Indian Journal of Geo Marine Sciences
Vol. 54 (12), December 2025, pp. 643-655
DOI: 10.56042/ijms.v54i12.23277

Review Article

Marine pollution: Advances in tracking, monitoring, and mitigation strategies for ecosystem restoration

A Fathima*[,a] & A Ayoob[b]

[a]Department of Biosciences, MES College Marampally, Mahatma Gandhi University, Aluva, Ernakulam, Kerala – 683 105, India

[b]Department of Public Health Dentistry, Amrita School of Dentistry, Amrita Vishwa Vidyapeetham, Kochi, Kerala – 682 041, India

*[E-mail: abyfathima@gmail.com]

Received 31 August 2025; revised 20 November 2025

Marine pollution has become a serious threat to oceanic ecosystems, biodiversity, and the livelihoods of people depending on the sea. This paper discusses the major sources of water contamination, which include land-based runoff, oil spills, chemical dumping, and emerging issues such as microplastics. The consequences of pollution for marine species and humans are also reviewed. Recent advances in sensor technology, forensic pollution analyses, and other innovative methodologies that facilitate the detection and assessment of contaminants and their impact on the environment are presented. Particular attention is devoted to modern treatment and management strategies, including waste reduction policies, mangrove restoration, bioremediation, biodegradable materials, and coral reef conservation. However, technological improvements are not sufficient to solve the problem, which requires multidisciplinary interventions at local and global levels. Awareness, engagement, and education of the general public and better governance are critically important to ensure effective action. Marine pollution is especially acute in coastal and developing countries, where urbanization, improper waste disposal, and inadequate surveillance infrastructures aggravate the effects of contaminants. Technological innovation, combined with sustainable and resilient practices, regulatory frameworks, and community participation, can help achieve the goal of effective pollution management and conservation of natural resources for future generations. Addressing this complex issue requires collaborative and multidisciplinary efforts on the part of scientists, governments, private industries, and communities.

[**Keywords**: Ecosystem, Marine pollution, Mitigation strategies, Monitoring, Tracking]

Introduction

Approximately 70 percent of Earth's surface is covered by oceans, which make up an important component of our biosphere. Oceans have many functions for regulating Earth's climate and for supporting biodiversity and livelihood of billions of people[1]. However, today marine ecosystems suffer from anthropogenic influences; among them, pollution is the key threat for the survival and resilience of these ecosystems to environmental impacts[2]. To address marine pollution, there should be not only environmental actions but also a complex approach combining ecological, social, economic, and political aspects of the problem[3]. Pollution does not affect marine ecosystems in isolation from other anthropogenic influences; rather, sometimes its effects become intensified in combination with others such as overfishing, unsustainability of marine resources harvesting, habitat loss, natural disasters, disease, and invasion by exotic species[4]. All these threats can change ecosystem structure and weaken its functioning.

Aligned with global priorities, the central developmental framework addressing marine pollution is Sustainable Development Goal 14 (*Life Below Water*), which calls for the conservation and sustainable use of oceans, seas, and marine resources to support sustainable development. Specifically, Target 14.1 seeks to prevent and significantly reduce all forms of marine pollution by 2025, with particular emphasis on tackling pollution originating from land-based activities such as marine debris and nutrient runoff[5].

Globally, it is estimated that up to 80 % of marine pollution originates from land-based sources. Agricultural runoff is a key driver of nutrient loading in coastal waters[6]. The Gulf of Mexico's so-called "Dead Zone", one of the largest hypoxic zones in the

world, is an alarming example of how excess nitrogen and phosphorus fertilisers from farmlands can trigger algal blooms that deplete oxygen levels and devastate marine life[7]. Similarly, urbanisation and poor solid waste management have produced shocking examples like the Great Pacific Garbage Patch a massive accumulation of plastic debris in the North Pacific Gyre that is estimated to cover an area twice the size of Texas[8].

In recent decades, research on marine pollution has evolved well beyond the traditional focus on oil spills, radioactive waste dumping, and chemical discharges. Recent research has expanded our understanding of marine pollution beyond traditional contaminants. Microplastics, pharmaceuticals, personal care products, pesticides, endocrine-disrupting chemicals, and complex mixtures of pollutants are now receiving increasing attention because their effects on marine organisms and ecosystems are not yet fully understood[9]. At the same time, researchers are using more advanced methods to track and monitor these pollutants. Remote sensing, in-situ sampling, and molecular techniques are helping scientists identify pollution pathways and assess environmental changes with greater speed and accuracy[10].

Plastic pollution is undoubtedly among the most extensive types of environmental pollution. Annually, approximately 8 million metric tons of plastics are added to oceans worldwide. This quantity may be represented by a garbage truck filled with plastics entering the ocean each minute[11]. With the degradation of large plastics, microplastics occur, which may remain suspended in water and get deposited in sediments as well as ingested by marine animals[12]. Microplastics were identified even in deep ocean trenches and Arctic sea ice[13].

Marine pollution adversely affects humans' well-being since its consequences extend far beyond ecosystems[14]. Coastal populations are especially prone to suffering the adverse effects of pollution, as many rely on the sea for their food, work, earnings, and leisure time[15]. Marine pollution may compromise the safety of seafood, introduce toxins and pathogens into the food chain, impact fishing and aquaculture production, and negatively influence tourism, etc.[16].

Effective monitoring and pollution control techniques are essential to solving these problems. The use of remote sensing, in-situ monitoring networks, and autonomous systems may assist in the identification of the pollution events and sources. In addition, solutions such as biodegradable materials, improved waste management, bioremediation, and innovative water treatment methods are also applicable[17].

It is obvious, however, that the use of technology alone is not enough. Environmental policies and regulations, the involvement of the industry and community are crucial for solving the problem as well. Bringing all these factors together would allow improving prevention and response to pollution, enhancing the resilience of marine ecosystems and protecting oceans and the resources they contain for future generations.

Methodology

A literature search was done in PubMed and Google Scholar databases for literature published from 2010 to 2025 using the following keywords: "marine pollution", "tracking", "marine monitoring", and "restoration". The preliminary search resulted in 3,530 papers. Title and abstract screening was carried out to eliminate duplicates, followed by full-text screening. Inclusion criteria for articles are listed below: (i) relevant to marine pollution tracking, monitoring, and restoration; (ii) published in English; (iii) full text available. A total of 68 articles are selected for review.

Sources and types of marine pollution

Marine ecosystems are among the most biologically diverse and productive environments on Earth. They provide habitat for countless species, regulate carbon and nutrient cycles, and act as buffers against extreme weather events. However, these ecosystems are increasingly threatened by a wide array of pollutants introduced through human activities.

Land-based pollution

Marine pollution occurs as a result of land-based activities whereby the contaminants get to the sea via water currents or drainage systems. Agricultural practices are significant contributors to pollution in the ocean. Fertilizers, pesticides, and animal manure get to the water systems then to the coastal waters. Nutrients especially nitrates and phosphates facilitate the growth of algae in a process known as eutrophication. As the algae die, the levels of oxygen in the water reduce to such an extent that the living things cannot get enough to sustain their lives. There are more than 400 cases of such zones reported in various parts of the world[18].

Urbanization and industrialization are other factors contributing to marine pollution. Raw sewage from homes and industries, as well as untreated stormwater runoff, transport disease-causing pathogens like E. coli, Vibrio Cholera and Salmonella bacteria in water systems and to the coast where people use the water. Wastewater from industrial operations may contain harmful heavy metals such as mercury, cadmium, and lead, and organic pollutants such as polychlorinated biphenyls (PCBs) in marine environment[19]. Such substances build up in the marine creatures then get transferred up the food chain leading to high levels of contaminants in marine animals like tuna, swordfish, and whales which in turn pose health risks to humans consuming the seafood.

Oil pollution

Oil spill incidents, whether large-scale accidents or normal operations, remain a serious concern to marine life. As dramatic accidents such as Exxon Valdez (1989) and Deepwater Horizon (2010) attract media attention, the fact that most cases of oil pollution come from small incidents, namely oil shipping, bilge discharge, pipelines leakage, and runoffs is often overlooked. Oil contamination causes insulation problems for birds and mammals, whereas toxic hydrocarbons may poison fish and invertebrates as well as coastal vegetation[20].

Plastic pollution

Plastics make up the bulk of marine debris that people can actually see. Plastic litter from shopping bags, discarded fishing lines and gear, micro-beads, and synthetic fibres finds its way into the ocean via rivers, storm sewers, direct dumping, and even through atmospheric deposition. Due to their resistance and slow degradation process, plastics can last in the marine environment for hundreds of years. Turtles, birds, and marine animals mistake plastic litter for food or become entangled in old fishing nets resulting in serious injuries or even death[21].

Radioactive pollution

Despite being a rare source of marine contamination compared to others, radioactive pollution may cause serious and lasting effects. Sources of radioactive pollution include nuclear power plants, hospitals, and historic nuclear weapons' testing sites. Radioactive compounds may be accumulated in sediments and organisms and may later reach the human food chain through infected shellfish and predatory fish[22].

Thermal and noise pollution

Thermal pollution is often related to industrial plants where warm water is used for cooling purposes. Even a slight change in water temperature may affect the distribution, reproduction, metabolism, and viability of temperature-sensitive marine creatures. The problem of noise in underwater environment becomes more serious each year because shipping, seismic surveys, offshore constructions and some other human activities create long-lasting and loud noises which prevent marine mammals and fish to communicate, navigate, feed themselves and reproduce[23] (see Fig. 1).

Cumulative impact of these various types of pollution is significant. Some pollutants may depress immunity and reproduction of marine organisms and affect the food web interactions, together with other environmental stresses. Coral reefs which suffer from sea temperature increase and acidification of oceans can experience additional stresses in the form of sediments and chemical contamination. Mangroves and salt marshes which play an important role in protecting shorelines from erosion and functioning as nursery areas for many species, can be damaged due to oil pollution and runoff[24]. These problems affect not only the life in oceans but also fisheries, coastal communities, food safety and living of people depending on the healthy ocean[25]. Knowledge of ways of pollutant's entrance into the marine ecosystems, their movements and accumulation is therefore necessary to develop integrated strategies of prevention, monitoring and mitigation of the pollution[26].

Microplastic pollution: An emerging problem

Microplastics have emerged as one of the most ubiquitous pollutants in the world's oceans and constitute a key focus of environmental studies today. Microplastics may be referred to as plastic particles that are less than 5 mm and can be produced both intentionally and unintentionally from larger plastic products. They have been found in many marine locations, such as polar sea ice and deep sea trenches[27].

Microplastics may be classified as primary and secondary microplastics. Primary microplastics are artificially produced particles for special purposes. These include microbeads formerly utilized in personal care products as well as abrasive microplastics[28]. There are efforts made to regulate the production and use of microbeads. For example, the

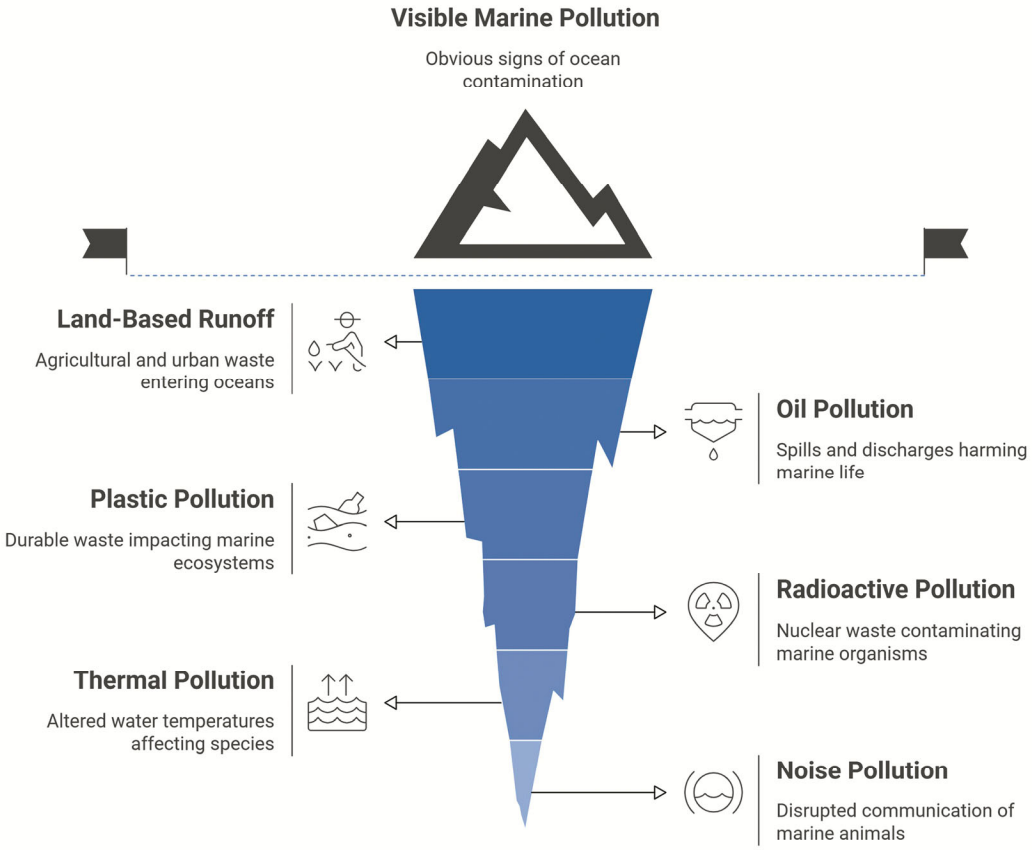


Fig. 1 — Major sources and types of marine pollution

U.S. Microbead-Free Waters Act of 2015 was a crucial piece of legislation passed by the United States to limit their use[29].

Secondary microplastics emerge as a result of disintegration of larger plastic products through exposure to sunlight, mechanical forces and other environmental factors. The most common sources of secondary microplastics include discarded packaging materials, fishing equipment, textile products, and tire wear[30]. According to estimations, millions of tons of plastic are dumped into the oceans every year. A considerable part of them is broken down into secondary microplastics[31]. Because of low weight and longevity of plastic materials, microplastic particles can travel vast distances across the ocean and atmosphere[32]. Their presence in Arctic sea ice and deep-water locations more than 10,000 meters deep illustrates their ubiquity[33].

Ecological and human health implications

Microplastics may have an effect on marine life at various trophic levels. Zooplankton might consume plastic particles since the latter resemble their natural food. Thus, they impair the feeding, development, and reproduction of zooplanktons and, consequently, organisms that rely on zooplankton as a source of food[34]. Filter-feeding species, such as mussels, oysters, and clams, are prone to the effect since they filter significant amounts of water constantly. Microplastics have been found in commercially valuable shellfish, posing a dietary threat to those who eat seafood[35]. Some estimates state that regular consumers of shellfish may ingest thousands of microplastics annually[36]. The impact of microplastics is not restricted only by their physical presence. Microplastics' surfaces may interact with chemicals present in the sea water, namely, PCBs, PAHs, and pesticides[37]. In addition, microplastics may serve as a surface for microorganisms to attach and move around with water. When consumed, chemicals might be released under the influence of conditions in the digestive system of animals and contribute to the contamination[38]. There is also information on the inflammatory and endocrine-related impacts of

microplastics on certain marine species. The effect on humans requires further investigation but includes gastrointestinal issues, chemical contamination, and possible reproductive and metabolic effects[39].

Monitoring, research, and policy response

The identification of the sources of pollution, their migration, and locations where particles accumulate is an important prerequisite to comprehending microplastic pollution. Monitoring programs have begun to investigate microplastics in seawater, beaches, sediment, and marine life. Methods like FTIR and Raman spectroscopy can be used to distinguish various types of plastic and characterize microplastics isolated from environmental samples[40].

There has also been an increase in policy actions. The EU Strategy for Plastics in a Circular Economy set out policy steps to help limit plastic waste and minimize plastic leakage into the environment. Countries such as Canada, the UK, India, and New Zealand have initiated measures to prohibit microbeads and particular single-use plastic products. But the increase in global production of plastic is a formidable problem[41]. However, improvements are always possible and public participation plays an important role in this matter. Citizen science and beach cleaning programs will not only gather information about the scope of the issue and types of plastic pollution but raise people's awareness. The International Coastal Cleanup program has inspired people to take action by registering for the cleanup of marine debris. Responsible consumption, segregation, and recycling of waste in addition to other materials as alternatives to conventional plastic waste will be useful in this respect.

Toward solutions

Prevention of microplastics from being deposited into the sea necessitates interventions on multiple fronts, ranging from plastic production and usage to wastewater treatment and waste management practices. Upgrading wastewater treatment facilities, using membrane treatment techniques and other forms of filtration could allow for the interception of microplastic particles prior to their discharge into rivers and coasts[44]. One promising area of bioremediation research involves the search for bacteria, fungi, and enzymes capable of breaking down some plastics.

However, no single intervention would be enough. Interventions such as reduced production of plastic when possible, product redesign, enhanced waste management and recycling efforts, increased consumption sustainability, regulation, among others should all play a part. The combination of all of these actions with efficient monitoring and engagement of communities would provide a more realistic approach to mitigating microplastic leakage[45] (Fig. 2).

Tracking and monitoring marine pollution

Effective management begins with knowing where pollution comes from, how it moves, how much is present, and what effects it has on marine ecosystems. Reliable monitoring data help researchers understand contamination patterns and allow policymakers and environmental agencies to assess whether control measures are working[46]. Advances in monitoring technologies over the past two decades have expanded the ability to observe marine pollution across both large and difficult-to-access areas.

Traditional in situ sampling

Direct sampling remains an important part of marine pollution monitoring. Researchers collect water, sediment, and biological samples and analyse them in laboratories for chemical, physical, and biological indicators. These methods can be used to measure contaminants such as heavy metals, petroleum residues, nutrients, microplastics, and pathogens[47]. Although in situ sampling provides detailed information from specific locations, it can be time-consuming and expensive when large areas need to be surveyed.

Remote sensing technologies

Remote sensing systems have greatly increased our ability to monitor large areas of the oceans, beyond the capability of ship-based observations to identify any environmental anomalies. Through remote sensing from high altitudes, one can easily detect oil slicks, algal blooms, murky water masses, and discrepancies in surface temperature of the sea[48]. The Synthetic Aperture Radar (SAR) proves useful in tracking activities such as oil spills because it operates on all-weather and around-the-clock basis and does not get affected by weather or light conditions. In addition to SAR, multispectral and hyperspectral sensors make it possible to detect particular biochemical factors such as chlorophyll and others related to algal blooms and changes in water quality[49].

Remote sensing satellites, such as the NASA Aqua satellite with its Moderate Resolution Imaging Spectroradiometer (MODIS) system, are crucial in

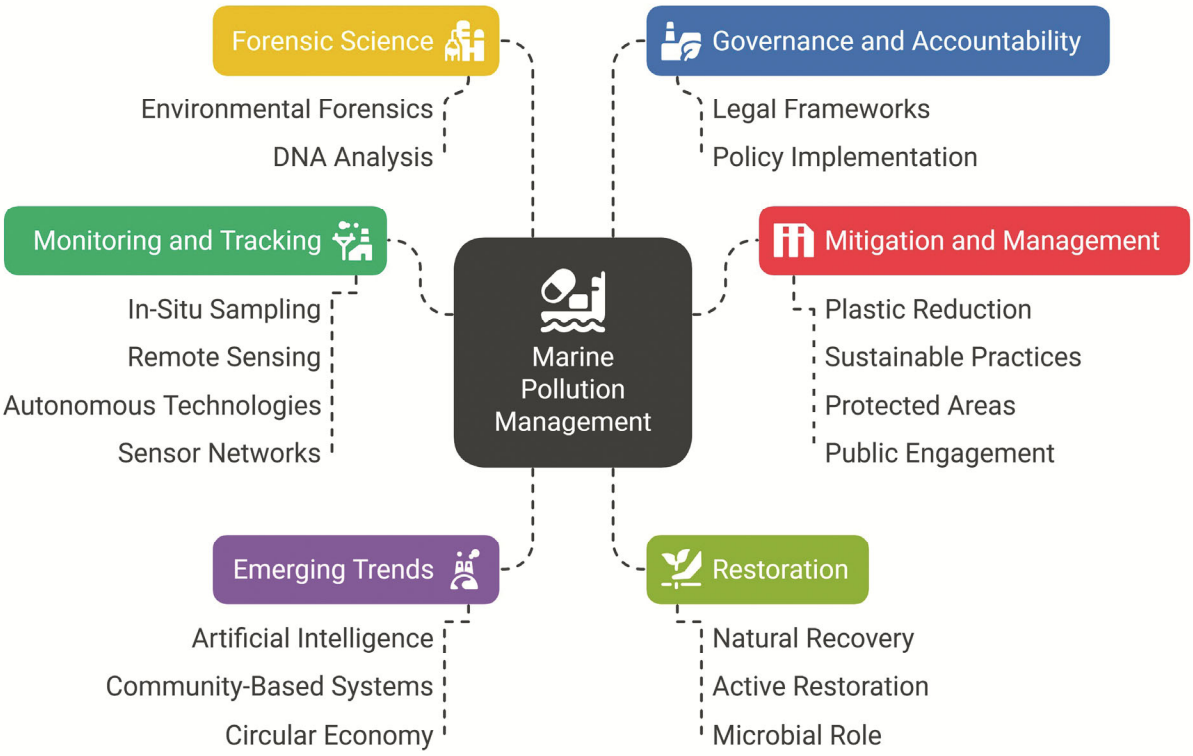


Fig. 2 — Future strategies for microplastic mitigation

recognizing harmful algal blooms and monitoring changes in the coastal regions[50]. Remote sensing, even though highly efficient in detecting surface pollution and oceanographic changes, is limited by some technical factors that make the process impossible to conduct. The sensors can detect only the topmost layer of the ocean; hence they cannot be used to detect pollutants buried within the sediments[51].

Autonomous and robotic technologies

The use of autonomous and robotic technology is improving the possibility of observing the oceanic environment that proves difficult with respect to logistics, safety, or costs for traditional research techniques. AUVs and ROVs have sensors for monitoring oceanographic parameters such as temperature, salinity, dissolved oxygen, turbidity, and certain contaminants at various depths of water. The use of these sensors is supplemented by profiling floats used in projects like Argo to observe the physical and biogeochemical properties of oceans[52].

The ocean glider is another innovative technology being employed in autonomous ocean monitoring. By altering buoyancy, they propel themselves in both horizontal and vertical directions, thus reducing their energy consumption. Due to their endurance and autonomous nature, they prove extremely useful in geographically distant locations like polar regions and deep sea areas[53].

Fixed sensor networks and real-time monitoring

Infrastructure of fixed sensors, which are part of buoys, moorings and coastal observatory systems, provides for continuous monitoring of the environment. Stationary stations accommodate different types of sensors, which allow monitoring the variables such as temperature, pH level, level of dissolved oxygen, nutrients' concentration, and turbidity. When the information is provided in real time, unusual situations like the cases related to harmful algal bloom, chemical discharges and oil spills can be detected in time, which allows authorities to conduct necessary investigations[54].

Additional sources of information on the issues connected with the pollution of the marine environment are provided by citizen science programs. The participants of these programs use special applications, such as Marine Debris Tracker, to provide information regarding marine debris, pollution incidents and other ecological phenomena[55].

Integrating data and new frontiers

New avenues for monitoring maritime pollution have been made possible by the rise of big data and Artificial Intelligence (AI). Machine learning algorithms are quicker and more accurate than traditional methods alone, and they can identify pollution hotspots and predict contamination trends by analysing large datasets from satellites, sensors, and field samples[56]. AI models, for instance, can predict how oil slicks will spread depending on wind and ocean currents, enabling more efficient containment and cleanup efforts. Blockchain technology is being tested to enhance plastic waste traceability, ensure supply chain accountability, and promote ethical waste management[57]. There are still issues despite these technological advancements. Funding and infrastructure for long-term monitoring projects are still lacking in many areas. Standardisation and data sharing are essential for facilitating cross-border collaboration, especially when it comes to transboundary environmental problems like plastic waste that is transported from one country's coast to another by ocean currents[58]. The best course for reliable marine pollution monitoring is to combine conventional techniques, state-of-the-art technologies, and community involvement. The capacity to identify, monitor, and react to pollution in real time will be essential for safeguarding marine ecosystems and the communities that rely on them as environmental stresses increase.

Emerging trends and technologies

The rapid advancements in data science and technology have opened previously unexplored opportunities to transform the way we observe, understand, and address marine pollution. In addition to improving detection and response capabilities, these technologies enable communities and politicians to make well-informed decisions based on up-to-date evidence.

Artificial intelligence and machine learning

Artificial intelligence (AI) and machine learning (ML) are transforming the methodologies employed in monitoring and interpreting marine pollution. The conventional way usually required the extensive manual processing of oceanographic and environmental data sets that could take weeks or even months to complete. With the use of AI, the process becomes faster as this technology allows for the quick analysis of large-scale and multi-dimensional data sets obtained with the help of satellites, unmanned aerial and underwater vehicles, drones and distributed sensors to identify patterns and predict pollution accidents[59].

With the help of the AI algorithm, one can analyze the satellite imagery and distinguish between the oil spillages and natural phenomena like seaweed concentrations and algae blooms. Besides, machine learning allows predicting the movement of the marine garbage using information about ocean currents, tides and wind patterns. Such a prediction makes it possible to plan better the process of oil spills containment and remediation[60]. The same progress is made in the field of monitoring of the microplastics. Using image recognition with the help of AI, scientists can automatically classify microplastics based on their morphology, size distributions and polymer composition[61].

Low-cost and community-based monitoring systems

With the advances in affordable technology, the monitoring of pollution is becoming increasingly possible. Community-level initiatives will allow members of the local communities, including students and citizens themselves, to become active participants in the process of observing the environment[62]. The inexpensive sensors may monitor key parameters such as pH level, turbidity, and water temperature in the coastal waters, rivers, and estuaries thus allowing tracking changes in the water quality. When connected to the cloud system, the data collected will be available for use by researchers, regulators, and the public at large[63].

The example of such tools includes the Marine Debris Tracker application, as well as such projects as Global Ocean Observing System. These approaches do not only help collect additional data but raise the environmental awareness among people and allow them to take a more active part in protecting their environment[64].

Bioremediation and green technologies

The tracking of pollution is merely one of many concerns facing researchers. Alternative methods of reducing contamination are being studied, as well. An example of such an effort involves the use of biological processes to reduce or eliminate pollution via the use of living organisms, including bacteria, fungi, and algae, in a process known as bioremediation[65].

These organisms are able to attack such contaminants as petroleum hydrocarbons, heavy

metals, and organic pollutants. Certain types of bacteria that are capable of consuming oil could be used to assist in the decomposition of petroleum hydrocarbons released into the water due to oil spills, for example. The ability of microbes and enzymes to digest plastic waste is currently being researched by scientists. Experiments in laboratories with the use of genetically engineered bacteria to break down PET have demonstrated some promising results[66].

Circular economy and product innovation

Preventing pollution at the source is equally important. The shift towards a circular economy system seeks to delink economic growth from higher material input. This involves using materials for as long as possible through processes such as reuse, repair, recycle, and better design[67]. Researchers and industries are working on alternative biodegradable packing materials and other compostable products that replace some plastics. Moreover, there is a growing interest in developing materials through mechanistic understanding for subsequent use and recycling.

Meanwhile, new recycling technologies capable of addressing the challenges presented by current approaches are also being explored. For example, chemical recycle technologies can break plastics into chemical building blocks. Furthermore, pyrolysis processes can be used to generate transport fuels and other products from plastic waste[68].

Integrating forensic science in pollution source identification

Identifying where marine pollution comes from is often difficult, particularly when contaminants have travelled long distances before being detected. Environmental forensic methods are increasingly being used to trace pollutants back to their sources. Techniques originally associated with criminal investigations are now helping scientists investigate environmental contamination and provide evidence that can support regulatory action.

Environmental forensics: tools and techniques

Environmental forensics involves the use of a number of approaches including molecular markers, stable isotope analysis, chemical fingerprint, and DNA-based methods[69]. For example, the chemical fingerprint of hydrocarbon pollutants can be compared to that of suspected sources based on their unique mixture of characteristic hydrocarbons and trace metals[70]. On the other hand, stable isotope analysis can be used to differentiate between natural and man-made materials. For example, the nitrogen and phosphorus isotope composition can be used to establish the source of nutrient pollution in coastal waters[71].

DNA analysis and marine forensics

Genetic methods are also expanding the role of forensic science in marine environmental research. DNA barcoding can help identify marine species affected by pollution, even when only small tissue samples or fragments are available[72]. Environmental DNA, or eDNA, provides another useful approach by detecting genetic material that organisms leave behind in water or other environmental samples. Comparing eDNA collected before and after a pollution event can help researchers identify changes in species presence and assess possible ecological damage. This information can support decisions about restoration and long-term ecosystem monitoring[73].

Supporting governance and legal accountability

Environmental forensics can also be used to enforce regulatory policies. Proof that connects environmental pollutants to a specific ship, facility, or action makes it easier for the regulatory agencies to assign responsibility and avoid passing on the cost of cleanup to taxpayers[74]. The use of forensics in environmental monitoring would lead to better databases of pollution information, prevent illegal dumping of pollutants, and make industries accountable for their environmental performance.

Mitigation and management

Improved monitoring will help us to know what the sources of pollution are, how the pollution is being spread, but ultimately, real change lies in decreasing pollution at the source[75].

Reducing plastic use and improving waste management

Decreasing the quantity of plastic that enters the waste stream is a very practical method for reducing marine plastic pollution. Regulations limiting the production of unnecessary single-use plastics, coupled with the adoption of more sustainable, reusable and compostable products, can be helpful in preventing the leaking of plastic materials[75]. Efficient waste management is also very critical. Inadequate waste management systems in coastal regions make it possible for large amounts of waste to end up in waterways and finally reach the oceans[76].

Sustainable industrial and agricultural practices

In addition to reducing pollution from chemicals and nutrients, efforts are required from agriculture and industries. Precision fertilization, vegetated buffer strips, and constructed wetlands can help farmers reduce nutrient runoff[77]. Improved wastewater management and substitution of harmful substances with safer ones are among the measures that industries can take[77].

Prevention should be the key strategy in addressing oil pollution as well, rather than just cleaning up after the spillage. Safe oil shipping, frequent vessel inspections, double hulls of oil tankers, and efficient contingency plans can help prevent oil spills[78].

Protected areas and ecosystem-based management

MPA's could contribute towards the conservation of biodiversity and offer damaged ecosystems a chance to rejuvenate themselves. This is done through the limiting of certain human activities that place pressures on marine environments, including oil exploration, dredging, and destructive fishing practices[79]. ICZM is more holistic in its approach as it places the government, industry, local community, and scientists under one management scheme. This could assist in reconciling the needs of economic development with conservation of coastal environments and ecosystems[80].

Public engagement and education

However, there is a need for improvement in the long run, and this will require public engagement, specifically, the role of education. In general, education, as well as community and school-based programmes, can ensure that people behave and act responsibly regarding consumption and waste disposal and actively participate in community programmes aimed at restoring the environment. Conducting community activities such as clean-up of beaches, waste analysis and surveillance programmes can promote the involvement of the public in restoration and protection of coastal ecosystems. Moreover, businesses and government can take an active part in tackling the issue of plastic pollution in oceans. Environmental accreditation, eco-labelling and codes of conduct, corporate social responsibility programmes and innovative technologies can all help tackle the negative impact on marine ecosystems. It should be noted, however, that this complex issue needs a comprehensive approach that will take into consideration interaction of communities, businesses, government and science organizations.

Marine habitat recovery and restoration

Although prevention, monitoring, and management are key to preventing pollution in the future, the simple truth is that decades of pollution have caused a lot of damage to marine habitats and they need to be restored. The process of doing so can be very difficult but is absolutely necessary.

Natural recovery *vs.* active restoration

Natural recovery of some marine ecosystems is possible if the pollution sources are identified and reduced, and minimal stress from humans is assured. In such circumstances, rapidly growing coral colonies can colonize damaged reefs in less than ten years if there is improved water quality and a reduction in physical disturbance. Likewise, seagrass meadows and mangroves will naturally recover if there is less sedimentation and improved hydrology. Unfortunately, there is often not enough time allowed for natural recovery to achieve conservation objectives, particularly in habitats such as deep-water corals, salt marshes, and reef communities that take centuries to form.

Techniques for active restoration

The active restoration methods differ depending on the type of ecosystem and its state. Some widely used restoration methods include:

i. *Rehabilitation of Coral Reefs:* Methods like coral gardening and transplantation imply growing coral colonies in a nursery and transplanting them into damaged coral reefs for further recovery. The latest trends in this field include the development of heat-resistant coral strains in order to make coral reefs more resilient to increased sea water temperature[81].

ii. *Mangroves and seagrass bed restoration:* Mangroves and seagrass beds are important ecosystems which protect shorelines and act as nursery grounds for many marine creatures. Restoration methods include planting native species, removal of invasive species, as well as restoring natural water flow through the area[82].

iii. *The creation of artificial reefs:* Artificial reefs made of environment-friendly materials may serve as additional habitats for marine organisms, increasing their biodiversity and fish population while natural reefs restore themselves[83].

iv. *Bioremediation:* In highly polluted environments, some specialized specialised microorganisms may be used for the degradation of toxic substances like oil and heavy metals[84].

Role of microbes in restoration

The rehabilitation of marine ecosystems depends heavily on microbial communities, which are underappreciated. Microbes cycle nutrients, break down organic contaminants, and promote primary productivity. Hydrocarbon-degrading bacteria, for instance, are frequently the first line of defence in oil-contaminated environments, breaking down complex contaminants into simpler, less dangerous chemicals. An emerging tactic is the use of microorganisms through field inoculation and laboratory cultivation. This approach provides a low-cost, low-impact tool for speeding recovery in polluted environments, but it is currently in the experimental stage[85].

Restoration faces numerous obstacles. Lack of funding, technical expertise, or long-term monitoring can all hinder projects. Furthermore, an additional stressor brought on by climate change is that years of restoration progress can be undone in a single catastrophic event due to rising water temperatures, ocean acidification, and bigger storms. However, successful restoration projects around the globe show that when people, scientists, and governments work together, recovery is achievable. Large-scale wetland restoration in the Gulf of Mexico, the Great Barrier Reef's coral nurseries, and the massive mangrove replanting initiatives in Southeast Asia all serve as examples of what may be accomplished with consistent work. Engaging the public is equally vital. Volunteers who take part in local monitoring, debris removal, or replanting develop a sense of care and ownership that supports long-term conservation objectives.

Challenges, limitations, and the way forward

This review points out some significant progress in our understanding of, monitoring and management of marine pollution; however, there remain a number of obstacles yet to be overcome. Evaluations, especially in the developing countries, are hampered by data deficiency, technological discrepancies and the lack of studies of new pollutants. The complex relations between pollution, overfishing, destruction of habitats and global warming create uncertainties in making predictions about the recovery of ecosystems. Even if the restoration processes appear promising, they will be hampered by the lack of financing and global warming.

For progress towards a solution, policies need to link up the local with the global, by ensuring compatibility with goals such as SDG 14, enhancing integrated monitoring involving remote sensing, AI, and citizen science, and promoting community stewardship. By broadening the scope of the circular economy, developing new treatment processes, and using environmental forensics, waste can be further reduced at the source. Through continued efforts, the findings of this review will contribute to the future of healthy oceans.

Conclusion

Oceans, covering 70 % of Earth's surface, regulate climate, generate oxygen, sequester carbon dioxide, and provide sustenance and livelihood to billions of people. Human actions such as pollution, exploitation, and destruction of habitats have put pressure on marine ecosystems. Life in oceans, as well as people living around it, are threatened by pollution in different forms, ranging from noise pollution, thermal pollution, waste pollution, oil pollution, plastics, chemical pollutants, and micro-plastics. In today's world, contaminants can be detected and tracked down with the help of advanced tools, such as satellite imagery, autonomous vehicles, forensics, and big data analytics. However, technology alone cannot solve this problem. The combination of effective waste management, legislation, industrial accountability, and sustainability in production and consumption is a necessary component for the solution. Healing damaged ecosystems is also crucial. The capacity of nature to rejuvenate itself with help from conservation activities on site, microorganism-based cleaning methods, and artificial coral nurseries proves that the healing process is possible with timely and cautious measures. We have to take care of each other. Governments are obliged to dissuade deter pollution and enforce environmental laws. Industries have to invest in sustainable activities and waste reduction. Scientists should keep up the good work and share their knowledge. We have to reduce waste, demand action, and hold our leaders accountable. The state of our oceans is the result of our daily choices of what to buy, what waste management measures to undertake, and how to lobby for change. We can restore the marine environment to balance and ensure that its vast blue expanses sustain life for years to come by combining technology, sound governance, and public will.

Conflict of Interest

The author(s) declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Author Contributions

AF & AA: Conceptualisation, writing – review & editing, supervision, and project administration. AA:

Investigation, resources, data curation, writing – original draft, and visualisation.

References

1 Talukder B, Ganguli N, Matthew R, Hipel K W & Orbinski J, Climate change-accelerated ocean biodiversity loss & associated planetary health impacts, *J Clim Chang Health*, 6 (2022) p. 100114.

2 Khan M I & Chang Y C, Advances in marine environmental protection: challenges, solutions and perspectives, *Front Mar Sci*, 12 (2025) p. 1593179.

3 Secretariat UN, *Ocean Action Panel 4: Preventing and significantly reducing marine pollution of all kinds, in particular from land-based activities*, Concept paper prepared by the Secretariat, UN, 2025, pp. 20. https://digitallibrary.un.org/record/4082384?v=pdf

4 Mello T J, Longhini C M, Wanderley B M S, Silva C A D, Lehrback B D, *et al*., Pollution affects even oceanic marine protected areas in Southwestern Atlantic, *Environ Pollut*, 366 (2025) p. 125485. https://www.doi.org/10.1016/j.envpol.2024.125485

5 The Global Goals, *Goal 14: Life Below Water*, World Wide Web electronic publication. Accessed online at: https://globalgoals.org/goals/14-life-below-water/; (Accessed on October 2024).

6 United Nations Environment Programme (UNEP), *Marine and Land-Based Pollution*, World Wide Web electronic publication. Accessed online at: https://www.unep.org/topics/ocean-seas-and-coasts/regional-seas-programme/marine-and-land-based-pollution; (Accessed on October 2024).

7 Beusen A H, Doelman J C, Van Beek L P, Van Puijenbroek P J, Mogollón J M, *et al*., Exploring river nitrogen and phosphorus loading and export to global coastal waters in the Shared Socio-economic pathways, *Glob Environ Change*, 72 (2022) p. 102426.

8 Kibria M G, Masuk N I, Safayet R, Nguyen H Q & Mourshed M, Plastic Waste: Challenges and Opportunities to Mitigate Pollution and Effective Management, *Int J Environ Res*, 17 (1) (2023) p. 20. https://www.doi.org/10.1007/s41742-023-00507-z

9 Li X, Shen X, Jiang W, Xi Y & Li S, Comprehensive review of emerging contaminants: Detection technologies, environmental impact, and management strategies, *Ecotoxicol Environ Saf*, 278 (2024) p. 116420. https://www.doi.org/10.1016/j.ecoenv.2024.116420

10 Hafeez S, Wong M S, Abbas S, Kwok C Y, Nichol J, *et al*., Detection and monitoring of marine pollution using remote sensing technologies, In: *Monitoring of Marine Pollution*, edited by Fouzia H B, (IntechOpen), 2018, pp. 7–32. https://www.doi.org/10.5772/intechopen.81657

11 National Academies of Sciences, Engineering, and Medicine, *Reckoning with the U.S. role in global ocean plastic waste*, (National Academies Press, Washington DC), 2022, pp. 268. https://www.doi.org/10.17226/26132

12 Jeong E, Lee J Y & Redwan M, Animal exposure to microplastics and health effects: a review, *Emerg Contam*, 10 (4) (2024) p. 100369.

13 Ziani K, Ioniță-Mîndrican C B, Mititelu M, Neacșu S M, Negrei C, *et al*., Microplastics: a real global threat for environment and food safety: a state of the art review, *Nutrients*, 15 (3) (2023) p. 617. https://www.doi.org/10.3390/nu15030617

14 Thushari G G N & Senevirathna J D M, Plastic pollution in the marine environment, *Heliyon*, 6 (8) (2020) e04709. https://doi.org/10.1016/j.heliyon.2020.e04709

15 Nash K L, Van Putten I, Alexander K A, Bettiol S, Cvitanovic C, *et al*., Oceans and society: feedbacks between ocean and human health, *Rev Fish Biol Fish*, 32 (1) (2022) 161–187. https://doi.org/10.1007/s11160-021-09669-5

16 Bashir I, Lone F A, Bhat R A, Mir S A, Dar Z A, *et al*., Concerns and threats of contamination on aquatic ecosystems, In: *Bioremediation and biotechnology: sustainable approaches to pollution degradation*, (Springer International Publishing, Cham), 2020, pp. 1–26.

17 Essamlali I, Nhaila H & El Khaili M, Advances in machine learning and IoT for water quality monitoring: a comprehensive review, *Heliyon*, 10 (6) (2024) p. e27920. https://doi.org/10.1016/j.heliyon.2024.e27920

18 Demeneix B & Hahn M E, Human health and ocean pollution, *Ann Glob Health*, 86 (1) (2020) p. 151.

19 United Nations Environment Programme, *Wastewater, sewage and sanitation*, World Wide Web electronic publication, Accessed online at: https://www.unep.org/cep/wastewater-sewage-and-sanitation; (Accessed on October 2024).

20 Abera B D & Adimas M A, Health benefits and health risks of contaminated fish consumption: current research outputs, research approaches, and perspectives, *Heliyon*, 10 (13) (2024) p. e33905. https://doi.org/10.1016/j.heliyon.2024.e33905

21 Purohit B K, Tewari S, Prasad K S, Talari V K, Pandey N, *et al*., Marine oil spill clean-up: a review on technologies with recent trends and challenges, *Reg Stud Mar Sci*, 80 (2024) p. 103876.

22 United Nations Environment Programme, *Plastic pollution*, World Wide Web electronic publication. Accessed online at: https://www.unep.org/plastic-pollution; (Accessed on October 2024).

23 United Nations Environment Programme, *Radioactive substances*, World Wide Web electronic publication. Accessed online at: https://www.unep.org/cep/radioactive-substances; (Accessed on October 2024).

24 Geurdes M, Thermal pollution and its impact on the environment, *J Pollut Eff Control*, 11 (2023) p. 361.

25 United States Environmental Protection Agency, *Threats to coral reefs*, World Wide Web electronic publication. Accessed online at: https://www.epa.gov/coral-reefs/threats-coral-reefs; (Accessed on October 2024).

26 Geneva Environment Network, *The ocean and the environment*, World Wide Web electronic publication. Accessed online at: https://www.genevaenvironmentnetwork.org/ resources/ updates/the-ocean-and-the-environment/; (Accessed on October 2024).

27 Li X, Shen X, Jiang W, Xi Y & Li S, Comprehensive review of emerging contaminants: detection technologies, environmental impact, and management strategies, *Ecotoxicol Environ Saf*, 278 (2024) p. 116420.

28 Lee Y, Cho J, Sohn J & Kim C, Health effects of microplastic exposures: current issues and perspectives in South Korea, *Yonsei Med J*, 64 (5) (2023) 301–308. https://doi.org/10.3349/ymj.2023.0048

29 Jolaosho T L, Rasaq M F, Omotoye E V, Araomo O V, Adekoya O S, *et al*., Microplastics in freshwater and marine ecosystems: occurrence, characterization, sources, distribution dynamics, fate, transport processes, potential mitigation strategies, and policy interventions, *Ecotoxicol Environ Saf*, 294 (2025) p. 118036. https://doi.org/10.1016/j.ecoenv.2025.118036

30 McDevitt J P, Criddle C S, Morse M, Hale R C, Bott C B, *et al*., Addressing the issue of microplastics in the wake of the Microbead-Free Waters Act—a new standard can facilitate improved policy, *Environ Sci Technol*, 51 (12) (2017) 6611–6617. https://doi.org/10.1021/acs.est.6b05812

31 Rashid S, Majeed L R, Mehta N, Radu T, Martín-Fabiani I, *et al*., Microplastics in terrestrial ecosystems: sources, transport, fate, mitigation, and remediation strategies, *Euro-Mediterr J Environ Integr*, 10 (2025) 2633–2659. https://doi.org/10.1007/s41207-025-00766-6

32 Ashrafy A, Liza A A, Islam M N, Billah M M, Arafat S T, *et al*., Microplastics pollution: a brief review of its source and abundance in different aquatic ecosystems, *J Hazard Mater Adv*, 9 (2023) p. 100215.

33 Sharma S, Sharma V & Chatterjee S, Contribution of plastic and microplastic to global climate change and their conjoining impacts on the environment - a review, *Sci Total Environ*, 875 (2023) p. 162627.

34 Kanhai L D, Gardfeldt K, Krumpen T, Thompson R C & O'Connor I, Microplastics in sea ice and seawater beneath ice floes from the Arctic Ocean, *Sci Rep*, 10 (1) (2020) p. 5004.

35 Muniz R & Rahman M S, Microplastics in coastal and marine environments: a critical issue of plastic pollution on marine organisms, seafood contaminations, and human health implications, *J Hazard Mater Adv*, 18 (2025) p. 100663. https://doi.org/10.1016/j.hazadv.2025.100663

36 Cáceres-Farias L, Espinoza-Vera M M, Orós J, Garcia-Bereguiain M A & Alfaro-Núñez A, Macro and microplastic intake in seafood varies by the marine organism's feeding behaviour: is it a concern to human health? *Heliyon*, 9 (5) (2023) p. e16452.

37 Gateuille D & Naffrechoux E, Transport of persistent organic pollutants: another effect of microplastic pollution? *Wiley Interdiscip Rev Water*, 9 (5) (2022) p. e1600.

38 Ghosh T, Microplastics bioaccumulation in fish: its potential toxic effects on hematology, immune response, neurotoxicity, oxidative stress, growth, and reproductive dysfunction, *Toxicol Rep*, 14 (2025) p. 101854.

39 Vasudeva M, Warrier A K, Kartha V B & Unnikrishnan V K, Advances in microplastic characterization: spectroscopic techniques and heavy metal adsorption insights, *TrAC Trends Anal Chem*, 183 (2025) p. 118111.

40 Knoblauch D & Mederake L, Government policies combatting plastic pollution, *Curr Opin Toxicol*, 28 (2021) 87–96.

41 Fraisl D, See L, Bowers R, Seidu O, Fredua K B, *et al*., The contributions of citizen science to SDG monitoring and reporting on marine plastics, *Sustain Sci*, 18 (6) (2023) 2629–2647.

42 Thelma C C, Chitondo L & Ngulube L, Plastic pollution: causes, effects, and solutions, *Int J Res Publ Rev*, 5 (3) (2024) 6570–6581.

43 Ahmed S F, Islam N, Tasannum N, Mehjabin A, Momtahin A, *et al*., Microplastic removal and management strategies for wastewater treatment plants, *Chemosphere*, 347 (2024) p. 140648.

44 Dewika M, Markandan K, Ruwaida J N, Sara Y Y, Deb A, *et al*., Integrating the quintuple helix approach into atmospheric microplastics management policies for planetary health preservation, *Sci Total Environ*, 954 (2024) p. 176063.

45 Anthony D, Siriwardana H, Ashvini S, Pallewatta S, Samarasekara S M, *et al*., Trends in marine pollution mitigation technologies: scientometric analysis of published literature (1990–2022), *Reg Stud Mar Sci*, 66 (2023) p. 103156.

46 Ngamile S, Madonsela S & Kganyago M, Trends in remote sensing of water quality parameters in inland water bodies: a systematic review, *Front Environ Sci*, 13 (2025) p. 1549301.

47 Srivastava A & Jain S, Remote sensing for environment assessment: multispectral, hyperspectral, and thermal imaging applications, In: *Remote sensing for environmental monitoring*, edited by Saritha V, Pande C B, Singh R & Shahid M, (Springer, Singapore), 2025, pp. 1-31. https://doi.org/10.1007/978-981-96-5546-5_1

48 Jaywant S A & Arif K M, Remote sensing techniques for water quality monitoring: a review, *Sensors*, 24 (24) (2024) Art No. 8041.

49 Tholkapiyan M, Shanmugam P & Suresh T, Monitoring of ocean surface algal blooms in coastal and oceanic waters around India, *Environ Monit Assess*, 186 (7) (2014) 4129–4137.

50 Candela A, Edelson K, Gierach M M, Thompson D R, Woodward G, *et al*., Using remote sensing and in situ measurements for efficient mapping and optimal sampling of coral reefs, *Front Mar Sci*, 8 (2021) p. 689489.

51 Jones D O, Gates A R, Huvenne V A, Phillips A B, *et al*., Autonomous marine environmental monitoring: application in decommissioned oil fields, *Sci Total Environ*, 668 (2019) 835–853.

52 Rudnick D L, Ocean research enabled by underwater gliders, *Annu Rev Mar Sci*, 8 (1) (2016) 519–541.

53 Shukla A, Ross R, Bhattacharya B & Stumpf A, Autonomous water sampling and quality monitoring in remote locations: a novel approach using a remote-controlled boat, *HardwareX*, 22 (2025) p. e00634.

54 Popa C L, Dontu S I, Savastru D & Carstea E M, Role of citizen scientists in environmental plastic litter research—a systematic review, *Sustainability*, 14 (20) (2022) p. 13265.

55 Olawade D B, Wada O Z, Ige A O, Egbewole B I, Olojo A, *et al*., Artificial intelligence in environmental monitoring: advancements, challenges, and future directions, *Hyg Environ Health Adv*, 12 (2024) p. 100114.

56 Singh U, Acharya D & Mishra S, Oil spill detection & monitoring with artificial intelligence: a futuristic approach, In: *Workshop on Control and Embedded Systems, (WCES 2022)*, April 22 – 24, 2022, Chennai, India, 2022, pp. 12–22.

57 Bilawal Khaskheli M, Wang S, Zhang X, Shamsi I H, Shen C, *et al*., Technology advancement and international law in marine policy, challenges, solutions and future prospective, *Front Mar Sci*, 10 (2023)p. 1258924.

58 Alotaibi E & Nassif N, Artificial intelligence in environmental monitoring: in-depth analysis, *Discov Artif Intell*, 4 (1) (2024) p. 84.

59 Akhmedov F, Nasimov R & Abdusalomov A, Developing a comprehensive oil spill detection model for marine environments, *Remote Sens*, 16 (16) (2024) p. 3080.

60 Jin H, Kong F, Li X & Shen J, Artificial intelligence in microplastic detection and pollution control, *Environ Res*, 262 (2024) p. 119812.

61 Danielsen F, Eicken H, Funder M, Johnson N, Lee O, *et al*., Community monitoring of natural resource systems and the environment, *Annu Rev Environ Resour*, 47 (1) (2022) 637–670.

62 Suhardono S, Lee C H & Suryawan I W, Trends in citizen influencing willingness to participate in marine debris management and social well-being in Bali metropolitan, Indonesia, *Urban Gov*, 4 (4) (2024) 362–373.

63 Dharmarathne G, Abekoon A M, Bogahawaththa M, Alawatugoda J & Meddage D P, A review of machine learning and internet-of-things on the water quality assessment: methods, applications and future trends, *Results Eng*, 26 (2025) p. 105182. https://doi.org/10.1016/j.rineng.2025.105182

64 Bala S, Garg D, Thirumalesh B V, Sharma M, Sridhar K, *et al*., Recent strategies for bioremediation of emerging pollutants: a review for a green and sustainable environment, *Toxics*, 10 (8) (2022) p. 484.

65 Navina B K, Velmurugan N K, Kumar P S, Rangasamy G, Palanivelu J, *et al*., Fungal bioremediation approaches for the removal of toxic pollutants: mechanistic understanding for biorefinery applications, *Chemosphere*, 350 (2024) p. 141123.

66 Ali S S, Abdelkarim E A, Elsamahy T, Al-Tohamy R, Li F, *et al*., Bioplastic production in terms of life cycle assessment: a state-of-the-art review, *Environ Sci Ecotechnol*, 15 (2023) p. 100254.

67 Hasan M M, Haque R, Jahirul M I & Rasul M G, Pyrolysis of plastic waste for sustainable energy recovery: technological advancements and environmental impacts, *Energy Convers Manag*, 326 (2025) p. 119511.

68 Toranzos G A & Cano R J, Definitions and historical perspectives in environmental forensics, *Microbiol Spectr*, 6 (2) (2018) p. 1-15. https://doi.org/10.1128/microbiolspec.EMF-0016-2018

69 Radović J R, Rial D, Lyons B P, Harman C, Viñas L, *et al*., Post-incident monitoring to evaluate environmental damage from shipping incidents: chemical and biological assessments, *J Environ Manag*, 109 (2012) 136–153.

70 Hill J M, Kaehler S & Hill M P, Baseline isotope data for *Spirodela* sp.: nutrient differentiation in aquatic systems, *Water Res*, 46 (11) (2012) 3553–3562.

71 Gong S, Ding Y, Wang Y, Jiang G & Zhu C, Advances in DNA barcoding of toxic marine organisms, *Int J Mol Sci*, 19 (10) (2018) p. 2931. https://doi.org/10.3390/ijms19102931

72 Schadewell Y & Adams C I, Forensics meets ecology–environmental DNA offers new capabilities for marine ecosystem and fisheries research, *Front Mar Sci*, 8 (2021) p. 668822.

73 Oosthuizen T, Howes L & White R, Forensic science and environmental offences: litter, DNA analysis and surveillance, 2 (2022) p. 100042. https://doi.org/10.1016/j.fsiae.2022.100042

74 Abubakar I R, Maniruzzaman K M, Dano U L, AlShihri F S, AlShammari M S, *et al*., Environmental sustainability impacts of solid waste management practices in the Global South, *Int J Environ Res Public Health*, 19 (19) (2022) p. 12717.

75 Nuruzzaman M, Bahar M M & Naidu R, Diffuse soil pollution from agriculture: impacts and remediation, *Sci Total Environ*, 962 (2025) p. 178398.

76 Little D I, Sheppard S R & Hulme D, A perspective on oil spills: what we should have learned about global warming, *Ocean Coast Manag*, 202 (2021) p. 105509.

77 Laffoley D, Baxter J M, Day J C, Wenzel L, Bueno P, *et al*., Marine protected areas, In: World seas: an environmental evaluation, (Academic Press), 2019, pp. 549–569.

78 Maccarrone V, Scandura P & La Rosa S D, The integrated coastal zone management in the Anthropocene, In: *Coastal sustainability: insights from Southeast Asia and beyond*, (Springer Nature, Cham, Switzerland), 2024, pp. 1–20.

79 Ajith N, Ramasamy K, Robin R S, Mugilarasan M, Tudu D, *et al*., Marine litter management along the coastal and marine area: a citizen approach initiative in India, National Centre for Sustainable Coastal Management, Ministry of Environment, Forest and Climate Change, 2023, pp. 12.

80 Zhang J, Islam M S, Jambulingam M, Lim W M & Kumar S, Leveraging environmental corporate social responsibility to promote green purchases: the case of new energy vehicles in the era of sustainable development, *J Clean Prod*, 434 (2024) p. 139988.

81 Schaffelke B, Mellors J & Duke N C, Water quality in the Great Barrier Reef region: responses of mangrove, seagrass and macroalgal communities, *Mar Pollut Bull*, 51 (1–4) (2005) 279–296.

82 Cecchini P, Nitta T, Sena E & Du Z Y, Saving coral reefs: significance and biotechnological approaches for coral conservation, *Adv Biotechnol*, 2 (4) (2024) p. 42.

83 Paxton A B, Runde B J, Smith C S, Lester S E, Vozzo M L, *et al*., Leveraging built marine structures to benefit and minimize impacts on natural habitats, *BioScience*, 75 (2) (2025) 172–183. https://doi.org/10.1093/biosci/biae135

84 Maglione G, Zinno P, Tropea A, Mussagy C U, Dufossé L, *et al*., Microbes' role in environmental pollution and remediation: a bioeconomy focus approach, *AIMS Microbiol*, 10 (3) (2024) 723–755.

85 McGenity T J, Folwell B D, McKew B A & Sanni G O, Marine crude-oil biodegradation: a central role for interspecies interactions, *Aquat Biosyst*, 8 (1) (2012) p. 10. https://doi.org/10.1186/2046-9063-8-10