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A Review of Recent Advances in Microplastic Research and ROVs to Aid the Development of an Integrated Solution for Microplastic Pollution

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Abstract: Microplastic pollution poses a critical threat to aquatic ecosystems, especially marine ecosystems along with freshwater ecosystems, as these infiltrate food chains and disrupt aquatic life. Despite ongoing efforts to mitigate this issue, the complexity of microplastic detection and filtration in underwater environments presents several challenges, including the limitations of current filtration technologies and the lack of efficient, low-cost identification systems. This review synthesizes recent research on key technologies and methodologies for addressing these challenges, including habitat monitoring with robotic systems, microplastic filtration using various principles, and underwater acoustic network synchronization to enhance data collection.
Additionally, this study explores emerging techniques for optical detection of microplastics and methods for assessing microplastic distribution at varying depths. Gaps in the existing literature, particularly in the areas of biodegradation and real-time detection, are highlighted. By integrating findings from these diverse fields, this paper aims to serve as a starting point for a combined system that utilizes filtration techniques, deep-learning detection algorithms, and synchronized communication networks to improve the efficiency of microplastic identification and removal in aquatic environments.
Keywords: Microplastic Pollution; Acoustic Communication; Filtration Systems; Detection Algorithms; Habitat monitoring; ROVs

I. INTRODUCTION

The escalating presence of microplastics in aquatic ecosystems has become a critical environmental challenge, sparking growing concerns about their far-reaching impacts on both ecological systems and human health. Microplastics, defined as particles smaller than 5 millimetres, are now ubiquitous in oceans, rivers, and lakes, where their persistence and ability to carry harmful chemicals make them a significant pollutant. Although much research has focused on the sources and harmful effects of microplastics, there remains a notable gap in the development of efficient and scalable methods for detecting, monitoring, and removing these particles from water bodies. Existing approaches, while promising, often fall short in addressing the full complexity of the problem. Limitations in current detection technologies, combined with challenges in removal techniques and insufficient large-scale monitoring systems, hinder our ability to fully mitigate the risks posed by microplastics. This review attempts to bridge these gaps by synthesizing recent advancements in detection methods, removal technologies, and the design of Remotely Operated Vehicles (ROVs) and underwater communication systems. Our aim is to provide a comprehensive assessment of current strategies, explore their limitations, and suggest pathways for future innovation

II. MICROPLASTIC POLLUTION AND ITS EFFECTS

Microplastic pollution has become a major environmental concern, threatening both ecosystems and human health. Microplastics are plastic particles smaller than 5 millimetres (mm), originating either from the breakdown of larger plastics or as microbeads in products like cosmetics. Current estimates suggest that approximately 5.25 trillion microplastic particles are circulating in ocean surface waters [1]. Around 80% of marine plastic pollution comes from land-based sources, with uncollected waste accounting for 75% and waste from mismanaged systems contributing 25% [1][2]. These plastics degrade slowly, persisting in the environment for hundreds or even thousands of years, which exacerbates their harmful effects [3][4].
In aquatic ecosystems, the majority of floating microplastics are composed of low-density polymers like polyethylene (54.5%) and polypropylene (16.5%). In contrast, denser plastics such as polyvinyl chloride (PVC) and polystyrene (PS) sink to the seafloor, contributing to deep-sea pollution [3][5]. Microplastics are produced or break down through photodegradation, mechanical weathering, and chemical reactions, depending on environmental factors like sunlight, water movement, and temperature [2][6].

The production of plastic has skyrocketed, reaching 335 million tons globally by 2016, further compounding the spread of microplastics in aquatic environments [5]. The ingestion and entanglement of microplastics pose serious risks to marine organisms. Studies have documented over 800 marine species affected by microplastics, which have been found in the digestive systems of various organisms, including fish, invertebrates, and marine mammals [1]. Once ingested, microplastics can translocate from the digestive system into other tissues, impairing organ function. For example, research has found microplastics in the livers and gills of zebra fish and seabass, affecting their physiological processes [2]. Smaller species that ingest microplastics are consumed by larger predators, resulting in the transfer of these pollutants throughout the food chain [2],[5].

Humans are primarily exposed to microplastics through the consumption of contaminated seafood. Studies have shown that farmed mussels contain up to 178 microfibers per sample, compared to 126 microfibers in wild mussels [1]. In fish markets in Indonesia and California, between 25% and 28% of fish samples were found to contain microplastics [6][4]. Microplastics have also been detected in other human food sources, such as sea salt and bottled water, raising additional concerns about potential health impacts [3].

In addition to the physical risks of ingestion, microplastics also pose chemical hazards. They can absorb and carry harmful chemicals, including persistent organic pollutants (POPs) such as polychlorinated biphenyls (PCBs) and dichlorodiphenyltrichloroethane (DDT). These pollutants adhere to the surface of microplastics at concentrations much higher than in the surrounding water, increasing the likelihood of bioaccumulation in marine organisms [7]. When humans consume contaminated seafood, these chemicals can enter the body, potentially leading to long term health issues. Plastic additives like phthalates and bisphenol A (BPA) are also of concern. For example, BPA concentrations on microplastics in marine environments can reach up to 729.9 nanograms per gram (ng/g), and exposure to such chemicals has been linked to endocrine disruption, cancer, and reproductive disorders [7],[8],[5].

Microplastics have also been shown to contaminate freshwater ecosystems, with effects similar to those observed in marine environments. Rivers and lakes act as conduits for microplastics, transporting these pollutants into the ocean. Freshwater organisms, including fish, molluscs, and invertebrates, have been found to ingest microplastics, leading to bioaccumulation and adverse effects on aquatic ecosystems [4]. The accumulation of microplastics in rivers and lakes can further exacerbate pollution in downstream marine environments [5].

Microplastic pollution presents a severe and growing threat to both aquatic ecosystems and human health. Microplastics originate from a variety of sources, including the degradation of larger plastics and the direct release of microbeads. Once in the environment, they persist for long periods due to their low biodegradability. Marine and freshwater organisms are increasingly ingesting microplastics, which not only cause physical harm but also act as carriers for toxic chemicals, leading to bioaccumulation and potential health risks for humans. Effective solutions require a combination of improved waste management, stricter regulations on plastic production and use, and enhanced monitoring and removal techniques in aquatic systems. Addressing this global issue is critical for protecting environmental and public health.

III.MICROPLASTIC DETECTION AND MONITORING

The detection and monitoring of microplastics (MPs) in aquatic environments are essential to understanding their environmental impacts and informing strategies to mitigate pollution. Microplastics, defined as plastic particles smaller than 5 millimetres, pose a significant risk due to their persistence and widespread distribution in marine, freshwater, and even atmospheric systems [9].

Historically, researchers have used manual sampling techniques followed by laboratory analysis to detect MPs. Standard methods include microscopy, Fourier Transform Infrared (FTIR) spectroscopy, and Raman spectroscopy, which are effective for identifying MPs based on their size, shape, and chemical composition [10]. However, these methods are time-consuming and labour-intensive. In sediment sampling, researchers commonly use density separation techniques involving sodium chloride (NaCl), sodium iodide (NaI), or zinc chloride ($ZnCl_2$) solutions, which allow the separation of MPs based on their buoyancy. These methods report high recovery rates—between 91% and 99% for common polymers such as polyethylene (PE) and polypropylene (PP) [11], [12].

Recent advancements have led to the development of real-time, in situ detection systems that address the limitations of manual methods. Researchers have integrated artificial intelligence (AI) with computer vision to develop systems capable of detecting and tracking MPs in water in real-time. For instance, an AI-based system using the YOLOv5 model and DeepSORT tracking algorithm has achieved a detection accuracy of 97% in controlled conditions and 96% in field tests. This system can track MPs at water velocities ranging from 15 centimetres per second (cm/s) to 46 cm/s, making it suitable for large-scale monitoring across diverse water bodies [13].

To facilitate large-scale MP monitoring, researchers have developed low-cost, portable sensors for use in marine environments. One notable innovation involves sensors that use infrared-sensitive photodiodes to detect floating MPs, specifically targeting polymers such as PE and PP. These sensors, which can be mounted on marine drifters, offer a cost-effective solution for monitoring MPs over large oceanic areas. The system achieves an impressive classification accuracy of approximately 90%, making it an ideal tool for extensive, real-time monitoring [14], [15].

Another approach to enhance MP detection involves the design of energy-efficient underwater robotic systems. Researchers have focused on reducing energy consumption in underwater vehicles to enable long-term monitoring of MPs in marine environments. These robots are equipped with sensors to detect MPs while minimizing the need for frequent human intervention. By optimizing the energy efficiency of these systems, researchers can extend their operational range and duration, contributing to more comprehensive monitoring efforts [16].

In freshwater systems, standardized pollution indices such as the Microplastic Pollution Load Index (MPPLI) and Microplastic Contamination Factor (MPCF) have proven valuable in assessing MP contamination. A study conducted in Nigeria applied these models to assess microplastic pollution in rivers, reporting an MPPLI value of 23.25, indicative of severe environmental risks [17]. These indices provide a standardized framework for comparing MP pollution across regions, offering essential insights for policymakers and environmental managers [18].

Despite progress in developing detection technologies, monitoring MPs in freshwater systems remains challenging due to the diverse physical properties of MPs, such as size, shape, and polymer type. For example, studies along India's coastline have revealed considerable variations in MP concentration based on the location and environmental conditions. Sampling conducted along the Tamil Nadu coast reported MP concentrations ranging from 1323 ± 1228 milligrams per square meter (mg/m^2) at high tide to 178 ± 261 mg/m^2 at low tide [19]. Meanwhile, in the Ganges River, MP contamination reached levels of 409.86 items per kilogram of sediment, demonstrating the significant pollution originating from land-based sources [20], [21].

Researchers have also developed smart sensor systems that integrate multiple detection methods, such as visual, infrared, and ultraviolet imaging, to improve detection accuracy. For example, the SmartIC system employs machine learning algorithms to automate MP detection in marine environments. This system effectively addresses challenges posed by varying water conditions, such as changes in light and flow, ensuring continuous monitoring [22]. By utilizing multimodal sensing techniques, such as combining acoustic and visual data, researchers can improve detection accuracy for smaller MPs (below 1 millimetre) in both freshwater and marine environments [23], [24].

Although the development of AI-powered systems and low-cost sensors has enhanced MP detection, researchers continue to face challenges related to environmental variability. Factors such as fluctuating water currents, varying light conditions, and the diverse physical characteristics of MPs make detection complex. Current systems, while accurate, still struggle to detect MPs smaller than 1 millimetre [25], [26], [27].

To address these challenges, future research should prioritize improving the scalability and accuracy of detection systems. This can be achieved by integrating multiple sensing modalities and refining AI models to adapt to environmental changes. Additionally, combining real-time monitoring systems with pollution indices such as MPPLI could offer a more comprehensive understanding of MP pollution trends across ecosystems [28], [29].

IV. MICROPLASTIC REMOVAL TECHNIQUES

Microplastic (MP) pollution in aquatic environments is a growing global concern, particularly due to its potential ecological and health risks. Efficient removal of microplastics from wastewater and water bodies has become a critical priority, and numerous techniques have been developed, ranging from filtration systems to biological and chemical treatments. This section synthesizes findings from a wide range of studies to provide an overview of current microplastic removal techniques.

A. Filtration Techniques

Filtration systems are the most commonly employed methods for removing microplastics from water. Membrane Bioreactors (MBRs) are one of the most effective techniques, achieving microplastic removal rates of over 99%, which is higher than traditional methods such as the Activated Sludge Process (ASP), which typically removes around 98% of microplastics [30], [31].

Advanced filtration technologies, including Ultrafiltration (UF) and Reverse Osmosis (RO), are highly effective for capturing microplastic particles. RO systems, operating under high pressure, can remove up to 99.9% of microplastics, particularly when combined with pre-filtration processes like UF [32].

Dynamic Membranes (DMs), which use a secondary filtration layer formed by fouling particles, offer another promising approach. Studies have shown that DMs can reduce water turbidity to less than 1 Nephelometric Turbidity Unit (NTU) in just 20 minutes, making them highly efficient for wastewater treatment [33].

Disc filtration systems, sand filtration, and other physical filtration techniques have also been shown to remove up to 97% of microplastics, particularly in Wastewater Treatment Plants (WWTPs). While these methods are effective for larger particles, smaller microplastics (less than 100 micrometres) often require more advanced techniques such as UF or RO [34], [35].

B. Hybrid Treatment Technologies

Hybrid systems, which integrate physical, chemical, and biological methods, have shown the greatest promise for microplastic removal. Membrane Bioreactors (MBRs), when combined with Electrocoagulation or Advanced Oxidation Processes (AOPs) like Fenton reactions and photo-Fenton degradation, can remove over 99% of microplastics. These chemical reactions help break down microplastic particles, allowing filtration systems to capture even smaller fragments [36], [37].

Hybrid systems that combine Ultrafiltration (UF) with chemical treatments, such as coagulation, are also widely used. For example, adding Polyacrylamide (PAM) to iron-based coagulants increases the removal efficiency of polyethylene (PE) microplastics from 13% to 91% [38]. Studies comparing multiple advanced filtration methods, including Disc Filters, Rapid Sand Filtration (RSF), and Dissolved Air Flotation (DAF), found that hybrid systems integrating MBRs consistently outperformed others in terms of efficiency [39].

C. Biological and Green Treatment Methods

Biological methods represent an eco-friendly alternative for microplastic removal. Biosorption and biodegradation are two prominent strategies. Certain microorganisms, such as the algae Pseudokirchneriella subcapitata, have shown adsorption efficiencies as high as 94.5%, while Fucus vesiculosus, a species of seaweed, improves microplastic adhesion through the production of alginate compounds [40], [41].

Bacterial degradation is another area of interest, with bacteria like Zalerion maritimum and Bacillus cereus being investigated for their ability to degrade plastic polymers. Although biological methods are slower than physical filtration techniques, they provide a sustainable, long-term solution to microplastic pollution. Membrane Bioreactors (MBRs) that incorporate biodegradation with physical filtration have been found to remove over 70% more microplastics than traditional systems [42].

D. Chemical Treatment Methods

Chemical treatments, such as oxidation, coagulation-flocculation, and photocatalysis, have emerged as effective methods for microplastic removal. Fenton reactions, which use hydrogen peroxide and iron catalysts, and photo-Fenton degradation, have shown significant promise in breaking down microplastics into smaller fragments that can then be removed through filtration [43], [44].

The coagulation-flocculation process, which involves aggregating small plastic particles into larger clusters, has proven particularly effective for microplastics that are difficult to filter directly. Studies have shown that adding iron-based coagulants and PAM to water treatments can significantly enhance the removal of small microplastics like polyethylene [38], [45].

E. Challenges and Future Directions

While current technologies for microplastic removal are effective, several challenges remain. Smaller microplastics, particularly those less than 100 micrometres in size, are difficult to capture, even with advanced filtration techniques like Ultrafiltration (UF) and Reverse Osmosis (RO). Moreover, the high operational costs and energy demands associated with these technologies limit their large-scale application [46].

Future research should focus on optimizing hybrid systems that combine the strengths of physical, chemical, and biological treatments. Developing novel membrane materials and improving dynamic membrane (DM) technology will be crucial to reducing energy consumption and improving scalability. Additionally, there is growing interest in the recycling and reuse of membrane materials to minimize environmental impact [47], [48].

Efforts to improve membrane recycling, as demonstrated by projects like LIFE+ TRANSFOMEM, which recycles used Reverse Osmosis (RO) membranes into Nanofiltration (NF) membranes, offer a promising route for reducing waste from membrane technologies [49]. Moreover, emerging bio-based polymers for membrane production offer further environmental benefits, potentially reducing reliance on petrochemical-based products [50].

V. ROV DESIGN

Remotely Operated Vehicles (ROVs) have emerged as essential tools for various underwater tasks, such as exploration, environmental monitoring, and sample collection. These unmanned vehicles allow operators to access and interact with underwater environments in real time, eliminating the need for direct human involvement in hazardous conditions. The design of an ROV encompasses several important factors, including structural integrity, propulsion systems, control electronics, communication methods, and functional adaptations for specific applications.

A. Structural Design and Waterproofing

ROV design begins with a robust structural framework capable of withstanding high underwater pressures while maintaining waterproofing for sensitive electronic components. In the work by Vu Minh Hung et al., a 6-DOF underwater robot was designed using PVC pipes mounted on an aluminium frame, with electrical connections protected by submersible plugs. The robot can operate effectively at depths with the aid of a compartmentalized hull structure [51]. Other designs, such as those by Fowles et al., incorporate acrylic enclosures sealed with Weld-On 4 adhesives for waterproof integrity, enabling operation at depths of up to 30 meters [52]. For deeper underwater missions, materials like PVC with steel reinforcement, calculated to endure pressures at 1724 kPa, enable ROVs to operate safely at depths of 100 meters [53].

B. Propulsion and Mobility

Propulsion systems are critical for the mobility and manoeuvrability of ROVs. Brushless motors are widely used for their high thrust-to-weight ratio and efficiency in underwater environments. A cost-effective design uses 4500 KV brushless motors arranged in a four-thruster configuration to enable full movement along the x, y, and z axes, allowing depth control and directional movement [52]. In more advanced ROVs, six brushless motors are controlled by PID controllers with pulse-width modulation (PWM), which enables precise motor control for complex underwater navigation [53]. The hybrid fuzzy P+ID controller, proposed by Vu Minh Hung et al., significantly improves stability in pitch and yaw, crucial for maintaining accurate movements in challenging underwater environments [51].

C. Control Systems and Electronics

Modern ROVs rely on powerful and compact control systems to manage real-time video transmission, motor control, and sensor data processing. Raspberry Pi boards are commonly used due to their low cost and high processing power. For instance, a design by Fowles et al. uses a Raspberry Pi 3 to capture real-time video at 42 frames per second and control the propulsion and sensor systems via an Ethernet connection [53]. Similarly, the underwater robot SILVER2 employs a ROS (Robot Operating System) to coordinate its legged locomotion and sampling functions, demonstrating the flexibility and scalability of this control architecture for research-oriented applications [54].

D. Communication and Data Transmission

Effective communication between the ROV and the operator is vital, particularly in remote or deep-sea environments where radio signals attenuate quickly. Acoustic communication has proven to be the most reliable method for long-distance underwater transmission. As noted by Vu Minh Hung et al., the optimal frequency range for underwater communication lies between 8 to 16 kHz, allowing robust data transmission over several kilometres [51]. Acoustic transducers like the ITC-3013 used in these systems can generate acoustic signals at power levels up to 330W, ensuring stable communication even in noisy underwater environments [51]. In contrast, electromagnetic and optical communication, although capable of higher data rates, are limited to shorter distances and clearer waters [5].

E. Sampling and Application-Specific Designs

ROVs can be tailored for specialized applications such as environmental sampling, particularly in studies involving microplastic pollution. SILVER2, a legged underwater robot, is designed to collect sediment samples from the top 5 cm of the seabed with minimal disturbance, an important capability for ecological assessments [54]. The robot's legs provide stability on uneven terrain, while its sampling mechanism can store multiple sediment samples in a single mission. This capability makes it well-suited for monitoring microplastic distribution in various water bodies [56]. Another study by Karbalaei et al. highlights the use of ROVs equipped with rotating brushes and filtration systems for the collection and analysis of microplastics from sea beds and water columns, further emphasizing the adaptability of ROVs for environmental purposes [56].

F. Cost-Effective Approaches

Designing cost-effective ROVs without compromising functionality is a priority in many research and educational institutions. A prime example of this is the use of 3D-printed components made from Polylactic Acid (PLA), reducing manufacturing costs while maintaining structural integrity. Open-source electronics, such as the Raspberry Pi, further reduce costs while enabling sophisticated features like real-time video capture and motor control [52]. The affordability of these systems makes them accessible to a wider range of researchers and students, encouraging the development of underwater technologies for scientific exploration and environmental monitoring.

VI. UNDERWATER COMMUNICATION

Underwater communication is a critical enabler for various applications such as environmental monitoring, marine research, and autonomous underwater vehicles (AUVs). The primary methods of underwater communication include acoustic, electromagnetic (EM), and optical waves, each with its strengths and limitations.

A. Acoustic Communication

Acoustic waves are the most widely used method for long-range underwater communication. Acoustic signals can travel up to several kilometers, with a speed of about 1500 m/s in water. However, they have low data transmission rates, typically up to 20 kbps, and are affected by factors such as signal multipath propagation, reverberation, and the underwater environment's varying conditions like temperature and salinity [57], [58].

Recent advances in acoustic modems, particularly the S2C series developed by Evologics, utilize Sweep-Spread Carrier (S2C) technology to handle multipath propagation and Doppler shifts more effectively [59]. The S2C modems are capable of measuring channel characteristics like signal-to-interference ratio (SIR) and multipath intensity profiles, which are critical for evaluating communication performance in real-world environments [60]. Experimental trials with these acoustic modems during the NATO CommsNet13 sea campaign demonstrated the challenges of maintaining signal integrity and managing multipath arrivals in underwater acoustic channels [59].

Additionally, these modems have shown improved performance in reverberant environments, allowing for accurate propagation time measurements that enhance clock synchronization between modems during data exchange [61]. Despite these advancements, acoustic communication is still limited by significant signal attenuation over long distances and environmental factors such as water depth and salinity [57].

B. Electromagnetic Communication

Electromagnetic (EM) waves, while offering higher data rates compared to acoustic communication, are significantly attenuated in water, especially saltwater, limiting their effective range to a few meters [62]. EM waves are better suited for short-range communication, often used in shallow waters or near the surface where data rates can reach up to 10 Mbps. However, the energy required for EM communication and the rapid attenuation in conductive saltwater environments pose challenges to its widespread use in deep-sea applications [62].

C. Optical Communications

Optical communication provides the highest data rates among underwater communication methods, with data rates reaching several Gbps. This method is best suited for short-range applications, typically within 100–200 meters in clear water environments. The primary limitation of optical communication is the rapid absorption and scattering of light in water, particularly in turbid environments where particles in the water can distort and weaken the optical signals [63]. Advances in underwater wireless optical communication (UWOC) have focused on maintaining reliable connections between mobile AUVs and surface vessels. For instance, a proposed optical wireless communication system utilizes a cone-shaped beam to maintain a line-of-sight link between an AUV and a surface ship, ensuring data transmission with low bit error rates despite background noise and environmental challenges [64].

D. Hybrid Communication Systems

Hybrid communication systems, which combine acoustic, EM, and optical technologies, are emerging as a solution to overcome the limitations of individual methods. By leveraging the strengths of each technology—acoustic for long-range, optical for high data rates, and EM for short-range, low-latency applications—hybrid systems can provide more reliable communication networks for underwater robotics and sensor systems [63]. For instance, a hybrid system using acoustic communication for long-distance transmissions and optical communication for high-bandwidth short-distance communication has been shown to improve the performance of underwater sensor networks and AUVs [64].

In summary, while significant advancements have been made in underwater communication technologies, challenges related to signal propagation, synchronization, and environmental conditions remain critical areas for ongoing research and development.

VII. CONCLUSION

The widespread presence of microplastics in aquatic environments presents a multifaceted threat that extends beyond ecological disruption, with implications for public health and global environmental sustainability. This review has critically examined current methods for the detection, monitoring, and removal of microplastics, while also exploring the technological advances in ROV design and underwater communication systems that support these efforts. Advances in detection, particularly real-time monitoring technologies, have improved our capacity to track microplastics, but significant challenges remain, especially in detecting smaller particles and addressing the limitations posed by environmental conditions. Similarly, while filtration and hybrid treatment systems show considerable promise for microplastic removal, issues of scalability and operational cost continue to hinder widespread implementation.

The use of ROVs has expanded our ability to conduct underwater research and environmental monitoring in challenging environments, while new developments in underwater communication technologies have enhanced the transmission of data necessary for effective control and analysis. However, the next phase of research must focus on integrating these approaches to create more robust, energy-efficient, and scalable solutions. Future innovations should concentrate on developing hybrid systems that combine the strengths of various detection, removal, and monitoring methods, while ensuring cost-effectiveness and operational efficiency. By addressing these key challenges, future work can pave the way for more comprehensive strategies to mitigate the global issue of microplastic pollution, protecting both aquatic ecosystems and human health.

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