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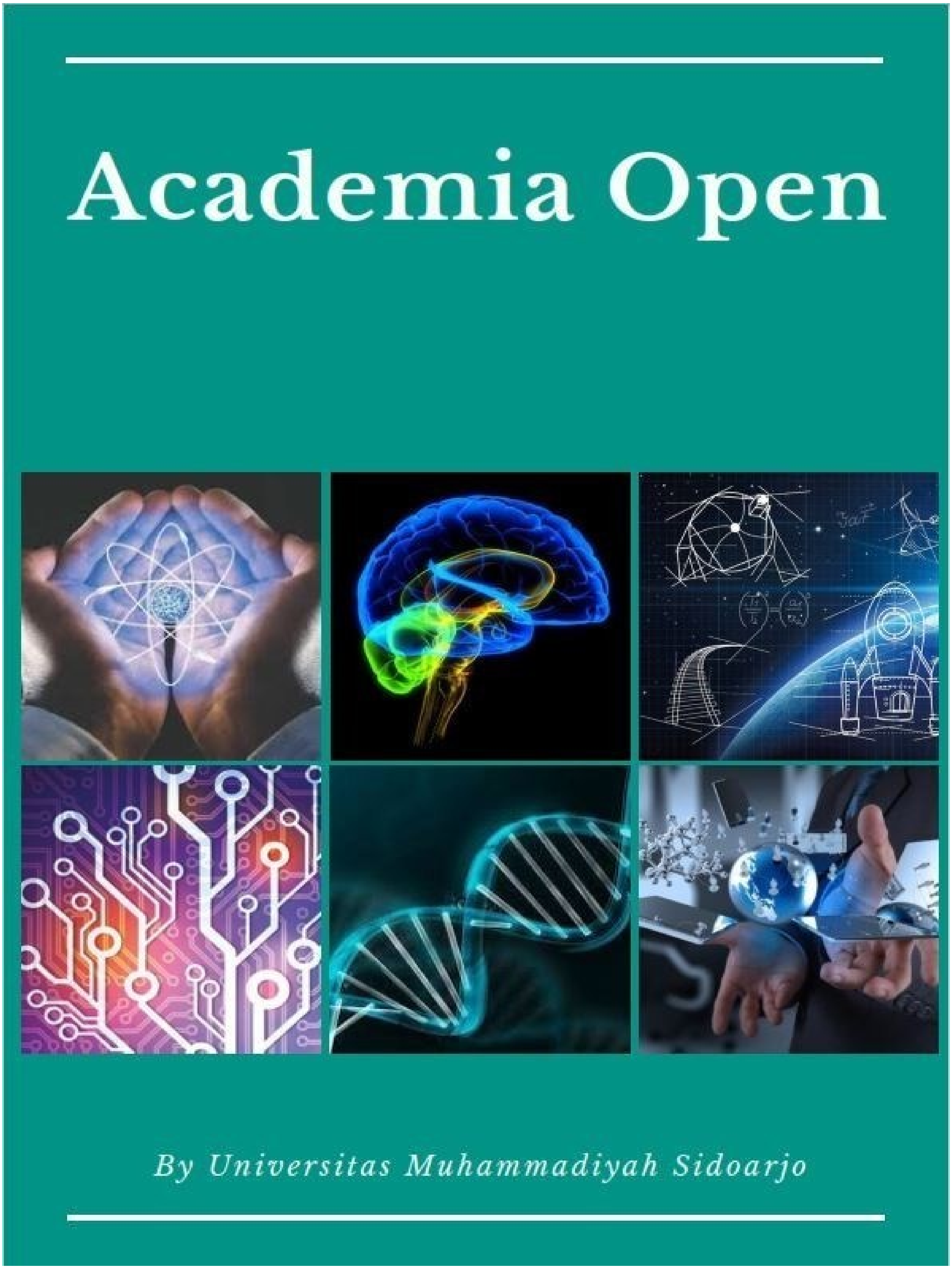

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Bioremediation of Microplastic and Associated Pollutants Using Medicinal Plants as an Environmentally Friendly Approach

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Abstract

General Background: Microplastics have become pervasive contaminants in aquatic systems, where their small size and persistence enable wide ecological dispersion. Specific Background: These particles readily adsorb organic toxins and heavy metals, intensifying their environmental and biological impact as they move through food webs. Knowledge Gap: Despite advances in physical, chemical, and microbial removal methods, sustainable strategies that simultaneously address pollutant binding, ecological safety, and long-term remediation remain limited. Aims: This review examines the characteristics of microplastics, their ecological and health effects, and evaluates emerging plant-based bioremediation technologies integrated with modern approaches. Results: Evidence shows that medicinal plants such as Aloe vera, Mentha spicata, Ocimum basilicum, and Lemna minor can absorb, translocate, and enzymatically degrade pollutants associated with microplastics, while integration with nanotechnology, enhanced filtration, and catalytic processes significantly improves removal efficiency. Novelty: The synthesis highlights the synergistic potential of phytoremediation combined with advanced technologies, offering a holistic, low-cost, and environmentally compatible alternative to conventional treatment methods. Implications: These findings underscore the promise of plant-based systems for mitigating microplastic pollution, supporting ecosystem resilience, and reducing risks to human health while guiding future sustainable water-treatment strategies.

Highlight :

- The content stresses how microplastics accumulate pollutants and pose risks to aquatic organisms and humans.
- It highlights the role of plant-based bioremediation in absorbing and breaking down pollutants linked to microplastics.
- It notes the importance of integrating phytoremediation with modern techniques to enhance pollutant removal and support environmental sustainability.

Keywords : Microplastics, bioremediation with plants, heavy metals, organic pollutants, aquatic systems.

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Introduction

Among all the modern environmental hazards, the microplastic particles hold a prominent position. According to studies, these are microplastic particles less than 5 millimeters in diameter that are distributed everywhere, from aquatic to terrestrial ecosystems[1] . These particles come from two sources: primary microplastics, which are used directly in different industrial products, cosmetics, and detergents, and secondary microplastics, which have been generated from the decomposition of larger size plastic materials such as bags, containers, and bottles through environmental factors like ultraviolet radiation, waves, and weathering .

These particles have distinctive physico-chemical features, among which high surface area and great capacity to adsorb organic pollutants and heavy metals from the surrounding media, such as cadmium (Cd), lead (Pb), and mercury (Hg), are the most outstanding[2]. For this reason, these particles become very active and mobile vectors of environmental toxins in aquatic and food chains . Hence, its danger is not confined to physical pollution but extends to complex chemical and biological dimensions, resulting from its interaction with living organisms and toxic elements in the environment .

Several researches in the past decade or so have shown that microplastics are able to penetrate into the tissues of microscopic and macro aquatic organisms like plankton, fish, and mollusks, which reach humans through the food chain[3]. They also established that accumulation within animal and human tissues can be associated with disorders in health, such as chronic inflammation, immune system dysfunction, and hormonal imbalances.

Because the environmental and health importance of microplastics is immense and continuously growing, their removal in an aquatic environment has already become of great concern to present global research[4]. Therefore, scientific efforts are focused on sustainable and effective technologies based on physical, chemical, and biological treatments that reduce accumulation of such particles with a view toward preserving ecosystem health and human health .

The Problem and Objectives of the Article

The continuous rise in microplastic levels within the aquatic environment and their resultant hazardous environmental and health effects is the problem of this study[5]. Owing to the rapid rise in plastic consumption and their exponential increasing uses in various industrial and domestic areas, a great quantity leaks into lakes, rivers, and oceans due to the inadequacy of their disposal methods. These minute particles cannot be traced or removed by traditional methods; thus, this is called a hidden pollutant, posing a threat to aquatic life and indirectly to humans through the food chain, microplastics absorb chemical pollutants and toxins, the problem of pollution significantly worsens in that these particles transfer to the tissues of living organisms, further causing complex environmental and health crises. In addition, another serious challenge facing researchers and policymakers of environmental protection is the limited availability of technologies able to remove those particles from water[6].

The aims of the research are as follows:

Characterization, for size, shape, and chemical composition, of microplastics present in the aquatic environment, with the aim of understanding their behavior and distribution. Identification of the primary sources of microplastics in different ecosystems, whether industrial in origin, domestic, or from environmental degradation of plastic material. Study of the environmental and health impacts, with particular attention to the mechanisms of accumulation and transfer of microplastics within the food chain, and evaluation and comparison - in terms of efficiency, cost, and environmental sustainability - of the technologies currently available for their removal[7]. To propose innovative and sustainable solutions aimed at reducing the contamination by microplastics and their treatment in an environmentally friendly manner.

Importance of the Article

This study is relevant because it focuses on one of the most dangerous kinds of modern environmental pollutants-microplastics-which have turned into an emerging global threat to ecosystems and human health. Ecological Significance: This study identified microplastic particles to be among the most serious contributors to surface and groundwater pollution, leading to an imbalance in aquatic ecosystems, the presence of these particles interferes with the natural processes of water purification and further decreases biodiversity due to their accumulation within the bodies of aquatic organisms, which leads to either the suffocation or impairment of their vital functions[8].

The research gains relevance for human and health reasons, since it is scientifically acknowledged that microplastics can migrate through the food chain into the human organism. This brings up many questions regarding toxic effects on the digestive system, the immune system, and the endocrine system. It will be opportune in arriving at a scientific understanding of such effects; hence, it contributes to raising awareness with respect to the need for health awareness regarding the dangers of continued exposure to the aforementioned particles.

Applied Importance: This is expressed in focusing on the evaluation and selection of sustainable technologies for the removal of microplastics from water and, consequently, providing new opportunities to include research outcomes in environmental policy and sustainable management of water[9]. These findings can also go a long way in designing sophisticated filtration and treatment systems, reducing microplastic intrusion into water bodies.

Methodology

Theoretical Overview (Theoretical framework of the research)

The theoretical overview represents the range of concepts and studies that provide a scientific basis for the problem of microplastic in the aquatic environment. This can be explored under the following points:

A. Concept and classification of microplastics:

Microplastics are defined as plastic particles with a diameter less than 5 mm. They can be divided into two general categories:

A- **Primary Microplastics:** These are produced directly from manufacturing processes and are used in cosmetics, detergents, and pharmaceuticals.

B- **Secondary microplastics**: These form as a result of the gradual breakdown of larger plastics due to ultraviolet radiation and mechanical and biological factors.

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Main sources of microplastics in the aquatic environment are sewage, industrial activities, the washing of synthetic fabrics, tire wear, and decomposition of plastic waste dumped into the environment, the following environments are among the ones most susceptible to the accumulation of these particles: coastal cities and industrial discharge areas.

B. Physical and chemical properties:

Microplastic particles generally feature light weight and high resistance to degradation, meaning that they can remain in the environment for a long period of time, also maintain large surface areas able to absorb various kinds of chemical pollutants, including hydrocarbons and heavy metals, thus increasing their environmental toxicity.

1- Environmental and health effects: Microplastic particles hamper aquatic organisms by blocking their digestive tracts, inhibiting growth and reproduction processes, and transferring absorbed pollutants into the tissues of these organisms, the human level, it has been shown that microplastics enter the human body through consumption of seafood, bottled water, and sea salt, potentially causing long-term cellular and toxic effects.

2. There are global efforts to address the problem: Many organizations and research institutions engage in putting into place developed strategies aimed at reducing microplastic spread. These include introducing legislation that limits the use of single-use plastics, promotion of recycling technologies, use of biodegradable alternatives, and development of new filtration and treatment technologies with the capability of removing microplastics from water.

Result and Discussion

Microplastics as carriers of Organic Pollutants and Heavy Metals:

Due to their unique physical and chemical properties, microplastic particles are active carriers of organic pollutants and heavy metals in the aquatic environment, acting as effective adsorption platforms for a wide variety of toxic compounds. This is because they have large surface areas, negative electrical charges, and hydrophobic natures, which give them a high potential for attracting and retaining nonpolar chemicals from the environment .

It has been shown that microplastics bind strongly to complex organic compounds such as PAHs, phthalates, and industrial pesticides. These compounds attach to the surface of the particles through van der Waals forces and hydrophobic interactions . In this way, microplastics act as mobile carriers of toxins since they can be transported over long distances due to water currents, causing the redistribution of pollution to new areas quite far from its original source[10] .

As for heavy metals like cadmium (Cd), lead (Pb), mercury (Hg), and nickel (Ni), microplastics act as an attraction and ion exchange surface for these elements in water, enhancing their accumulation on the surface of the particles. After some time, with alterations in environmental conditions of temperature, pH, and ion concentration of the water, these metals are released from microplastics into the aquatic environment or into the bodies of ingested organisms, which causes a redistribution of pollution within the aquatic system .

During ingestion by aquatic organisms, these microparticles release the substances adsorbed on their surface under digestive enzymes and acidity variation in the digestive tract. The chemical bonds are then broken, and the absorbed pollutants migrate into the tissues of the organism [11]. This results in cell destruction and disturbances of the metabolic pathway, developing a chronic toxicity that may be transferred upward through the trophic chain to human beings .

Recent research has shown that microplastics are not passive vectors of contaminants but, instead, interact with the aquatic environment. They have the capability to modify the chemical reactivity of metals by temporarily absorbing and then releasing them under different environmental conditions, which will alter the biodistribution and bioavailability of heavy metals within ecosystems [12]. This makes microplastic one active mediator in the growing complexity of the problem in water pollution and even more difficult to tackle with conventional methods.

Biological Effects of Microplastics on Aquatic Organisms

While there are several potential environmental risks owing to plastic pollution, probably the biological effects of microplastic particles on aquatic organisms would be most important. These particles will affect the organisms through many processes, including physical effects, chemical toxicity, and behavioral disturbances .

The first one is that microplastic particles physically block the digestive tracts of planktonic organisms, crustaceans, and small fish. Due to the ingested material, the nutrient absorption capability of organisms is reduced; hence, energy deficiencies, reduced growth, and reproductive dysfunction may result [13]. Sharp or irregularly shaped particles can also induce physical trauma in the digestive tract, sometimes tearing internal tissues and further increasing mortality rates in several sensitive species.

In this respect, microplastics are capable of absorbing organic pollutants and heavy metals; hence, from the point of view of chemical toxicity, they can be considered active vectors of toxins to biological tissues. It is this process, following digestion that under conditions of changed acidity and enzymatic digestion, favors the release of previously absorbed chemical compounds, promoting toxin accumulation in the liver, kidneys, and adipose tissue [14]. All this culminates in cell dysfunction, oxidative stress, and nucleic acid damage, further increasing chronic disease incidences and lowering resilience against environmental stressors.

Thirdly, the microplastic debris can cause behavioral disturbances to aquatic organisms; this includes changed feeding and migration patterns and delays in reproductive activity. In such situations, organisms spend their energies digesting non-nutritive particles, hence lowering their efficiencies in foraging or avoiding predators[15]. The disturbances, studies have documented, affect the ecological balance of crucial populations, a decline in some important species in the food chain, the perspective of cumulative effects and food chains, microplastics have the potential to migrate up the food chain from the lowest to the highest rungs: for example, the plankton that ingest microplastics will be consumed by small fish, then larger fish, marine mammals, and even humans . This covers the gradual toxic buildup through bioaccumulation and an increase in biological health impacts in organisms higher up the food chain, hence it is an environmental and a human problem[16].

Indeed, recent studies have shown that the chemical and surface composition of microplastics can induce abnormal immune responses in aquatic organisms, such as chronic inflammation and necrosis, apart from affecting the internal microbiome of the organisms and impairing their digestive

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and absorption capacities, further compromising their general health[17] . These linked effects give rise to microplastics as a chronic environmental stressor contributing to changing dynamics in aquatic ecosystems.

Strategies and Techniques to Remove Microplastics from Aquatic Environments

Development of the effective and sustainable methods for removal of microplastics from water is increasingly warranted by several environmental and health impacts. Various recent researches have focused on several technological and innovative approaches, ranging from physical and chemical to biological treatments[18].

First, the physical techniques include mechanical filtration and size and density separation. These methods have been used in separating microplastic particles from water by microscreens, filters, and centrifuges, which capture the microplastics before they reach natural environments or water distribution networks . Advanced filtration systems have also been developed for wastewater treatment plants that are able to remove a high percentage of microplastic particles before the water is discharged into the rivers and seas.

The second is the chemical techniques that rely on the degradation of plastics into lesser harmful compounds using either oxidizing agents or by photocatalysis. These methods allow for the degradation of microplastics into biodegradable particles or their transformation into less toxic substances, hence reducing accumulation of the toxins associated with them in the ecosystem . Other modern techniques involve the use of chemical membranes that can absorb microplastics together with heavy metals associated with them[19].

Third, there is the biological technique, wherein biodegradation by microorganisms and enzymes is in play. Certain bacteria and fungi have the ability to depolymerize microplastics into smaller compounds that become easily absorbable or biodegradable without the use of expensive chemical techniques that may result in further pollution[20] . It has been determined that these microorganisms are capable of processing specific types of plastics, such as PET and PE, while attaining high efficiency in the reduction of plastic particle size in water.

Fourth, management strategies and environmental policies complement the technical effort through the reduction of the primary sources of microplastics involves limiting the use of single-use plastics, incentivizing recycling, strictly regulating plastic waste disposal, and raising public awareness about plastic pollution and its impact on the environment and health .

Fifth, innovative and future-oriented technologies, such as biomagnets, nanomaterials, and biodegradable floating materials, have the potential to rapidly capture microplastics from the surface of the water[21]. These novel methods are thus promising avenues for the elaboration of eco-friendly and low-cost solutions that minimize the impact on aquatic organisms during cleaning procedures .

These methodologies therefore show that a combination of physical, chemical, and biological measures with environmentally viable policy will provide the best approach toward reducing the spread of microplastics in aquatic systems. This study also shows that investing in research and development and in new technologies will be very important in effectively protecting the aquatic environment for the safety of aquatic organisms and human beings in the long run .

Phytoremediation:

Phytoremediation is a method for cleaning the environment in which plants are used to remove, stabilize, or break down aquatic and terrestrial environment pollutants, including heavy metals, organic compounds, and industrial wastes . Medicinal plants are among the most promising in this field for the content of active secondary compounds such as phenols and terpenoids, stimulating plant enzymes responsible for the breakdown and recycling of toxic compounds in an ecologically friendly manner[22] . Examples of medicinal plants used include: *Aloe vera:* It is featured by its capacity for the absorption of heavy metals from water, like lead, mercury, and cadmium, storing them in its tissue in a form that reduces environmental toxicity . *Mentha spicata* (peppermint): Studies have shown high effectiveness in absorbing lead and copper from polluted water, and it also contributes to improving water quality by reducing suspended organic matter . *Ocimum basilicum* (basil): It is used in the inhibition of free radicals resulting from chemical pollution, thus reducing oxidative stress in aquatic plants and animals . *Lemna minor* (water lentil): This is an excellent plant model for the treatment of pollutants in stagnant water due to its rapid dispersal and possibility of fast and effective pollutant uptake[23] . The mechanisms involve three interconnected stages of plant treatment in absorption and biodegradation: Adsorption: The attachment of the pollutants to the root surfaces due to electric charges and hydrogen bonds allows these pollutants to be concentrated in the roots before their translocation to other parts of the plant . Translocation: The movement of pollutants from the root to the stem and the leaves through the xylem allows some of the stored compounds or their conversion into less toxic compounds to be stored in the upper tissues . Biodegradation: The breaking of pollutants by plant enzymes, such as peroxidase and catalase, besides the action of plant byproducts that neutralize the free radicals and diminish oxidation, mitigating thus the toxic effects of microplastics . The symbiotic interaction of plants and rhizobacteria can contribute to increased biodegradability efficiency-the bacteria help to break down the complex compounds and absorb heavy metals more quickly[24] .

A few practical aquatic applications of medicinal plant bioremediation are in treatment ponds of wastewater from industrial effluents containing plastics and metals, where the plants absorb pollutants and prevent their spread into the environment ; urban ecosystems comprising rivers and canals that receive plastic waste along with organic compounds, whereby plants aid in decreasing the concentration of pollutants ; and coastal areas that are exposed to a great accumulation of plastic pollutants, where plants may reduce the pollution and increase marine biodiversity[25] .

This technology is characterized by its low cost; it is friendly to the environment and non-polluting; thus, it contributes to restoration of biodiversity, improving water quality, and reduction of the carbon footprint of human activities .

Over the last years, the increasing demand for holistic approaches that would withdraw microplastics from aquatic systems has urged researchers to investigate plant-based bioremediation techniques combined with modern technologies for better effectiveness and sustainable efficiency[26]. This depends entirely on the amalgamation of medicinal plants' inherent potential for absorption and degradation of pollutants with advanced physical and chemical methods, aimed at a faster pace and enhanced environmental results.

Integration of Plants and Modern Technologies

A- **Plant-Assisted Filtration**:

Medicinal plants such as Aloe vera and Mentha spicata can be integrated into advanced filtration basins in which the stabilized roots retain microplastics along with other attached pollutants, while mechanical filtration techniques and microfilters may be applied to capture the

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unabsorbable particles. In this way, the integration increases efficiency in the removal of microplastics from wastewater and surface water .

B-**Biochemical Enhancement:**

Plants stimulate plant enzymes and root bacteria, further enhancing the breakdown of organic pollutants associated with microplastics, when combined with photocatalysis or environmental oxidizers, complex organic pollutants can be degraded more rapidly and reduce environmental toxicity .

C**-Plant-nanotechnology integration:**

Magnetic or absorbent nanoparticles are applied together with medicinal plants in order to help capture microplastics and associated heavy metals. Nanoparticles bring the pollutants into the planes of high plant activity or degradation, increasing the rate of removal of microplastics and the efficiency of the entire process .

Models of Living Systems:

Integrating plants with artificial water treatment systems, for instance, artificial ponds, living canals, and industrial wastewater ponds, allows monitoring the interactions of microplastics with plants and rhizobia in a semi-natural environment[27]. Such an approach allows the estimation of processing speed and efficiency of biodegradability before large-scale application in nature.

These integrated methods of plants with advanced technologies have considerable environmental sustainability and low-cost advantages. It decreases the consumption of hazardous chemicals, saves biodiversity, and recycles polluted water resources. This kind of treatment results in a low carbon footprint compared to traditional chemical treatment and at the same time enhances the applicability for urban and coastal areas with continuous microplastic pollution .

Challenges and Future Prospects:

Although many successes have been achieved in using bioremediation with medicinal plants to remove pollutants, various environmental and technical challenges must be overcome for the large-scale development of this technology[28]. Examples of such challenges include the following:

1- **Slow Decomposition Rate**: Since plants have a usual capacity to slowly absorb and decompose pollutants, their removal by microplastics and heavy metals is expected to take quite some time as compared to faster physical or chemical means .

2- **Accumulation of Pollutants within Plant Tissues:** The efficiency of the absorption may be so high that toxic compounds and heavy metals might build up in the plant tissues themselves, hence presenting another source of environmental hazard if the residues are not disposed of after harvesting or processing.

3. **Difficulty in the management of post-treatment waste**: After the treatment cycle, a scientist has to have plans that can ensure the safe disposal or recycling of the contaminated plants to avoid the release of pollutants back into the environment [29].

Recent research focuses on overcoming these challenges by incorporating phytoremediation with advanced technologies such as:

1- **Nanobiotechnology**: Plants can be coupled with magnetic or absorbent nanoparticles to enhance their efficiency of uptake by governing the pathway of the pollutant and hence decreasing its accumulation in plant tissues .

2. **Employing the use of genetically modified enzymes**: developing plants or rhizobia that can produce enzymes to degrade toxic compounds related to microplastics more effectively.

3. **Integrated application of artificial aquatic systems:** design treatment ponds or ecological pools that integrate plants with rhizobia, physical and chemical technologies to quickly and fully remove pollutants.

4**. Expand urban and coastal ecosystems through phytoremediation: I**n view of sustainable environmental management practices that prevent the influx of microplastics into the natural aquatic systems[30].

The future trends discussed have opened promising perspectives toward better effectiveness and sustainability of the bioremediation of medicinal plants, involving the best possible balance among pollution reduction, protection of ecosystems, and preservation of health for both humans and other living organisms.

Conclusions

1. Widespread Prevalence of Microplastics particles are minute, capable of disseminating in aquatic and terrestrial ecosystems, hence presenting environmental and health threats all over the world.
2. Accessibility of Pollutants, these particles possess physical and chemical properties that enable them to absorb organic pollutants and heavy metals, thus serving as very effective carriers of toxins throughout the food chain.
3. Health and Biological Effects microplastics can penetrate into aquatic organisms' tissues and are further transferred to humans, causing chronic health problems such as inflammation, immune disorders, and hormonal disturbances.
4. Importance of Phytoremediation, the medicinal plants represent an efficient tool in the removal, stabilization, and breakdown of pollutants. They operate through absorption, transport, and biodegradation, though efficiency is enhanced with interaction with mycorrhizal bacteria.
5. Integration with Modern Technologies: The combination of phytoremediation with nanotechnology, advanced filtration, and chemical catalysis increases the efficiency of microplastic removal and reduces accumulation in plants and water.

The necessity of sustainability in spite of the challenges about speed of decomposition and waste management, the incorporation of physical, chemical, biological, and phytoremediation methods is environmental and efficient, as it concerns the long-term protection of aquatic systems and human health

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References

1. A. K. Ajay, D. Behera, S. Bhattacharya, P. K. Mishra, Y. Ankit, and A. Anoop, “Distribution and Characteristics of Microplastics and Phthalate Esters From a Freshwater Lake System in Lesser Himalayas,” Chemosphere, vol. 283, p. 131132, 2021.
2. C. Bretas Alvim et al., “Effect of Polyethylene Microplastics on Activated Sludge Process: Accumulation in the Sludge and Influence on the Process and on Biomass Characteristics,” Process Safety and Environmental Protection, vol. 148, pp. 536–547, 2021.
3. X. Chen et al., “Isotherm Models for Adsorption of Heavy Metals From Water: A Review,” Chemosphere, vol. 307, p. 135545, 2022.
4. M. S. Bank and S. V. Hansson, “The Microplastic Cycle: An Introduction to a Complex Issue,” in Microplastic in the Environment: Pattern and Process. Cham: Springer, 2022, pp. 1–16.
5. G. Kalčíková, T. Skalar, G. Marolt, and A. Jemec Kokalj, “An Environmental Concentration of Aged Microplastics With Adsorbed Silver Significantly Affects Aquatic Organisms,” Water Research, vol. 175, p. 115644, 2020.
6. Y. Pan et al., “Removing Microplastics From Aquatic Environments: A Critical Review,” Environmental Science & Ecotechnology, vol. 13, p. 100222, 2023.
7. G. Kalčíková, A. Žgajnar Gotvajn, A. Kladnik, and A. Jemec, “Impact of Polyethylene Microbeads on the Floating Freshwater Plant Lemna minor,” Environmental Pollution, vol. 230, pp. 1108–1115, 2017.
8. L. C. Dovidat, B. W. Brinkmann, M. G. Vijver, and T. Bosker, “Plastic Particles Adsorb to the Roots of Freshwater Vascular Plant Spirodela polyrhiza but Do Not Impair Growth,” Limnology and Oceanography Letters, vol. 5, pp. 37–45, 2020.
9. F. Julienne, N. Delorme, and F. Lagarde, “From Macroplastics to Microplastics: Role of Water in the Fragmentation of Polyethylene,” Chemosphere, vol. 236, p. 124409, 2019.
10. L. Li, S. Geng, Z. Li, and K. Song, “Effect of Microplastic on Anaerobic Digestion of Wasted Activated Sludge,” Chemosphere, vol. 247, p. 125874, 2020.
11. F. De Falco, E. Di Pace, M. Cocca, and M. Avella, “The Contribution of Washing Processes of Synthetic Clothes to Microplastic Pollution,” Scientific Reports, vol. 9, p. 6633, 2019.
12. C. Bertoldi et al., “First Evidence of Microplastic Contamination in the Freshwater of Lake Guaíba, Porto Alegre, Brazil,” Science of the Total Environment, vol. 759, p. 143503, 2021.
13. V. S. Koutnik et al., “Distribution of Microplastics in Soil and Freshwater Environments: Global Analysis and Framework for Transport Modeling,” Environmental Pollution, vol. 274, p. 116552, 2021.
14. G. Kalčíková, “Beyond Ingestion: Adhesion of Microplastics to Aquatic Organisms,” Aquatic Toxicology, vol. 258, p. 106480, 2023.
15. E. E. Esiukova, O. I. Lobchuk, A. A. Volodina, and I. P. Chubarenko, “Marine Macrophytes Retain Microplastics,” Marine Pollution Bulletin, vol. 171, p. 112738, 2021.
16. F. Murphy, C. Ewins, F. Carbonnier, and B. Quinn, “Wastewater Treatment Works as a Source of Microplastics in the Aquatic Environment,” Environmental Science & Technology, vol. 50, pp. 5800–5808, 2016.
17. A. A. Horton et al., “Large Microplastic Particles in Sediments of Tributaries of the River Thames, UK: Abundance, Sources and Methods for Effective Quantification,” Marine Pollution Bulletin, vol. 114, pp. 218–226, 2017.
18. L. Gutow, A. Eckerlebe, L. Giménez, and R. Saborowski, “Experimental Evaluation of Seaweeds as a Vector for Microplastics Into Marine Food Webs,” Environmental Science & Technology, vol. 50, pp. 915–923, 2016.
19. M. C. Ariza-Tarazona et al., “New Strategy for Microplastic Degradation: Green Photocatalysis Using a Protein-Based Porous N-TiO2 Semiconductor,” Ceramics International, vol. 45, pp. 9618–9624, 2019.
20. S. Datu, S. Sora, Supriadi, and A. Tahir, “Microplastic in Cymodocea rotundata Seagrass Blades,” International Journal of Environment, Agriculture and Biotechnology, vol. 4, pp. 1758–1761, 2019.
21. A. A. Horton and S. J. Dixon, “Microplastics: An Introduction to Environmental Transport Processes,” WIREs Water, vol. 5, p. e1268, 2018.
22. A. M. Elgarahy, A. Akhdhar, and K. Z. Elwakeel, “Microplastics Prevalence, Interactions, and Remediation in the Aquatic Environment: A Critical Review,” Journal of Environmental Chemical Engineering, vol. 9, p. 106224, 2021.
23. V. Godoy, M. A. Martín-Lara, M. Calero, and G. Blázquez, “Physical-Chemical Characterization of Microplastics Present in Some Exfoliating Products From Spain,” Marine Pollution Bulletin, vol. 139, pp. 91–99, 2019.
24. H. Kye et al., “Microplastics in Water Systems: A Review of Their Impacts on the Environment and Their Potential Hazards,” Heliyon, vol. 9, p. e14359, 2023.
25. K. Lange, H. Österlund, M. Viklander, and G.-T. Blecken, “Occurrence and Concentration of 20–100 µm Sized Microplastic in Highway Runoff and Its Removal in a Gross Pollutant Trap, Bioretention and Sand Filter Stormwater Treatment Train,” Science of the Total Environment, vol. 809, p. 151151, 2022.
26. A. Patchaiyappan et al., “Prevalence and Characteristics of Microplastics in Freshwaters,” Environmental Science and Pollution Research, vol. 27, pp. 1–12, 2020.
27. A. Mateos-Cárdenas et al., “Polyethylene Microplastics Adhere to Lemna minor (L.), Yet Have No Effects on Plant Growth or Feeding by Gammarus duebeni (Lillj.),” Science of the Total Environment, vol. 689, pp. 413–421, 2019.
28. J. W. Cross, “Duckweed Roots: Their Role in Vegetative Dispersal,” International Steering Committee on Duckweed Research and Applications, vol. 5, pp. 58–59, 2017.
29. P. Di Martino, “Extracellular Polymeric Substances: A Key Element in Understanding Biofilm Phenotype,” AIMS Microbiology, vol. 4, pp. 274–288, 2018.
30. I. E. Napper, L. S. Wright, A. C. Barrett, F. N. Parker-Jurd, and R. C. Thompson, “Potential Microplastic Release From the Maritime Industry: Abrasion of Rope,” Science of the Total Environment, vol. 804, p. 150155, 2022.

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