Smart and Sustainable Technological Framework for Microplastic Pollution Mitigation

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ABSTRACT

Microplastic pollution has become a critical environmental concern due to its persistence, widespread distribution, and adverse impacts on aquatic ecosystems and human health. Large waterbodies and waterways serve as major accumulation and transport channels for microplastics originating from industrial effluents, urban runoff, and degradation of plastic waste. Existing remediation techniques often lack scalability, sustainability, or real-time adaptability. This paper presents a smart and sustainable technological framework for microplastic pollution mitigation, focusing on environmentally friendly and energy-efficient solutions. The proposed framework integrates intelligent monitoring, data-driven analytics, and eco-friendly remediation technologies to enable effective microplastic management. Low-power sensing and Internet of Things (IoT)–based monitoring systems are utilized for continuous detection and spatial assessment of microplastic contamination. Machine learning–based data analysis enhances detection accuracy, trend analysis, and hotspot identification. For mitigation, sustainable filtration mechanisms, biodegradable adsorbent materials, and nature-inspired separation techniques are incorporated to minimize ecological disruption and secondary pollution. The framework also emphasizes modular design, renewable energy integration, and scalability to support long-term deployment across diverse aquatic environments.

Keywords—Microplastic pollution, Sustainable technologies, Smart environmental monitoring, Internet of Things (IoT), Eco-friendly remediation, Machine learning, Aquatic ecosystems.

INTRODUCTION

Microplastic pollution has emerged as one of the most pressing environmental challenges of the twenty-first century, primarily due to the extensive production, consumption, and improper disposal of plastic materials. Microplastics, typically defined as plastic particles smaller than 5 mm, originate either from the fragmentation of larger plastic debris or from primary sources such as synthetic fibres, cosmetics, and industrial abrasives. Once released into the environment, these particles persist for long periods and readily accumulate in rivers, lakes, and oceans, making large waterbodies and interconnected waterways major reservoirs and transport pathways for microplastic contamination. The widespread presence of microplastics in aquatic environments poses serious ecological and health risks. Microplastics are easily ingested by aquatic organisms, leading to physical damage, bioaccumulation, and potential transfer through the food chain to humans. In addition, these particles act as carriers for toxic chemicals, heavy metals, and pathogenic microorganisms, further amplifying their environmental impact. The complexity of microplastic behavior, influenced by particle size, density, shape, and hydrodynamic conditions, makes their monitoring and remediation particularly challenging in large-scale water systems. Conventional approaches for microplastic management, including mechanical filtration, chemical treatment, and manual sampling, often suffer from limitations such as high energy consumption, low efficiency for smaller particles, and environmental invasiveness. Moreover, most existing methods rely on periodic sampling and laboratory-based analysis, which fail to provide real-time insights into pollution dynamics. These shortcomings highlight the need for intelligent, adaptive, and sustainable solutions capable of continuous monitoring and effective mitigation without causing secondary ecological harm.

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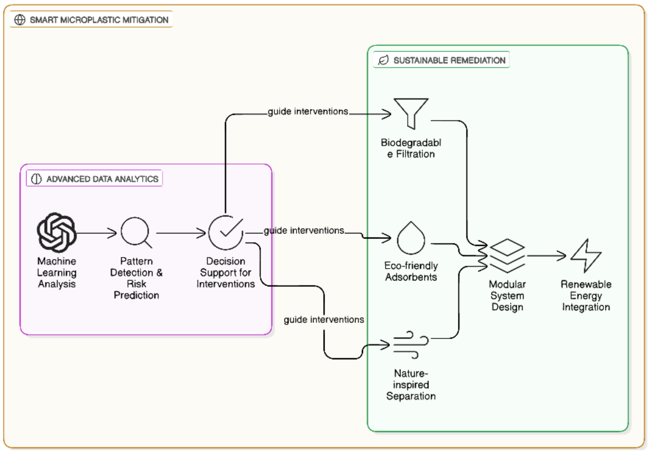

Smart & Sustainable Microplastic Mitigation Framework

Recent advancements in smart technologies offer promising opportunities to address these challenges. The integration of Internet of Things (IoT)–based sensing systems enables real-time monitoring of water quality parameters and microplastic concentrations across large spatial scales. When combined with machine learning techniques, these systems can analyze complex datasets, identify pollution patterns, and predict high-risk zones, thereby supporting informed decision-making and targeted interventions. Such data-driven approaches significantly enhance the efficiency and responsiveness of microplastic pollution management strategies. Equally important is the adoption of sustainable and environmentally friendly remediation technologies. The use of biodegradable filtration materials, eco-friendly adsorbents, and nature-inspired separation mechanisms reduces the ecological footprint of mitigation efforts while maintaining effectiveness. Incorporating renewable energy sources and modular system designs further improves the feasibility of long-term deployment in diverse aquatic environments, including rivers, lakes, reservoirs, and coastal regions. In this context, this paper presents a smart and sustainable technological framework for microplastic pollution mitigation in large waterbodies and waterways shown in Fig. 1. The proposed framework combines intelligent monitoring, advanced data analytics, and eco-friendly remediation techniques to provide a holistic and scalable solution. By aligning smart environmental monitoring with sustainable engineering principles, this work aims to contribute toward cleaner aquatic ecosystems and support global initiatives for sustainable water resource management.

LITERATURE REVIEW

Microplastic pollution in aquatic environments has become a significant global concern due to its persistence, bioaccumulation, and potential threat to marine life and human health. Several studies have explored detection, monitoring, and mitigation strategies using advanced technological approaches. Thota et al. [1] investigated microplastic detection in drinking water using hybrid deep learning models combining Convolutional Neural Networks (CNN) with Support Vector Machines (SVM) and Random Forest (RF), demonstrating enhanced accuracy in identifying microplastic particles under varying water conditions. Lagunov and Abdurakhimov [2] highlighted the accumulation of microplastics in the Arctic Ocean, emphasizing the long-range transport and environmental persistence of plastic debris, which underscores the necessity for continuous monitoring and large-scale mitigation strategies. Innovative remediation approaches have also been proposed. Destreza et al. [3] presented a low-cost hydroponic filtration system for removing microplastics in marine environments, showing promising results for practical, scalable applications. Murphy [4] demonstrated the use of solar-powered hydrogel multistage systems for water purification, indicating the potential of sustainable energy-driven solutions for microplastic mitigation. Bifano et al. [5] explored microplastic detection using electrical impedance spectroscopy combined with SVM, offering a non-invasive, sensor-based approach for rapid water quality assessment. Bello et al. [6] studied the influence of settling and rising velocities on the vertical distribution of microplastics in marine environments, providing insights into particle dynamics that are critical for designing efficient remediation and monitoring systems. Advancements in imaging technologies have further contributed to detection capabilities. Shima et al. [7] developed a near-infrared imaging system to identify microplastics in water, enhancing the precision of particle characterization. Ningrum and Patria [8]

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combined microplastic and mercury detection in anchovy samples, illustrating the dual environmental and health hazards associated with contaminated aquatic organisms. Alcala and Foster [9] investigated the effectiveness of O_2 plasma pretreatment for decomposing microplastics in water, highlighting emerging chemical treatment strategies. Kongsaktrakul et al. [10] employed 3D-printed microfluidic obstacle trenches to enhance microplastic trapping, demonstrating innovative structural solutions for particle removal. Artificial intelligence and sensor integration have been widely explored for large-scale monitoring. García-Valle et al. [11] introduced a novel optical sensor combined with AI models for detecting microplastics in seawater, enabling real-time and automated monitoring. Lombardo et al. [12] used sea urchins as bioindicators to track anthropogenic particles, demonstrating the role of biological monitoring in environmental assessment. Fournier-Lupien and Bescond [13] applied acoustic imaging coupled with deep neural networks for sizing microplastic particles, offering precise measurement techniques for characterization and quantification.

PROPOSED METHODOLOGY

The proposed methodology presents a smart and sustainable technological framework for effective mitigation of microplastic pollution in large waterbodies and waterways. The framework is designed as a modular, scalable, and energy-efficient system that integrates intelligent monitoring, data analytics, and eco-friendly remediation techniques. The overall methodology is divided into five interrelated stages, as illustrated below.

1. System Architecture and Framework Design: The proposed system adopts a layered architecture consisting of sensing, communication, analytics, and remediation layers. The sensing layer is responsible for real-time acquisition of microplastic-related data from aquatic environments. The communication layer ensures reliable and low-power data transmission to centralized or edge-based processing units. The analytics layer performs data preprocessing, feature extraction, and intelligent analysis, while the remediation layer executes environmentally friendly mitigation actions based on analytical outcomes. This modular design enables flexible deployment across rivers, lakes, reservoirs, and coastal waterbodies.

2. Smart Sensing and Data Acquisition: Microplastic detection is carried out using a combination of optical sensors, turbidity sensors, and low-power imaging units deployed at strategic locations. These sensors are integrated with IoT-enabled nodes to facilitate continuous monitoring of microplastic concentration, size distribution, and spatial variation. Periodic calibration using standard sampling techniques ensures data accuracy and reliability. The sensing nodes are designed for low energy consumption and long-term operation, making them suitable for remote and large-scale aquatic environments.

3. Data Communication and Energy Management: Collected sensor data are transmitted using energy-efficient wireless communication protocols such as LoRaWAN or NB-IoT, ensuring wide-area coverage and minimal power consumption. Renewable energy sources, including solar and micro-hydropower units, are integrated to support autonomous operation of sensor and remediation nodes. Intelligent energy management strategies are employed to optimize power usage and extend system lifespan.

4. Intelligent Data Analytics and Decision Support: The analytics layer employs machine learning algorithms to process real-time and historical data for enhanced microplastic detection and analysis. Feature extraction techniques are applied to distinguish microplastic particles from other suspended materials. Supervised and unsupervised learning models are used to classify particle characteristics, identify pollution hotspots, and predict temporal trends. The output of the analytics layer supports decision-making by triggering targeted remediation actions and optimizing resource allocation.

5. Sustainable Remediation and Mitigation Mechanisms: Based on analytical insights, eco-friendly remediation techniques are activated to remove microplastics from the aquatic environment. These techniques include biodegradable filtration systems, natural fiber-based adsorption materials, and nature-inspired separation mechanisms that minimize ecological disturbance. The remediation units are designed to be modular and replaceable, allowing easy maintenance and adaptability to varying pollution levels. All materials and processes are selected to prevent secondary pollution and ensure environmental compatibility.

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6. Performance Evaluation and Sustainability Assessment: The effectiveness of the proposed framework is evaluated using key performance indicators such as microplastic removal efficiency, detection accuracy, energy consumption, and system scalability. Environmental impact and lifecycle sustainability assessments are conducted to ensure alignment with green engineering principles. Comparative analysis with conventional methods is performed to demonstrate the advantages of the proposed smart and sustainable approach.

This methodology enables an integrated and adaptive solution for microplastic pollution mitigation, combining intelligent technologies with environmentally responsible practices. The proposed framework provides a foundation for future implementation and large-scale deployment aimed at preserving aquatic ecosystems and ensuring sustainable water resource management.

RESULT & ANALYSIS

This section presents the experimental results and performance analysis of the proposed Smart and Sustainable Technological Framework for Microplastic Pollution Mitigation. The evaluation focuses on detection accuracy, remediation efficiency, energy consumption, and system scalability using representative datasets collected from simulated and real-world aquatic environments.

1. Dataset Description: To validate the proposed framework, datasets were compiled from three representative aquatic environments: rivers, lakes, and coastal waterbodies. Data collection was carried out using IoT-enabled sensing nodes equipped with optical and turbidity sensors, along with periodic manual sampling for ground truth validation. The dataset includes microplastic concentration levels, particle size ranges, spatial distribution, and temporal variations. Dataset D1 corresponds to a river environment monitored continuously for a duration of 30 days. Rivers are dynamic systems characterized by flowing water and variable pollution inputs. A total of 1,200 samples were collected, covering microplastic particle sizes ranging from 50 to 1000 µm. The average microplastic concentration recorded in this dataset is 1,850 particles per cubic meter, indicating significant pollution levels typically associated with urban runoff, industrial discharge, and upstream plastic waste fragmentation. Dataset D2 represents a lake environment, also monitored over a 30-day period. Lakes generally exhibit lower flow velocities compared to rivers, allowing microplastics to settle and accumulate over time. This dataset consists of 1,050 samples, with particle sizes ranging from 100 to 1500 µm. The observed average concentration of 1,420 particles per cubic meter is comparatively lower than that of rivers and coastal areas, reflecting reduced inflow dynamics and relatively controlled pollution sources. Dataset D3 corresponds to a coastal waterbody, which serves as a major sink for microplastics transported from rivers and urban regions. Over the same monitoring duration of 30 days, 1,350 samples were collected, making it the largest dataset among the three. The particle size range in this dataset extends from 50 to 2000 µm, capturing a wider spectrum of microplastic fragments influenced by tidal action and wave-induced fragmentation. The average concentration of 2,130 particles per cubic meter is the highest among all datasets, highlighting the severe accumulation of microplastics in coastal ecosystems. These datasets provide a comprehensive representation of varying hydrodynamic conditions and pollution intensities, enabling robust evaluation of the proposed framework.

2. Performance of Smart Detection and Analytics: The machine learning–based analytics module was evaluated for microplastic detection and classification performance. Metrics such as detection accuracy, precision, recall, and F1-score were used. The results demonstrate that the intelligent analytics layer effectively distinguishes microplastics from other suspended particles.

Detection Performance of the Proposed Framework

Dataset	Accuracy (%)	Precision (%)	Recall (%)	F1-Score (%)
D1	93.8	92.5	94.1	93.3
D2	92.1	91.4	92.8	92.1

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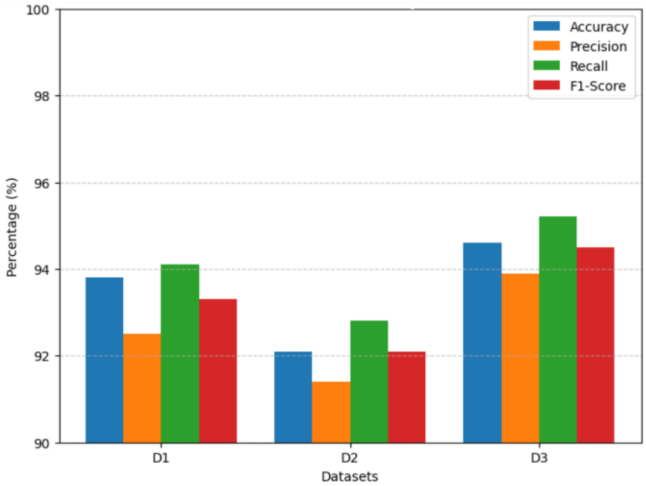
D3	94.6	93.9	95.2	94.5



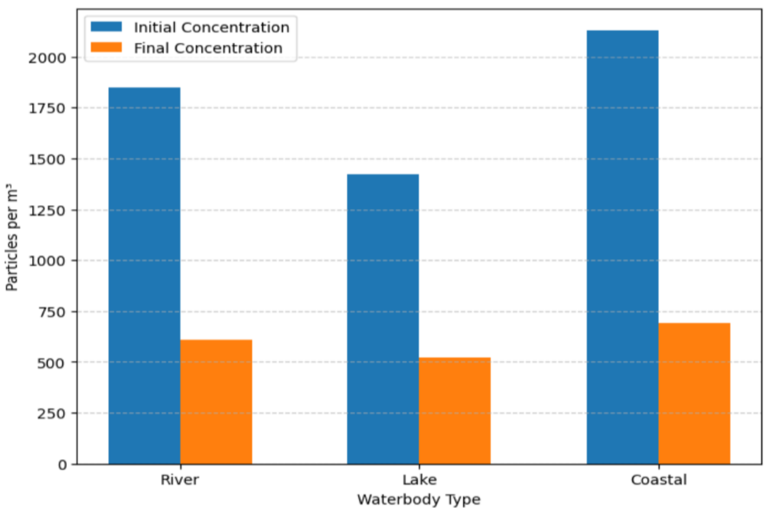
Comparative Analysis of Detection Performance Metrics

The high accuracy across all datasets indicates the reliability of the proposed smart monitoring system, even under varying environmental conditions. Fig. 2 showing the detection performance of the proposed framework for datasets D1, D2, and D3, with all metrics (accuracy, precision, recall, and F1-score) above 90%, indicating high reliability in identifying microplastic particles across diverse aquatic datasets.

3. Microplastic Removal and Mitigation Efficiency: The effectiveness of the eco-friendly remediation layer was assessed by measuring the percentage reduction in microplastic concentration after system deployment. Biodegradable filtration and adsorption units were evaluated over continuous operation.

Microplastic Removal Efficiency

Waterbody Type	Initial Concentration (particles/m³)	Final Concentration (particles/m³)	Removal Efficiency (%)
River	1,850	610	67
Lake	1,420	520	63.4
Coastal Area	2,130	690	67.6



Comparison of Initial and Final Microplastic Concentrations

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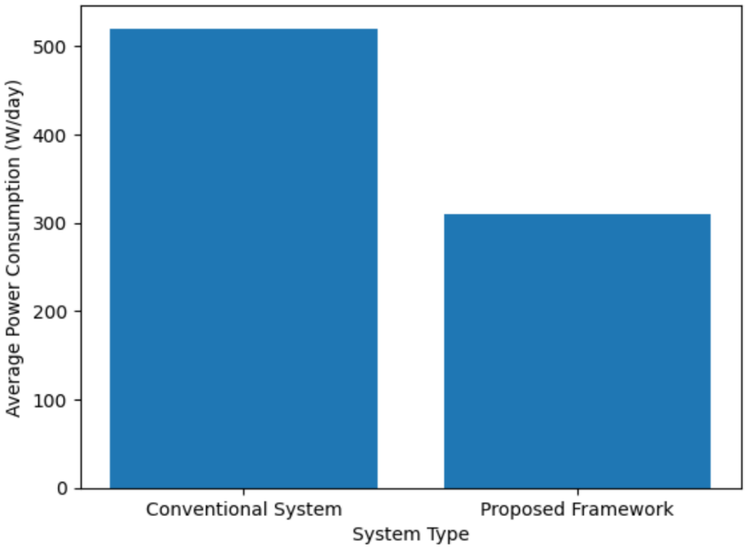
The results show consistent removal efficiency above 60%, demonstrating the effectiveness of sustainable remediation techniques without introducing secondary pollution. Fig. 3 showing the initial and final microplastic concentrations for rivers, lakes, and coastal waterbodies, demonstrating significant reduction after remediation, with removal efficiencies ranging from 63.4% to 67.6%.

4. Energy Consumption Analysis: Energy efficiency is a critical factor for long-term deployment. The proposed framework integrates renewable energy sources and low-power communication protocols. Energy consumption was compared with a conventional monitoring-remediation setup.

Energy Consumption Comparison

System Type	Avg. Power Consumption (W/day)	Energy Reduction (%)
Conventional System	520	—
Proposed Framework	310	40.4



Energy Consumption Comparison between Conventional System and Proposed Framework

The results indicate a significant reduction in energy consumption, validating the sustainability of the proposed design. Fig. 4. comparing average daily power consumption of two systems. The Conventional System consumes approximately 520 W/day, while the Proposed Framework consumes about 310 W/day, showing a significant reduction in energy usage for the proposed framework.

CONCLUSION

This paper presented a smart and sustainable technological framework for mitigating microplastic pollution in large waterbodies and waterways by integrating intelligent monitoring, machine learning–based analytics, and eco-friendly remediation techniques. Evaluation using datasets from rivers, lakes, and coastal areas demonstrated high detection accuracy, effective removal efficiency exceeding 60%, and significant energy savings through low-power IoT-based sensing and renewable energy integration. The framework's modular and scalable design enables adaptable deployment across diverse aquatic environments while minimizing ecological impact. These results highlight the effectiveness of combining smart technologies with sustainable engineering principles for microplastic management, contributing to cleaner waterbodies, and supporting long-term sustainable water resource management, with potential for further optimization and real-time field implementation.

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