STRATEGY
PAPER
22

Microplastics Pollution: Remediation Strategies for Sustainable Environmental Management

NATIONAL ACADEMY OF AGRICULTURAL SCIENCES, NEW DELHI
March 2026

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CITATION : NAAS 2026. Microplastics Pollution: Remediation Strategies for Sustainable Environmental Management. Strategy Paper No. 22, National Academy of Agricultural Sciences, New Delhi: pp. 12

EXECUTIVE COUNCIL 2026

Published by Executive Director on behalf of
NATIONAL ACADEMY OF AGRICULTURAL SCIENCES
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Preface

The enhanced production and indiscriminate use of plastic products have resulted in the emergence of microplastics (MPs) as a new class of environmental contaminants. Sources of these MPs may include botched plastic waste, plastic mulch used in agriculture, layered fertilizers, manures and fertilizers derived from solid waste, and wind-driven transport from prevalent areas. The growing concern of MPs pollution across all environmental compartments is being explored worldwide, though comparatively limited research work has been conducted in India. Among the studies published on MPs occurrence in Indian environments, marine systems have acknowledged significantly more than other domains such as freshwater, atmosphere, and terrestrial environments, particularly soil. Moreover, implementing strict regulations, strengthening legal initiatives, developing comprehensive waste management strategies, and encouraging active public participation are crucial for raising awareness about plastic pollution in soil and mitigating the harmful effects of land-based plastics. Researchers should evaluate the findings through these approaches to help mitigate plastic consumption and its impact on the soil ecosystem.

Against this background, the Academy convened a brainstorming session on "*Microplastics Pollution: Strategies for Remediation in Sustainable Environmental Management*" to deliberate on the potential impact of MPs on the environment and human health, and explore strategies for their remediation and sustainable management. I am sure this strategy paper will assist the Government of India and other pertinent bodies in formulating strategic plans for investing in plastic pollution research and technology development, with a special focus on agricultural revolution.

I appreciate the efforts made by the convener (Dr. S.P. Datta), co-convener (Dr. Tapan Adhikari), reviewers (Dr. T.K. Adhya & Dr. S. Naresh Kumar) and editors (Dr. R.K. Jain & Dr. R.K. Pal) in bringing out the document in present form.

March 2026
New Delhi

(M.L. Jat)
President, NAAS

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1. INTRODUCTION

Over the past few decades, plastic pollution has become a major global concern. Plastic waste with >20 mm diameter is classified as macroplastic, while <5 mm diameter is microplastic. Microplastics (MPs) are further classified into primary microplastics, those are intentionally manufactured having < 5 mm diameter and secondary microplastics, which result from the degradation of larger plastic items (Boctor, 2025). Excessive use, improper disposal, non-biodegradable nature and undesirable physical & chemical properties of plastic have been significantly contributing to environmental pollution. The extent of plastic pollution in agricultural soil systems and landfills has been gradually increasing mainly due to the extensive use and disposal of single-use plastic items, such as poly-mulch, waste from plastic net houses, and plastic cover for horticultural plants. Disposed plastic waste interacts with its surroundings and releases various degradation products, including additives and polymers.

In 2024, the global total plastic production was expected to be 413.8 million tons (Mt) using 4% of global fossil fuel. Plastic production increased significantly (79%) between 2000 and 2015 alone, and plastic pollution has been elevated to a potential issue of high concern for exceeding planetary boundary (Villarrubia-Gómez *et al*., 2024). As population grows and development continues, the volume of plastic wastes is rising rapidly, which significantly contributes to environmental pollution. The impact on the soil environment is determined by the type of released chemicals, the kind of plastic, and its size. Once released into the soil environment, MPs accumulate in a wide variety of toxic and persistent organic contaminants such as pesticides, flame retardants, and polychlorinated biphenyls (PCBs), thereby worsening soil pollution. A blend of analytical procedures, either physical or chemical, is required for the separation and identification of MPs, demanding significant effort and expertise. While recent research has concentrated on quantifying, characterizing, and understanding the toxicology of MPs in marine and freshwater ecosystems, our knowledge related to their ecological impacts in soil and agricultural ecosystems remains comparatively limited. MPs are of emerging public health concern, as their toxicity to human and animal health including dairy and livestock is yet to be fully understood. Although global literature reported the presence of MPs in some plant parts particularly accumulated at root surface (Yu *et al*., 2024), such data are not available in India in respect of vegetables and fruits from agroecosystems or cultivated fields. Recent observations also indicated that MPs particles can cross the blood-brain barrier, and significant amount of MPs residues have been quantified from human brain (Nihart *et al*., 2025). In India, plastic waste management rules were amended in 2021 to mandate an increase in the minimum thickness of plastic carry bags. In July 2022, the government proclaimed a ban on specific single-use plastic items, including plates, cups, and polystyrene (Thermocol). However, India is yet to implement a dedicated policy on MPs. This strategy paper provides a comprehensive view of the sources, degeneracy, and impacts of MPs in the soil-plant system, identifies existing research gaps, and outlines potential forthcoming threats to agroecosystems **(Figure 1)**.

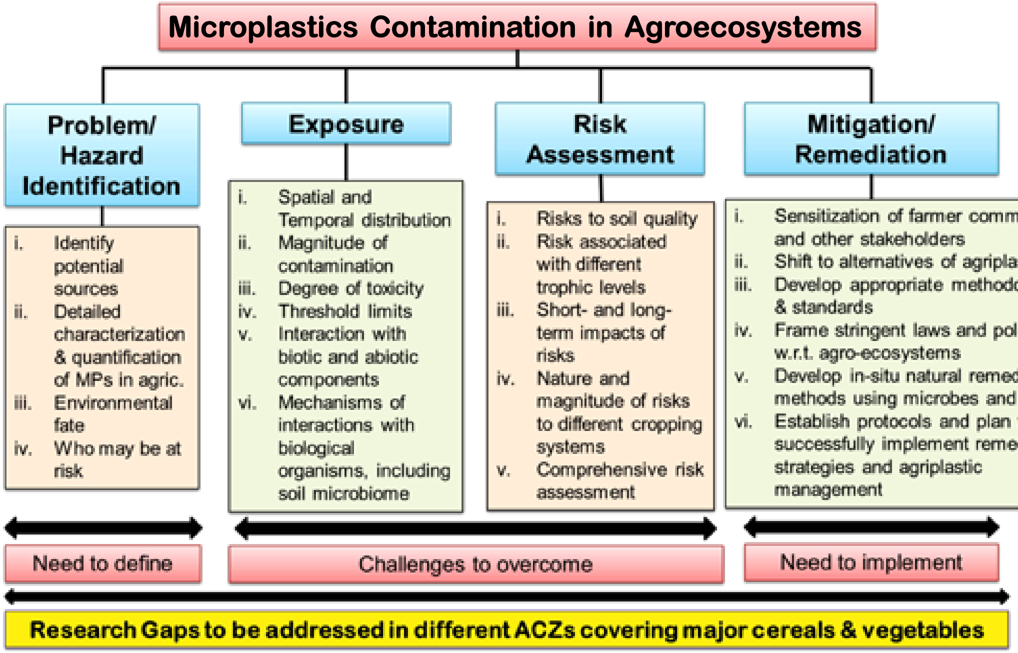

Figure 1. Microplastics (MPs) contamination and remediation strategies in agroecosystems

2. STATUS OF MICROPLASTICS (MPs) POLLUTION IN DIFFERENT ECOSYSTEMS

India is ranked as the largest global source of plastic pollution, emitting approximately 9.3 Mt annually, accounting for nearly 20% worldwide plastic emissions. Based on a study published in *Nature*, 56.8 Mt/year of municipal solid waste was subjected to open burning in India, of which 5.8 Mt/year comprises plastic waste (Cottom *et al*., 2024). Although per capita plastic consumption remains modest at around 11 kg per year, India contributes nearly 26 Mt of plastic waste annually. During industrial manufacturing, plastics produced may enter the environment through accidental spillages. MPs are also deliberately added to consumer products such as cosmetics during the product use phase and are subsequently released into sewage systems or directly into the environment. Additionally, the ongoing use of synthetic materials leads to physical degradation, releasing microplastics in the form of textile microfibers during washing, tire wear particles from road transport, and paint fragments from buildings. By 2050, an estimated 22 Mt of synthetic textile microfibers are expected to enter the environment. In India, plastic consumption is heavily concentrated in Western regions, which account for 47% of national usage, particularly across Karnataka, Gujarat, Maharashtra, Madhya Pradesh, Daman & Diu, Chhattisgarh, and Dadra & Nagar Haveli.

Microplastic particles in the ecosystem offer a long-lasting interphase that microorganisms eventually colonize. The development of the biofilm by microbial colonization on plastic surfaces is known as the plastisphere and influences the behaviour of plastic in the water bodies, like its movement, accretion of contaminants, and physicochemical changes (Behera and Das, 2023). Various studies have reported that in the marine environment, the plastisphere is primarily colonized by microorganisms such as diatoms (*Mastogloia*, *Navicula*, *Cyclotella*, etc.), algae and bacteria (*Flavobacterium*, *Rhodococcus*, and *Pseudomonas*, etc.) (Behera and Das, 2023). In general, the biodegradation of MPs is facilitated by the synthesis of various extracellular and intracellular depolymerase enzymes secreted by organisms within the plastisphere **(Figure 2)**.

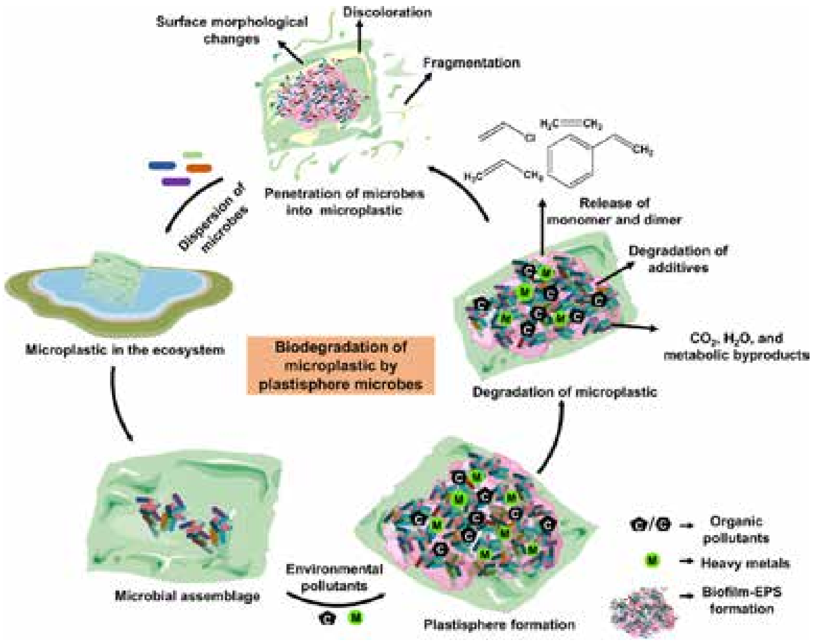

Figure 2. Biofilm-based bioremediation of microplastics (MPs) by plastisphere microbes

2.1 Water

Based on a United Nations Environment Programme (UNEP) assessment project, the plastic waste emissions into aquatic ecosystems could nearly triple (23-37 Mt) annually by 2040 without intervention, mainly from mismanaged waste in landfills, open dumping, and direct environmental discharge. At least three-quarters of this comes from human-generated wastes, particularly in African and Asian watersheds, entering oceans via rivers and terrestrial pathways. By 2025, India is projected to release approximately 0.39 Mt of MPs in its waterways, making it the second-largest polluter globally after China. This figure also includes the release of around 31483 t of chemical additives associated with MPs. Microplastics pollution is particularly notable along India's coasts and in major rivers like the Ganga, with widespread presence in marine sediments, groundwater, food products, and even airborne particles. The Ganga River network is one of the largest rivers which contributes 0.12 Mt of discharged plastics per year. The National Centre for Coastal Research (NCCR) covered 19 transects surveyed from Porbandar (Gujarat) to Kanyakumari (Tamil Nadu) under West Coast and 25 transects sampled from Puri (Odisha) to Thoothukudi (Tamil Nadu) under East Coast, and found that the riverine inputs and abandoned fishing gear were the major sources of MPs pollution along India's coasts.

Wastewater treatment plants (WWTPs) have also been often significant sources of MPs pollution in aquatic environments, as MPs originating from personal care products, synthetic fabrics, and tyre wear are insufficiently removed (Sadia *et al*., 2022). Additionally, urban runoff is another substantial source of MPs, with particles from tire abrasion, synthetic fibres from clothing, and fragmented plastic debris that are transported into rivers and oceans and aggravate the pollution (Hale *et al*., 2020). In ocean system, MPs mainly originate from the breakdown of larger plastic debris such as bottles, fishing nets, and plastic bags through physical processes like UV exposure, wave action, and mechanical abrasion. Moreover, water bodies are increasingly contaminated by industrial effluents and agricultural runoff, which introduce a wide variety of microplastic particles into aquatic ecosystems (Wang *et al*., 2024). Removal of MPs from wastewater using coagulation and sedimentation, and the use of biochar in rapid sand filters is possible. These techniques could remove more than 98% MPs from secondary treated wastewater.

Rising MPs pollution in freshwater ecosystems highlights the urgent need for monitoring and assessment. MPs are found in various freshwater systems worldwide, with most studies focusing on rivers. The primary concern with freshwater MPs contamination is the risk of these particles entering the human body through the consumption of polluted water or fish. The objectives of MPs studies in freshwater systems are focussed to understand temporal variation, morphological characterization, source apportionment, and assessing associated risk.

2.2 Soil

MPs contamination in soils is associated with agricultural practices, especially the extensive use of plastic mulching films, which help to boost crop yields by conserving soil moisture and suppressing weed growth. In the long-run, these plastic materials break down into MPs by ultraviolet (UV) radiation, mechanical abrasion, and other environmental factors. Moreover, the use of organic fertilizers, composts, and biosolids in agriculture can unintentionally introduce MPs into the soil, as these materials are often contaminated with plastic debris, including those found in sewage sludge (Shengwei *et al*., 2024). Common disposal practices—such as burning, field dumping, or crushing and reincorporating residues—can intensify pollution and serve as major pathways for MPs to enter the food chain, a problem further aggravated by limited environmental awareness among farmers (Wu, 2025).

Urban environment plays a major role in MPs pollution of soils, mainly through the degradation of road surfaces such as tire wear which are carried into surrounding soils by surface runoff. The gradual breakdown of plastic waste materials in landfills can release MPs into surrounding areas, typically through storm-water runoff or leachate leaks (Mosarrat *et al*., 2023). MPs also enter the soil through aerosol particles, particularly those generated by the textile, rubber, and plastic manufacturing industries. These particles can be deposited into the soil by wind or rainfall (Jahandari, 2023). Another source of MPs in soil environment is wastewater used for irrigation in agricultural fields. MPs present in untreated wastewater eventually enter the soil (Zonaira *et al*., 2023). Intensive tillage influences the redistribution of agricultural MPs, while irrigation can introduce synthetic fibres and enhance their mobility, particularly in sandy soils (Samiur *et al*., 2025). Soil erosion further contributes to substantial MPs losses from the surface, transferring particles from agricultural fields into adjacent aquatic systems (Rehm *et al*., 2021). Fine microplastic particles may also leach below the plough layer (0–20 cm) during tillage, and ploughing-induced inversion of soil layers facilitates the downward transport of MPs into deeper horizons. Additionally, climate-related factors shape MPs dynamics including soil cracking under dry conditions creates entry pathways, and repeated wet–dry cycles accelerate the vertical movement of MPs.

Global studies on MPs report 0 to $>10^6$ particles/kg, placing Indian values in the low-to-moderate range, but likely underestimates due to larger particle-size cutoffs used in many Indian analyses. Although India does not yet maintain a national-level MPs soil inventory, a growing body of peer-reviewed studies and sectoral assessments (2020–2025) confirms widespread presence of MPs across agricultural soils, peri-urban zones, and lake/river-associated sediments. Regional hot spots like Goa (101 particles/kg surface soils), Bhopal (up to 308 particles/kg), and Udupi paddy fields show higher levels, while lower values (12 particles/kg) in Indore suggest national variability influenced by irrigation from polluted rivers and plastic mulch use. It is expected that typical agricultural/urban soils in

India may contain tens to a few hundred particles/kg in many studied locations. Typical concentrations in agricultural and urban soils fall in the range of ~20–300 particles/kg dry soil. In 2025 plastic mulching and irrigation-borne MPs have been found to contribute ~100.9 ± 64.2 particles/kg in paddy fields in Goa. In Karnataka, lake sediment cores near agricultural catchments recorded historical accumulation of MPs up to ~1,475 particles/kg, illustrating long-term deposition and potential transfer to adjoining soils.

3. MICROPLASTICS (MPs) POLLUTION AND ITS IMPACT

3.1 Impact on Soils

Globally, several publications since 2021 explore interactions of MPs with soil processes including nitrogen storage and GHG emissions, while Indian research on soil MPs primarily focuses on contamination levels in agricultural soils such as paddy fields in regions like Karnataka, Goa, and Northern India, with sources including irrigation from polluted rivers, plastic mulch, and industrial effluents. Few Indian studies address microplastic emissions from soils, with no direct evidence of GHG-specific findings in the queried timeframe (Iqbal et al., 2024). The threat of soil contamination from MPs varies based on the type of agricultural plastics materials and their application. Single-use conventional agricultural plastics that are designed for direct contact with soil or intended for incorporation into the soil are associated with higher risks. Co-contaminants such as antibiotics/ Antibiotic Resistance Genes (ARGs)**,** POPs (Persistent Organic Pollutants) and PAHs (Polycyclic Aromatic Hydrocarbons), heavy metals, and pathogens pose additional risks when associated with MPs in soil and agroecosystems, potentially exacerbating the toxicity due to the dual nature of the affected recipients (Kumar *et al*., 2025). The country needs baseline data on plastic pollution to devise strategies for the mitigation of MPs.

Microplastics reduce soil productivity by changing water-holding capacity and pH, indirectly stunting later growth stages despite potential early germination benefits. Impacts are species-specific; for instance, certain grasses may show increased biomass due to improved soil aeration, while others may exhibit a decline. Remediation strategies like biochar or growth regulators show promise but depend on MPs properties. Numerous studies worldwide document increased CO_2 emissions from microplastic contaminated soils due to accelerated soil organic matter (SOM mineralization, often linked to altered oxygen dynamics, dissolved organic matter (DOM) composition, and microbial activity. For instance, MPs like polyethylene and polylactic acid boosted cumulative CO_2 emissions by 160–613% via oxygenated microhabitats and enhanced electron transfer in DOM. Biodegradable microplastics further amplify CO_2 release, with meta-analyses showing 4–20% higher emissions in fine, saturated, or high-carbon soils. While CO_2 increases align closely with the statement, CH_4 and N_2O effects are less uniform: some studies reveal higher N_2O (up to 63% in larger microplastics) contributing to global warming potential, but CH_4 often decreases (45–503%) due to improved soil aeration.

The impact of MPs on biogas production from sewage sludge was also studied and high abundance of MPs in the solid fraction was observed primarily due to polystyrene microbeads whose exact source could not be determined, though they were likely linked to industrial activities (Yli-Rantala *et al*., 2025). Based on the latest studies, more than 13,000 chemicals have been identified as associated with plastics and plastic production across a wide range of applications. Ten groups of chemicals (based on chemistry, uses, or sources) have been identified as major concern due to their high toxicity and potential to migrate or get released from plastics to soil and water (Yli-Rantala *et al*., 2025).

3.2 Impact on Plants

The impact of MPs pollution on plant growth may include : i) reduced adventitious root development; ii) reduced leaf area; iii) decreased seed germination; iv) reduced root and shoot growth; v) declined grain yield; vi) declined photosynthesis and chlorophyll; vii) altered leaf and root biology; viii) oxidative stress; and ix) impaired hormonal regulation. These stresses/ toxicity of MPs to crops need to be investigated with special emphasis on major types of MPs prevailing in the different agro-climatic zones of India and major crops being cultivated there. The soil microbiome in the vicinity of plant rhizosphere would also provide insights about the kind of soil microflora dwelling in response to MPs in soil. Microplastics impose stress on plant growth and development primarily through physical blockages, oxidative damage, and soil alterations, often reducing seed germination, root elongation, and overall biomass. These effects vary with microplastic type, size, dose, and plant species, with common outcomes including decreased chlorophyll levels, heightened reactive oxygen species (ROS), and impaired nutrient uptake. MPs clog pores in seed coats and roots, hindering water and nutrient absorption, while also entering root cracks to damage vascular tissues. This leads to reduced shoot and leaf growth, as seen in studies where polystyrene microplastics decreased root length by 35% in cherry radish. Exposure triggers excessive ROS production, lipid peroxidation, and disrupted hormonal regulation, lowering photosynthesis and altering ion homeostasis in leaves and roots. Chlorophyll and carotenoid contents decline, signalling oxidative stress, with effects more severe from high-density polyethylene (HDPE) than polyethylene terephthalate (PET) in vegetables like spring onion. These changes impair metabolic processes and antioxidant defences (Ahmad *et al*., 2025).

3.3 Impact on Humans

Exposure to MPs occurs through dietary intake, inhalation, and dermal contact, with mounting evidence suggesting potential adverse human health outcomes. MPs have been detected in rice, wheat, salt, sugar, honey, seafood, milk, and bottled water consumed in India (Mondal *et al*., 2025). Tap water and groundwater in urban and peri-urban regions show contamination, largely due to plastic pipelines, storage tanks, and wastewater infiltration. High dependence on plastic-packaged foods increases ingestion risk. Urban air in Indian megacities (Delhi, Mumbai, Kolkata, Bengaluru) contains airborne microplastic fibres from synthetic textiles, road dust, tyre wear and open waste burning. Although India-specific epidemiological data are limited, global toxicological evidence combined with Indian exposure scenarios suggests several risks:

- **Gastrointestinal effects:** MPs may cause gut inflammation, alter microbiota, and increase intestinal permeability.
- **Respiratory issues:** Inhaled MPs can induce oxidative stress, airway inflammation, and reduced lung function.
- **Endocrine disruption:** MPs act as vectors for plastic additives (phthalates, BPA) that interfere with hormonal regulation.
- **Immune system modulation:** Chronic exposure may trigger immune dysregulation and low-grade systemic inflammation
- **Chemical and biological vector effects:** MPs adsorb heavy metals (Pb, Cd, Cr), pesticides, and persistent organic pollutants prevalent in Indian environments, and may also carry pathogenic microbes, increasing infection risks.

Knowledge gaps in the Indian context are: lack of large-scale biomonitoring studies (blood, stool, lung tissue), limited data on nano-plastics, which may pose greater cellular toxicity, absence of standardized methods for exposure assessment in Indian foods & air, and weak linkage between environmental MPs & clinical health outcome. Given increasing exposure levels and scientific uncertainty, precautionary policy measures are urgently needed. These include regulating plastic additives, improving food and water safety standards, promoting biodegradable alternatives, and strengthening monitoring frameworks for MPs in environmental and biological matrices.

4. CHALLENGES AND MITIGATION STRATEGIES

4.1 Challenges

Measuring and quantifying MPs in agricultural soils posed challenges due to i) heterogeneous soil composition; ii) variability in MPs shape, size, color and polymer composition; iii) invalidated methodologies for extraction and quantification of MPs in soil; iv) lack of uniform analytical protocols hindering the comparability of results across different investigations; and v) lack of centre of excellence with state-of-art facility. Similarly, there are challenges in investigating the partitioning and specific toxicity of MPs in foodgrains and vegetables because of i) lack of standardized protocol; ii) small particle size; iii) matrix complexity; iv) sample preparation; v) diverse uptake mechanism; vi) complex uptake pathways; and vii) lack of center of excellence with state-of-art facility with reference to crops (cereals and vegetables). These challenges need to be tackled so that a country-wide baseline data of sources, types and fate of MPs can be generated to assess the magnitude of the problem.

4.2 Mitigation Strategies

- To mitigate the impact of MPs in terrestrial environments, alternatives to plastic mulch such as replacing it with biodegradable plastics derived from starch or other plant-based polymers should be explored and adopted.
- To mitigate MPs pollution in aquatic environments, upgrade wastewater treatment plants with advanced technologies such as membrane filtration, coagulation-flocculation, and activated carbon usage to enhance the removal of MPs from effluents typically missed by conventional treatment systems to significantly reduce the release of microplastics into aquatic and soil ecosystems.
- Reinforcing waste management systems by implementing efficient waste sorting and recycling processes. This cost-effective approach helps preventing direct plastic waste disposal at the source, thereby reducing environmental contamination.
- Combining effective wastewater treatment and management with biological methods such as bioremediation, bioaugmentation, and biodegradation by plastic-degrading microbes could be a crucial strategy for reducing microplastic contamination in soil.
- Improving urban stormwater management by implementing filtration units, settling ponds, and bio-retention systems can greatly decrease the entry of MPs into aquatic bodies from urban run-off.
- In the aquatic bodies, Seabin (a floating waste collector) and capture arrangements planned to intercept plastic wastes before their conversion into MPs have proven effective in minimising ocean microplastic pollution.
- In addition to technological solutions, raising public awareness about MPs pollution is essential step to prevent further contamination.
- Effectively protecting water ecosystems and human health from the long-term impacts of MPs pollution requires a combination of these approaches, underpinned by strong regulatory frameworks and ongoing technological innovation.

5. RECOMMENDATIONS

- A public portal should be created for centralized data collection and monitoring of specific sources of MPs pollution in soil, plants, human and environment.
- Methods used for analysing MPs, including sampling, digestion, filtration, and microscopic examination in fresh water reservoirs as well as soil has to be fine-tuned.

A source apportionment method to identify the main contributors of MPs based on polymer types and potential source materials need to be developed.

- Appropriate steps should be undertaken for removing plastic pollution by regular monitoring pollution sources, ensuring food safety and sustainable development, implementing quality management systems, enforcing stricter regulations, and fostering collaboration between citizens & government authorities.
- Farmers should be made aware of the guidelines for the collection and recycling of plastic materials, ensuring their participation in agricultural plastic recycling programs where available and empowering them to take more informed decisions.
- Cost-effective, user-friendly, and environmentally sustainable techniques for wastewater treatment including bioremediation methods for microplastic removal need to be developed and widely adopted.
- Long-term investigations should be initiated to enumerate the influence of micro- and nano-plastics on urban and peri-urban agriculture, as well as their subsequent effects on the soil-plant- water- animal continuum across different agro-ecosystems.
- Exploring and adopting cellulose-based films and natural materials such as bamboo as viable alternatives to conventional plastics.
- Developing monitoring strategies, understanding degradation pathways, and mitigation measures through research partnerships between National and International collaborations.
- Evolving strategies for use and management of plastic waste through a public-private partnership model. Government schemes such as the Smart City Development Programme, Swachh Bharat Abhiyan, and the Atal Mission for Rejuvenation and Urban Transformation (AMRUT) should be integrated with initiatives for plastic waste management.
- A national-level database on plastic usage in urban, semi-urban, peri-urban, and rural areas should be created to assist investors in scheduling, expansion, and supervising appropriate usage.

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