information about:

- Surface structure
- Weathering
- Particle morphology

8. Removal and Mitigation Strategies

Effective control requires:

Improved Waste Management

- Plastic recycling
- Reduction of single-use plastics
- Proper disposal systems

Advanced Wastewater Treatment

Technologies include:

- Membrane filtration
- Advanced oxidation
- Biological treatment methods

Policy and Awareness

- Plastic reduction policies
- Environmental education
- Sustainable alternatives

9. Future Perspectives

Future research should focus on:

1. Development of standardized methods for microplastic monitoring.
2. Long-term toxicity studies.
3. Understanding nanoplastic impacts.
4. Eco-friendly biodegradable materials.
5. Improved wastewater treatment technologies.
6. Artificial intelligence-based detection methods.
7. International policies for plastic pollution control.

10. Conclusion

Microplastic contamination represents a growing threat to freshwater ecosystems. Their persistence, ability to transport toxic substances, and interaction with aquatic organisms make them an emerging environmental challenge. Integrated approaches involving advanced detection techniques, sustainable plastic management, and strong environmental policies are necessary to reduce microplastic pollution and protect freshwater resources. Microplastic contamination represents a growing threat to freshwater biodiversity and ecosystem health. Future research should focus on standardized monitoring methods, long-term ecological studies and effective pollution control strategies.

11. References

1. Bhardwaj, L.K., Rath, P., Yadav, P., & Gupta, U. (2024).*Microplastic contamination, an emerging threat to the freshwater environment: A systematic review.*Environmental Systems Research, 13, 8. https://doi.org/10.1186/s40068-024-00338-7(Springer)
2. Hoang, V.H., Nguyen, M.K., Hoang, T.D., et al. (2024).*Sources, environmental fate, and impacts of microplastic contamination in agricultural soils: A comprehensive review.*Science of the Total Environment, 950, 175276.https://doi.org/10.1016/j.scitotenv.2024.175276(ScienceDirect)
3. Tayyab, M., Kazmi, S.S.U.H., Pastorino, P., et al. (2024).*Microplastics in agroecosystems: Soil–plant dynamics and effective remediation approaches.*Chemosphere, 362, 142641 https://doi.org/10.1016/j.chemosphere.2024.142641 (PubMed)
4. Talukdar, A., Kundu, P., Bhattacharya, S., & Dutta, N. (2024). *Microplastic contamination in wastewater: Sources, distribution, detection and remediation through physical and chemical-biological methods.*Science of the Total Environment, 916, 170254.https://doi.org/10.1016/j.scitotenv.2024.170254 (PubMed)
5. Chae, Y. & An, Y.J. (2018). *Current research trends on plastic pollution and ecological impacts on the soil ecosystem: A review.*Environmental Pollution, 240, 387–395.https://doi.org/10.1016/j.envpol.2018.05.008
6. Horton, A.A., Walton, A., Spurgeon, D.J., Lahive, E., & Svendsen, C. (2017).*Microplastics in freshwater and terrestrial environments: Evaluating the current understanding to identify the knowledge gaps and future research priorities.* Science of the Total Environment, 586, 127–141. https://doi.org/10.1016/j.scitotenv.2017.01.190

7. Eerkes-Medrano, D., Thompson, R.C., & Aldridge, D.C. (2015). *Microplastics in freshwater systems: A review of the emerging threats, identification of knowledge gaps and prioritisation of research needs.* Water Research, 75, 63–82. https://doi.org/10.1016/j.watres.2015.02.012
8. Rillig, M.C. (2012). *Microplastic in terrestrial ecosystems and the soil?* Environmental Science & Technology, 46(12), 6453–6454. https://doi.org/10.1021/es302011r
9. de Souza Machado, A.A., Kloas, W., Zarfl, C., Hempel, S., & Rillig, M.C. (2018). *Microplastics as an emerging threat to terrestrial ecosystems.*Global Change Biology, 24, 1405–1416. https://doi.org/10.1111/gcb.14020
10. Kumar, M., Xiong, X., He, M., et al. (2020).*Microplastics as pollutants in agricultural soils.* Environmental Pollution, 265, 114980.https://doi.org/10.1016/j.envpol.2020.114980
11. Cole, M., Lindeque, P., Halsband, C., & Galloway, T.S. (2011).*Microplastics as contaminants in the marine environment: A review.*Marine Pollution Bulletin, 62, 2588–2597.
12. Li, C., Busquets, R., & Campos, L.C. (2020).*Assessment of microplastics in freshwater systems: A review.* Science of the Total Environment, 707, 135482.
13. Zhang, K., Gong, W., Lv, J., Xiong, X., & Wu, C. (2015).*Accumulation of floating microplastics behind the Three Gorges Dam.*Environmental Pollution, 204, 117–123.
14. Auta, H.S., Emenike, C.U., & Fauziah, S.H. (2018). *Distribution and importance of microplastics in the environment: A review* Environmental International, 110, 80–92.
15. Prata, J.C., da Costa, J.P., Lopes, I., Duarte, A.C., & Rocha-Santos, T. (2020).*Environmental exposure to microplastics: An overview on possible human health effects.*Science of the Total Environment, 702, 134455.