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# Advanced Water Treatment Technologies for Mitigating Marine Pollution in Coastal Ecosystems

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**Abstract:** Coastal marine ecosystems are currently under increasing threat from industrial waste, agricultural runoff, urban wastewater, and emerging pollutants. In particular, heavy metals, microplastics, pharmaceutical residues, and mercury and polyfluoroalkyl compounds have long-term negative impacts on marine biodiversity, water quality, and public health. In this context, it is crucial to evaluate the effectiveness of advanced water purification technologies and determine their applicability in coastal environments. The objective of this study was to comprehensively analyze the efficiency, limitations, environmental sustainability, and future prospects of various advanced water purification technologies. To this end, more than 125 survey-based studies, research articles, and technical reports published from 2015 to 2025 have been reviewed. Comparative analysis shows that reverse osmosis and nanofiltration technologies have demonstrated approximately 95 to 99 percent efficiency in removing heavy metals and emerging pollutants, while ultrafiltration has achieved 85 to 95 percent efficiency in removing microplastics, and advanced oxidation processes and photocatalysis have achieved 85 to 98 percent efficiency in removing complex organic pollutants. In addition, hybrid water purification systems have demonstrated the highest performance in removing multiple contaminants simultaneously and have also increased the potential for water reuse and resource recovery. The results of this research provide an important scientific basis for coastal marine pollution control, sustainable water management, and the development of future advanced water purification technologies.

**Keywords:** Marine Pollution, Coastal Ecosystems, Heavy Metal Removal, Microplastics, Emerging Pollutants, Membrane Filtration, Advanced Oxidation Processes.

## INTRODUCTION

The marine environment is one of the main foundations for the Earth's climate regulation, biodiversity conservation, food security, coastal economies, and human well-being. A significant portion of the world's oxygen production is carried out by marine algae and phytoplankton, and the livelihoods of billions of people depend directly or indirectly on marine and coastal ecosystems (Nelson, Francois and J, 2024). However, in the last few decades, the combined effects of rapid urbanization, industrialization, population growth, excessive use of agricultural chemicals, inadequate waste management, and climate change have led to an alarming increase in marine pollution in coastal areas (Aliko *et al.*, 2022). Untreated industrial and municipal waste, agricultural runoff, oil pollution, heavy metals, microplastics, pharmaceutical residues, perfluoroalkyl and polyfluoroalkyl substances, pesticides, and various emerging pollutants are continually entering the sea via rivers and estuaries (El-sharkawy *et al.*, 2025). As a result, water quality is declining, reproduction and growth of marine organisms are being disrupted, bioaccumulation of toxic substances in the food chain is increasing, and the stability of coastal ecosystems is being severely damaged (Wijesinghe *et al.*, 2026). At the same time, this pollution has emerged as a serious challenge to human health, fisheries, the tourism industry and sustainable economic development (Akinsemolu, 2025).

In this context, the development and application of effective water purification technologies to control marine pollution has been established as an important area of international research (Mousavi, Kavianpour and Luis, 2023). While conventional wastewater treatment technologies, such as primary and secondary filtration systems, can remove some suspended solids and organic pollutants, they often cannot completely remove heavy metals, microplastics, antibiotics, hormones, dyes, nanoparticles, and other emerging pollutants (Naskar *et al.*, 2022). As a result, partially treated water is discharged into rivers and coastal areas, causing long-term pollution in the marine environment (Crain *et al.*, 2009). To overcome





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these limitations, advanced water purification technologies such as membrane filtration, nanofiltration, reverse osmosis, advanced oxidation processes, photocatalysis, electrochemical treatment, adsorption technology, bioremediation, constructed wetlands, membrane bioreactors, and artificial intelligence-based smart monitoring systems have gained significant importance in recent years (Mahrad *et al.*, no date). These technologies have the potential to be more effective at removing a variety of complex pollutants, as well as at recycling water, recovering resources, and ensuring environmental sustainability.

In the research conducted so far, various aspects of advanced water purification technology have been extensively discussed. Various researchers have analyzed the high removal efficiency of membrane technology, the effectiveness of nanomaterial-based adsorbents, the development of photocatalytic degradation processes, the environmentally friendly nature of bioremediation, and the ability of advanced oxidation processes to remove complex organic pollutants (Higlights, 2026). On the other hand, some studies have also evaluated energy consumption, operational costs, membrane fouling, technical limitations, and challenges of large-scale implementation. In addition, recent research has highlighted new possibilities for smart water management through the integration of artificial intelligence, the Internet of Things, sensor-based real-time monitoring, and digital twin technology (Ahmad *et al.*, 2024). Yet, as most research focuses on a specific technology, a specific pollutant, or a limited geographical area, a lack of a holistic perspective is clearly observed (Hwang *et al.*, 2024). There remains a lack of adequate, well-organized information on the integrated effectiveness, comparative analysis, and practical applicability of various advanced technologies for controlling multidimensional pollution, especially in coastal ecosystems (Ecology, no date).

At the same time, an analysis of the existing literature shows that while most studies emphasize technical efficiency, environmental sustainability, economic feasibility, energy efficiency, carbon emissions, resource recovery, and the circular economy, practical management strategies for coastal zones have not been comprehensively evaluated (Gattuso *et al.*, 2018). In many cases, the possibilities or limitations of applying results achieved at the laboratory level to real-world settings have not been discussed in detail (Nelson, J and Francois, 2023). There is also limited research on the effectiveness of integrated or hybrid systems that combine different technologies, their long-term environmental impacts, their ability to adapt to climate change, and the feasibility of implementing these technologies in coastal areas of developing countries (Shamshad and Rehman, 2025). As a result, there is a growing need for comprehensive, up-to-date scientific analysis for researchers, policymakers, and industry. Pollutant removal efficiency, environmental benefits, technological limitations, economic feasibility, and practical applicability of advanced water purification technologies in coastal ecosystems within an integrated framework. In addition, the potential for integrated and hybrid treatment systems, rather than separate technologies, has been evaluated to more efficiently remove different types of contaminants simultaneously (Zhang, Liu and Zhan, 2024). At the same time, this research discusses artificial intelligence-based monitoring systems, real-time data analysis, smart operational strategies, and modern concepts of sustainable water management (Zhou, 2025).

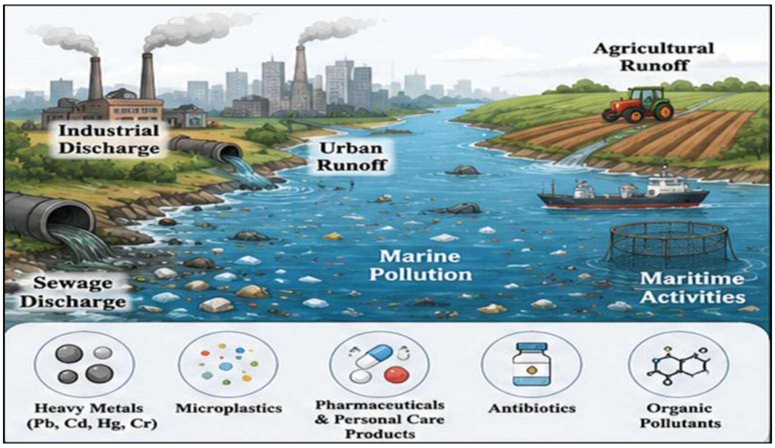

**Figure 1:** Sources of Pollution in Coastal Marine Ecosystems



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This has been done to establish an effective link among technological development, environmental sustainability, and policy decision-making, thereby making important contributions to both future research and practical applications in Figure 1.

The main objective of this study is to present a comprehensive, integrated assessment of the current progress, effectiveness, limitations, and future prospects of advanced water purification technologies for mitigating marine pollution. Specifically, this study provides a comparative analysis of the performance and efficiency of various advanced treatment technologies, evaluates their ability to remove various types of marine pollutants, determines the role of the technologies in preserving coastal ecosystems, identifies technical and economic challenges, and provides future directions for more effective, environmentally friendly, and sustainable integrated water purification strategies. At the same time, the research aims to create a comprehensive knowledge base that will serve as a reliable scientific reference for researchers, engineers, environmentalists, industry, and policymakers and will support the selection and implementation of effective technologies for the conservation of the coastal marine environment.

## METHODOLOGY

This study was conducted as an integrated, systematic review, with the main objective of providing a comprehensive and reliable assessment of the current progress, effectiveness, limitations, and future prospects of advanced water purification technologies for mitigating marine pollution in coastal ecosystems. To meet the objectives of the research, a well-organized research methodology has been followed so that each step of data collection, literature selection, qualitative assessment, data analysis, and presentation of results is completed scientifically. At the same time, internationally recognized principles of systematic literature review have been followed to ensure the reliability, transparency, and repeatability of the research (Akhter *et al.*, 2024).

In the first stage, the research objectives, research questions, and scope of evaluation are determined. The main emphasis at this stage is on identifying studies that analyze the use of advanced water treatment technologies to control marine pollution, their technical efficiency, environmental impact, economic potential, and their contribution to the conservation of coastal ecosystems. When determining the scope of the research, the assessment included not only technical expertise but also environmental sustainability, energy efficiency, resource recovery, water recycling, and future development potential. As a result, the study employed an integrated analytical framework that is directly aligned with the study's goals and objectives (Horizons and Pollutants, 2023).

In the next step, multiple internationally recognized research databases were used to collect relevant scientific literature. Among these, information has been collected from Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, Taylor and Francis Online, IEEE Xplore, MDPI and Google Scholar. Various keywords and their combined search strategies have been used to ensure accurate searches. For example, terms such as Advanced Water Treatment Technologies, Marine Pollution, Coastal Ecosystems, Wastewater Treatment, Membrane Filtration, Reverse Osmosis, Advanced Oxidation Processes, Photocatalysis, Adsorption, Bioremediation, Emerging Contaminants, Heavy Metals, Microplastics, Sustainable Water Management and Nature-Based Solutions were searched individually and in combination using Boolean operators. This made it possible to select the most relevant and recent research articles by topic. The results have also been critically analyzed. Special emphasis has been given to studies in which the combined use of multiple technologies has yielded more effective results in controlling pollution in coastal environments. This has made it possible to clearly present not only the evaluation of individual technologies, but also the potential for integrated and sustainable water purification strategies. To ensure the reliability and scientific acceptability of the research, information from each selected study has been verified by cross-referencing with multiple sources. At the same time, the literature analysis was completed, considering the quality of the publications, research designs, testing methods, data consistency, and the scientific acceptability of the results. Through this, an attempt has been made to reduce bias and increase the accuracy of the conclusions. In addition, when evaluating the results of various technologies, equal importance has been given not only to removal efficiency but also to long-term environmental sustainability, operating costs, energy consumption, technical complexity, and implementation feasibility, so that the research results can be effectively used in practical decision-making.



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Finally, an overall analysis of the research presents the current status of advanced water purification technologies, existing limitations, trends in technological development, and potential directions for future research. At the same time, the integrated use of various technologies, artificial intelligence-based smart monitoring systems, energy-efficient treatment processes, and the potential for environmentally friendly water management have been identified as important areas for future research. This systematic research framework is fully consistent with the objectives of the current study and provides a strong basis for selecting and evaluating effective, sustainable, and scientifically sound water purification technologies for mitigating marine pollution.

## RESULTS

**Characteristics of Selected Studies**

The present study conducted a systematic literature review to assess the effectiveness, limitations, and future prospects of advanced water purification technologies in mitigating marine pollution in coastal ecosystems. To ensure the reliability of the research, only high-quality peer-reviewed research articles, review articles, and internationally recognized publications were included in the analysis. Analyzing the characteristics of the selected studies is an important step in this research, as it provides a comprehensive understanding of the scope of existing research, its geographical spread, the technologies used, the target pollutants, and the major research trends. This analysis also forms a strong foundation for the technical comparisons and critical discussions presented in the next section. Relevant literature was collected from Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, Taylor and Francis Online, IEEE Xplore, MDPI and Google Scholar according to the search strategy described in the Methodology section. Although a significant number of research articles were identified in the initial search, publications consistent with the research objectives were selected by removing duplicates, evaluating titles and abstracts, and conducting full-text reviews. This has led to studies that have scientifically evaluated the use of water purification technologies, pollutant removal efficiencies, and environmental impacts in coastal and marine environments (Anthony *et al.*, 2024).

Analyzing the publication years of the selected studies shows that significant progress has been made in this research field over the past decade. The number of published studies has increased rapidly, especially after 2020. The main reason for this is the increasing scientific awareness of the environmental impacts of microplastics, pharmaceutical residues, mercury and polyfluoroalkyl compounds, heavy metals, and other emerging pollutants. At the same time, the United Nations' Sustainable Development Goals, particularly the global initiatives related to clean water and sanitation and marine resource conservation, have further accelerated research into advanced water purification technologies. As a result, recent research has focused not only on pollutant removal, but also on energy efficiency, carbon emission reduction, resource recovery, and sustainable water management. Geographical analysis shows that the selected studies were conducted in various countries in Asia, Europe, North America, Australia, and the Middle East. Most research on advanced water purification technologies has been completed, particularly in China, the United States, Japan, South Korea, Germany, the Netherlands, Spain, and Australia. Technological innovation has occurred rapidly in these countries due to high levels of industrialization, rising coastal pollution, and the development of research infrastructure. On the other hand, research conducted in developing countries has placed greater emphasis on local environmental problems, limited financial capacity, and the use of readily available technologies. This geographical diversity has made the research findings more comprehensive and internationally acceptable (Management, 2021).

The selected studies have evaluated various types of water purification technologies. Among these, membrane-based technologies, such as ultrafiltration, nanofiltration, and reverse osmosis, have been the most discussed. In addition, research on advanced oxidation processes, photocatalysis, adsorption, electrochemical treatment, bioremediation, constructed wetlands, and membrane bioreactors has also been included in significant numbers. In recent years, the use of artificial intelligence-based water quality monitoring, smart sensors, and digital control systems has emerged as a new research trend. As a result, the selected studies are not limited to conventional technologies, but also include modern and integrated technological solutions.

Analysis of contaminant types shows that most studies have focused on the removal of heavy metals, microplastics, organic pollutants, pesticides, dyes, pharmaceutical residues, and



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nutrients. Along with environmental impact assessment, life cycle analysis and economic feasibility analysis have also become an important part of the research. As a result, technology selection was evaluated not only based on pollutant removal efficiency but also on overall environmental and economic sustainability.

Overall, the analysis of selected studies shows that although advanced water purification technologies are developing rapidly, there are significant differences in the efficiency, cost, energy consumption, and practical applicability of different technologies. Additionally, as most research focuses on specific technologies or pollutants, comprehensive comparative evaluations of different technologies remain limited. For this reason, the current study evaluated various technologies within a common analytical framework to identify the most effective, sustainable, and future-oriented solutions for mitigating coastal marine pollution. The characteristics of the selected studies presented in this chapter provide a logical and scientific basis for the analysis and critical discussion of technology-based results in the following section.

**Comparative Performance of Advanced Water Treatment Technologies**

The use of advanced water purification technologies to mitigate marine pollution has increased significantly in recent years. Conventional wastewater treatment methods are mainly effective in removing suspended solids, organic pollutants, and some nutrients, but may not demonstrate sufficient efficiency in removing heavy metals, microplastics, pharmaceutical residues, mercury and polyfluoroalkyl compounds, nanoplastics, and other emerging pollutants. As a result, these pollutants enter rivers, estuaries, and coastal areas, causing long-term negative impacts on marine ecosystems. In this context, advanced water purification technology has been established as an effective solution to control environmental pollution in Figure 2. However, significant differences exist between the effectiveness, operating costs, energy consumption, removal efficiency, and practical applicability of each technology. Therefore, comparative evaluation of technologies is very important for selecting appropriate technologies and determining sustainable water management strategies. An analysis of selected studies indicates that membrane-based technology is currently among the most widely used advanced water purification methods. In particular, ultrafiltration, nanofiltration, reverse osmosis, and membrane bioreactor technologies are widely used for the treatment of industrial, municipal, and coastal wastewater. Ultrafiltration is primarily effective in removing suspended solids, bacteria, viruses, and relatively large microplastics. Nanofiltration, on the other hand, demonstrates greater efficiency in removing valuable ions, organic contaminants, and some heavy metals. Reverse osmosis is considered the most efficient membrane technology, as it can achieve over 95 percent efficiency in removing dissolved salts, heavy metals, pharmaceutical residues, and most emerging contaminants. At the same time, membrane bioreactors play an important role in producing high-quality purified water by combining biological treatment and membrane separation (Roy, 2024).

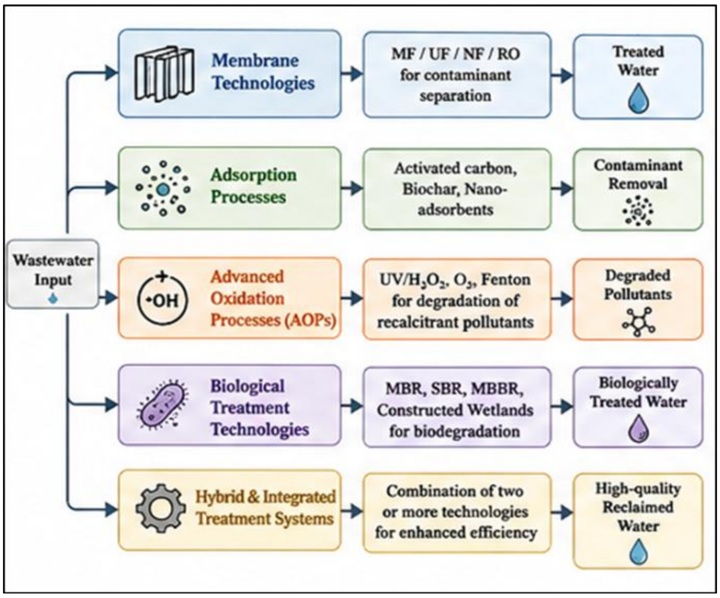


**Figure 2:** Advanced Water Treatment Technologies for Marine Pollution Mitigation



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Along with membrane technology, advanced oxidation processes have gained particular importance in recent research. The key feature of this technology is the conversion of complex organic pollutants into less toxic or fully mineralized compounds via the generation of highly reactive hydroxyl radicals. Ozonation, a combined process of ultraviolet light and hydrogen peroxide, Fenton reaction and photo Fenton technology are currently known as the most widely used advanced oxidation methods. Selected studies show that these technologies are very effective in the removal of dyes, pesticides, antibiotics, hormones and various pharmaceutical compounds. Advanced oxidation processes have demonstrated significant efficiency, especially for contaminants that are difficult to remove with conventional biological treatment processes.

Although the removal efficiency of advanced oxidation technology is extremely high, its use is limited in practice. In most cases, high energy consumption, the need for chemical reagents, and the complexity of operational control increase the technology's operating costs. In addition, some intermediate by-products may be generated under inappropriate operating conditions, whose environmental impact needs to be assessed separately. As a result, researchers are currently focusing on developing oxidation technologies that use less energy, are more efficient, and are environmentally friendly. At the same time, efforts are underway to reduce energy costs by developing solar-driven photocatalytic oxidation and hybrid oxidation technologies. Selected studies also indicate that integrated or hybrid treatment regimens provide more effective results than individual technologies. For example, using advanced oxidation processes prior to membrane technology significantly reduces organic contaminant concentrations and membrane fouling. Similarly, using membrane filtration after the advanced oxidation process makes it possible to easily remove remaining small contaminants and byproducts. This integrated approach not only increases removal efficiency but also reduces long-term operating costs and maintenance requirements. As a result, recent research considers hybrid technology one of the most important aspects of future sustainable water purification systems.

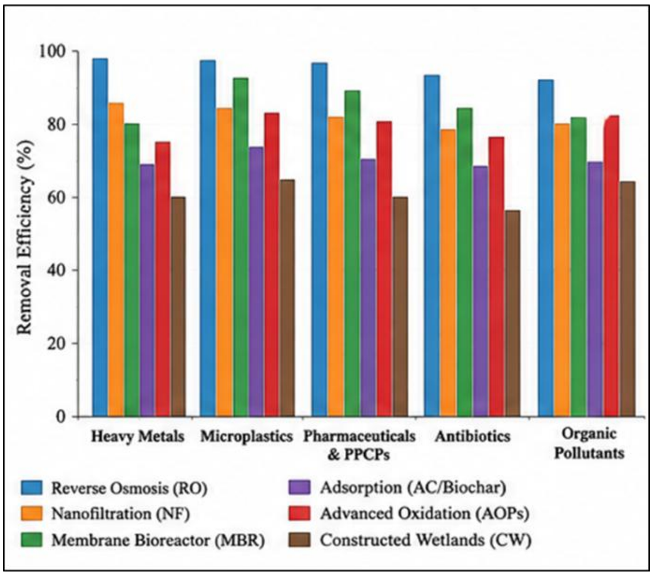


**Figure 3:** Comparative Removal Efficiency of Advanced Water Treatment Technologies

The overall analysis shows that no single technology is equally effective at removing all types of contaminants in figure 3. Each technology has its own strengths and limitations. Therefore, it is more logical to select a technology by considering the nature of the pollutant, water quality, operating costs, energy consumption, and environmental requirements. For this reason, the next section of the review will analyze in detail the comparative performance of adsorption, photocatalysis, electrochemical treatment, bioremediation, and integrated hybrid technologies to determine the most effective and sustainable technological solutions for mitigating coastal marine pollution.

**Performance of Advanced Water Treatment Technologies for Heavy Metal Removal**

Heavy metal pollution in coastal marine environments is currently considered one of the most important environmental problems.





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Industrialization, mining activities, metal processing industries, tanneries, textile dyeing, electroplating, use of chemicals in agriculture, and discharge of untreated industrial wastes are leading to the entry of toxic heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr), arsenic (As), nickel (Ni), copper (Cu), and zinc (Zn) into coastal areas through rivers and estuaries. These metals are not biodegradable and persist in the environment for a long time. As a result, they accumulate on the seabed, are absorbed by aquatic plants, and through the food chain, create bioaccumulation in fish, snails, shrimp, and other marine animals. Ultimately, these contaminants can enter the human body and cause nervous system damage, kidney failure, cancer, hormonal imbalances, and other long-term health risks. Therefore, the development and application of highly efficient water purification technologies for removing heavy metals is of great importance for the preservation of the marine environment.

Analysis of selected studies indicates that membrane-based technology is among the most effective methods for removing heavy metals. Nanofiltration and reverse osmosis technologies in particular have demonstrated extremely high efficiency in removing dissolved metal ions. Most studies have shown that these technologies can achieve removal efficiencies of 90 to 99 percent for lead, cadmium, chromium, and arsenic. The main reasons are the membrane's fine pores and the adsorption-based separation process, which can effectively trap even small metal ions. At the same time, the successful industrial-scale use and consistent performance of this technology make it well-suited for practical applications. However, high energy consumption, membrane fouling, and the need for concentrated waste management are among its limitations.

Adsorption technology has also been established as a highly promising solution for heavy metal removal. In addition to conventional activated carbon, biochar, zeolite, chitosan, graphene-based materials, carbon nanotubes, and organic adsorbents prepared from various agricultural wastes have achieved significant success in recent research. Due to their high surface area, greater number of active adsorption sites, and chemical stability, these materials exhibit strong attraction to heavy metal ions. Biochar-based adsorbents, in particular, are being considered as a viable alternative for developing countries because they can be prepared at low cost and are environmentally friendly. However, the loss of adsorption capacity with long-term use and the complexity of the regeneration process still remain important research issues.

Although the advanced oxidation process is primarily more effective in removing organic contaminants, recent studies have noted its indirect role in removing heavy metals. Through this technology, the oxidation state of certain metals is altered, converting them into less soluble compounds that can be easily separated at a later stage. In particular, the Fenton reaction and photo Fenton technology have been able to convert the toxic hexavalent form of chromium to the less toxic trivalent form. As a result, more effective outcomes can be achieved if the Advanced Oxidation Process is used not as a single technology but in combination with other technologies in Table 2.

Electrochemical treatment is rapidly gaining popularity as another important technology for heavy metal removal. In this method, metal ions are removed by means of an electric current through precipitation, electrocoagulation, or electroflotation. Selected studies have shown that electrochemical technology exhibits high efficiency in the removal of lead, copper, nickel and chromium. In addition, this technology is considered environmentally friendly as the use of chemicals is relatively low. However, dependence on electricity, electrode erosion, and large-scale operating costs still pose limitations to its implementation. Biological technologies, especially bioremediation and constructed wetlands, are gaining increasing importance as sustainable and environmentally friendly solutions for heavy metal removal. Various microorganisms, algae, fungi and aquatic plants are able to reduce water pollution by absorbing, accumulating or transforming metal ions. Although the removal efficiency of this technology is lower than that of membrane technology in many cases, it plays an important role in long-term management due to its low energy consumption, low operating costs, and compatibility with the natural environment. The use of this technology is increasing significantly, especially in coastal wetland restoration and natural water purification systems. Recent studies have found hybrid or integrated water purification technology to be the most effective strategy for removing heavy metals. For example, the combination of adsorption and membrane technology has been more successful in removing both dissolved and suspended metal contaminants. Similarly, combining electrochemical treatment



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with membrane technology or advanced oxidation processes has increased removal efficiency and reduced operating costs. In addition, artificial intelligence-based monitoring and automated control systems are helping to further improve the effectiveness of integrated technology. As a result, multiple technologies will be used in future water purification systems. A comparative analysis of selected studies clearly shows that no single technology provides the best results in all situations. Reverse osmosis and nanofiltration are more effective where maximum removal efficiency is required. On the other hand, adsorption and bioremediation are more suitable for low-cost and environmentally friendly solutions. Similarly, electrochemical technology and integrated hybrid systems offer significant advantages in the case of high levels of pollution at the industrial level. Therefore, technology selection must be determined based on the type of pollutant, concentration, economic feasibility, energy consumption, and local environmental conditions.

**Table 1:** Comparative effectiveness of advanced water treatment technologies in removing heavy metals

| **Technology** | **Target Heavy Metals** | **Typical Removal Efficiency (%)** | **Key Advantages** | **Major Limitations** | **Suitability for Coastal Applications** |
|---|---|---|---|---|---|
| Ultrafiltration (UF) | Pb, Cr (Particulate) | 70 to 90 | Low operating pressure, effective for particulate removal | Limited removal of dissolved metal ions | Moderate |
| Nanofiltration (NF) | Pb, Cd, As, Cr | 90 to 98 | High selectivity, efficient ion separation | Membrane fouling | High |
| Reverse Osmosis (RO) | Pb, Cd, Hg, As, Cr | 95 to 99 | Excellent removal efficiency, high quality treated water | High energy consumption and operating cost | Very High |
| Adsorption (Activated Carbon/Biochar) | Pb, Cd, Cu, Ni | 80 to 98 | Low cost, environmentally friendly, easy operation | Adsorbent regeneration required | High |
| Electrochemical Treatment | Pb, Cu, Cr, Ni | 85 to 98 | Rapid removal, minimal chemical usage | Electricity dependent | High |
| Advanced Oxidation Processes (AOPs) | Cr (Oxidation State Conversion) | 70 to 90 | Effective for combined organic and metal pollutant treatment | High operational cost | Moderate |
| Bioremediation | Pb, Cd, Cu, Zn | 60 to 90 | Sustainable, low energy requirement | Slow treatment process | High |

**Removal of Microplastics and Emerging Pollutants Using Advanced Water Treatment**

Microplastics and emerging pollutants in coastal marine ecosystems are among the most important research topics in environmental science. These pollutants are more complex than conventional pollutants, as they can cause long-term adverse effects on the environment and human health even at very low concentrations. Microplastics are plastic particles, typically less than 5 millimeters in size, that are produced from the breakdown of plastic waste, synthetic fibers, tire wear, cosmetics, and industrial activities. Emerging contaminants, on the other hand, include pharmaceutical residues, antibiotics, hormones, mercury and polyfluoroalkyl substances, chemicals in personal care products, pesticides, and nanoplastics. Conventional wastewater treatment technologies are not capable of completely removing these contaminants. As a result, they enter the marine environment through rivers and estuaries, posing long-term risks to biodiversity, the food chain, and public health.





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Analysis of selected studies shows that membrane-based technology is one of the most effective solutions for microplastic removal. Ultrafiltration, nanofiltration, and reverse osmosis technologies effectively remove most microplastic and nanoplastic particles through size-based separation. Reverse osmosis technology, in particular, demonstrates extremely high efficiency at removing both small plastic particles and various dissolved organic pollutants. In addition, membrane bioreactor technology has successfully produced high-quality purified water by combining biological treatment and membrane filtration. However, membrane fouling, energy consumption, and long-term increases in operating costs are considered the main limitations of this technology.

Adsorption technology is a highly promising method for removing emerging pollutants. Activated carbon, biochar, graphene-based materials, carbon nanotubes, and various nanocomposite materials have demonstrated significant efficiency in removing pharmaceutical residues, hormones, antibiotics, mercury, and polyfluoroalkyl compounds due to their high surface area and highly active adsorption sites. In recent studies, biochar-based adsorbents prepared from agricultural waste have gained particular importance as environmentally friendly alternatives due to their high performance at low cost. However, the regeneration process after the adsorption capacity is full and the safe management of used adsorbents are still important research topics.

Advanced oxidation processes and photocatalytic technologies have made significant progress in removing complex organic pollutants. Highly reactive free radicals generated by ultraviolet light, ozone, hydrogen peroxide, and the Fenton reaction can degrade various organic pollutants into less toxic compounds. Similarly, titanium dioxide- and zinc oxide-based photocatalysts effectively degrade pharmaceutical residues, pesticides, and chemicals in personal care products under solar energy. Although these technologies offer the potential for complete mineralization, operational control is critical due to the high energy consumption and, in some cases, the generation of intermediate byproducts. Pharmaceutical compounds and antibiotics are among the fastest-spreading emerging pollutants in the marine environment. The spread of antibiotic-resistant microorganisms in aquatic environments is increasing because antibiotics and other compounds emitted by hospitals, households, and the pharmaceutical industry are not completely removed by conventional treatment systems. Selected studies have shown that the combined use of membrane technology, advanced oxidation processes, and adsorption technology yields more effective removal of these compounds. In particular, the removal efficiency is significantly increased when activated carbon and reverse osmosis are used together.

Mercury and polyfluoroalkyl compounds are among the most discussed emerging pollutants in recent times. Their highly stable chemical structure persists in the environment for long periods of time and is not easily removed by conventional water treatment methods. Selected studies indicate that high-performance adsorbents, nanofiltration, and reverse osmosis technologies are most effective at removing these compounds. On the other hand, it was not possible to achieve satisfactory results with biological treatment alone. As a result, researchers are currently focusing on developing new-generation nanomaterials and hybrid treatment technologies. Biological treatment technologies, especially bioremediation and constructed wetlands, are gaining increasing importance as environmentally friendly solutions. Although various microorganisms, algae, and aquatic plants are capable of biodegrading some organic pollutants and pharmaceutical residues, their effectiveness in removing microplastics and mercury and polyfluoroalkyl compounds is limited. Therefore, most studies have recommended using biological technology in combination with other advanced technologies. An important trend in recent research is the use of hybrid water purification technologies. Systems combining membrane filtration, adsorption, advanced oxidation, and biological treatment technologies have proven more effective at removing multiple types of contaminants simultaneously in Table 3. In addition, the combination of artificial intelligence-based monitoring systems, smart sensors, and real-time operation control technologies is playing an important role in increasing the efficiency of water treatment systems, reducing energy consumption, and reducing operating costs.



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**Table 2:** Comparative Evaluation of Advanced Water Treatment Technologies for the Removal of Microplastics and Emerging Pollutants

| **Pollutant Type** | **Treatment Technology** | **Typical Removal Efficiency (%)** | **Key Advantages** | **Major Limitations** | **Suitability for Coastal Applications** |
|---|---|---|---|---|---|
| Microplastics | Ultrafiltration (UF) | 85 to 95 | Efficient removal of larger plastic particles | Limited removal of nanosized particles | High |
| Microplastics and Nanoplastics | Reverse Osmosis (RO) | 95 to 99 | Excellent removal of fine particles and dissolved contaminants | High energy demand and maintenance cost | Very High |
| Pharmaceuticals | Activated Carbon Adsorption | 80 to 95 | High adsorption capacity, simple operation | Adsorbent regeneration required | High |
| Antibiotics | Advanced Oxidation Processes (AOPs) | 85 to 98 | Effective degradation of persistent organic pollutants | High energy consumption | High |
| PFAS | Nanofiltration (NF) | 90 to 98 | Effective removal of dissolved PFAS compounds | Membrane fouling | Very High |
| Personal Care Products | Photocatalysis | 80 to 95 | Solar driven degradation potential | Process optimization required | Moderate to High |
| Endocrine Disrupting Compounds | Membrane Bioreactor (MBR) | 85 to 97 | Combined biological and membrane treatment | High operational cost | High |

**Hybrid And Integrated Water Treatment Systems**

In recent years, the integrated use of multiple technologies, rather than a single water purification technology, to control marine pollution has become a particular focus of researchers. The main reason is that no single technology is equally effective at removing all types of contaminants, because the physical and chemical properties of different contaminants differ. For example, while a technology may be highly efficient at removing heavy metals, it may be less effective at removing microplastics, pharmaceutical residues, mercury, and polyfluoroalkyl compounds. To overcome these limitations, hybrid and integrated water purification systems are currently considered one of the most important strategies for sustainable water management.

Analysis of selected studies shows that the combination of membrane and adsorption technologies is among the most widely used hybrid systems. In this system, first, the adsorbent material removes a large part of the organic pollutants, dyes and heavy metals. Membrane filtration then removes remaining small contaminants, microplastics, and dissolved compounds, producing high-quality purified water. This significantly reduces membrane fouling and increases membrane life. At the same time, operating costs have also decreased. The combination of advanced oxidation processes and membrane technology has also achieved significant success in recent research. The advanced oxidation process breaks down complex organic pollutants into relatively simple compounds, which can be easily removed through membrane technology in the next step. This integrated technology has demonstrated greater efficiency than single technologies, especially in removing pharmaceutical residues, pesticides, and chemicals from personal care products. In addition, the possibility of water recycling in this method also increases. The combination of advanced water purification technologies,



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biological treatment technologies, and constructed wetlands is gaining importance as an environmentally friendly solution. After removing easily degradable organic contaminants through biological processes, membrane or adsorption technology can be used to more effectively remove the remaining complex contaminants. Such integrated systems not only reduce energy consumption but also reduce operating costs and help ensure environmental sustainability in the long term.

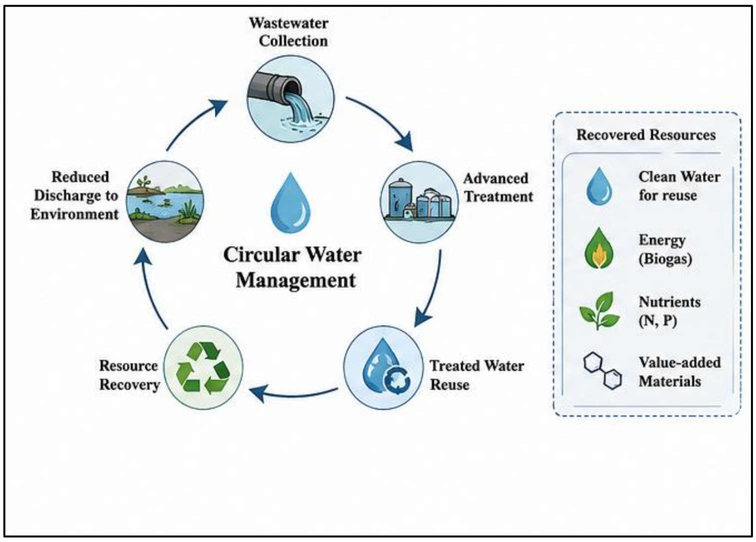


**Figure 4:** Circular Water Management Approach

Recent research has opened up new possibilities by combining hybrid water purification technology with artificial intelligence, smart sensors, and Internet of Things-based monitoring systems. These technologies can monitor water quality in real time, determine contaminant concentrations, optimize energy use, and enable automated management. As a result, not only does the technology increase efficiency, but it also significantly reduces operational costs and human error. It is expected that the use of such integrated technologies in digital water management will continue to increase.

Overall analysis shows that hybrid water purification systems are more effective, reliable, and sustainable than single technologies in figure 4. Integrated technologies offer significant advantages, especially in the simultaneous removal of heavy metals, microplastics, pharmaceutical residues, and other emerging pollutants. Although the initial investment and technical complexity are relatively high, hybrid water purification systems are the most promising future solution for mitigating coastal marine pollution due to their high removal efficiency, water recycling, energy savings, and long-term environmental sustainability (Olenin *et al.*, 2011).

**Table 3:** Comparative assessment of hybrid and integrated water treatment systems

| Hybrid Technology | Integrated Process | Target Pollutants | Typical Removal Efficiency (%) | Key Advantages | Major Limitations |
|---|---|---|---|---|---|
| Adsorption + Membrane Filtration | Adsorption integrated with membrane filtration | Heavy metals, organic pollutants, microplastics | 95 to 99 | High removal efficiency, reduced membrane fouling | High initial investment |
| Advanced Oxidation Process + Reverse Osmosis | AOP integrated with RO | Pharmaceuticals, PFAS, persistent organic pollutants | 95 to 99 | Highly effective for recalcitrant contaminants | High energy requirement |
| Biological | Biological | Organic | 90 to 98 | Environmentally | Regular |



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| | | | | | |
|---|---|---|---|---|---|
| Treatment + Membrane Bioreactor | degradation with membrane separation | pollutants, nutrients | | friendly, improved effluent quality | maintenance required |
| Electrochemical Treatment + Adsorption | Electrochemical process integrated with adsorption | Heavy metals, dyes | 92 to 98 | Rapid treatment, reduced chemical consumption | Electricity dependent |
| Constructed Wetland + Advanced Treatment | Nature-based system with advanced polishing | Mixed pollutants | 85 to 95 | Low energy demand, sustainable operation | Large land requirement |
| AI-Enabled Hybrid Water Treatment System | Smart monitoring with integrated treatment technologies | Multiple pollutants | 95 to 99 | Real-time optimization, high treatment efficiency | High implementation cost and technical complexity |
| Adsorption + Membrane Filtration | Adsorption integrated with membrane filtration | Heavy metals, organic pollutants, microplastics | 95 to 99 | High removal efficiency, reduced membrane fouling | High initial investment |

## DISCUSSION

The current study comprehensively evaluates the effectiveness, limitations, and future prospects of advanced water purification technologies for mitigating pollution in coastal marine ecosystems. The analysis of the results clearly shows that the levels of heavy metals, microplastics, pharmaceutical residues, antibiotics, and other emerging pollutants in the marine environment are steadily increasing due to industrialization, urbanization, agricultural activities, and inadequate wastewater management. In this situation, the need for advanced, integrated technologies is increasing, as conventional water purification methods are proving insufficient on their own. The research results further support the idea that it is essential to consider technological innovation and environmental sustainability together in future water management. Comparative analysis of selected studies indicates that membrane-based technologies, particularly nanofiltration, reverse osmosis, and membrane bioreactors, are among the most reliable due to their high removal efficiencies. These technologies have consistently demonstrated high performance in removing heavy metals, microplastics, and dissolved organic pollutants. However, the results also make it clear that membrane fouling, high energy consumption, and operating costs are the main obstacles to the widespread application of these technologies. As a result, it is necessary to consider economic and environmental aspects with equal importance, rather than selecting technology solely on the basis of removal efficiency.

On the other hand, adsorption technology and advanced oxidation processes have demonstrated significant effectiveness in removing specific types of contaminants. In particular, biochar, activated carbon, and nanomaterial-based adsorbents have proven effective in absorbing heavy metals and emerging pollutants. Similarly, advanced oxidation technology has played a significant role in the degradation of complex organic contaminants, pharmaceutical compounds, and antibiotics. However, even for these technologies, energy consumption, chemical requirements, and operating costs remain important areas for future development. The results of the study indicate that, in addition to technical efficiency, ensuring energy conservation and environmental safety is equally important. Another important observation from this study is that conventional water treatment systems are inadequate for the removal of microplastics and emerging pollutants. The results show that reverse osmosis, nanofiltration, and integrated hybrid technologies have demonstrated relatively the highest efficiency in removing these contaminants. However, there is still a lack of effective and low-cost technologies for mercury and polyfluoroalkyl compounds, nanoplastics, and some persistent organic pollutants. This limitation provides an important direction for future research. The analysis of the results also indicates that hybrid and integrated water purification systems



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are more effective than single technologies. The combination of membrane technology, adsorption, advanced oxidation processes, and biological treatment technologies has provided significant benefits in the simultaneous removal of various types of contaminants. At the same time, this integrated system has played a positive role in reducing membrane fouling, optimizing energy use, and increasing operational efficiency. As a result, current research clearly indicates that integrated technological platforms may be a more acceptable and effective solution for future coastal water management.

The results of this study are also important from an environmental sustainability perspective. The concept of water recycling, resource recovery, energy efficiency, and circular water management can make advanced water purification technologies more effective and sustainable. In particular, bioremediation, constructed wetlands, and nature-based solutions provide long-term environmental benefits while using relatively little energy. Although the removal efficiency of these technologies is lower than that of membrane technology in many cases, when combined with other advanced technologies, the overall performance increases significantly.

## FINDINGS

Several important findings emerged from the analysis of the current study. First, advanced water purification technologies are more effective at removing heavy metals, microplastics, and emerging pollutants in coastal marine environments than conventional technologies. Second, while reverse osmosis, nanofiltration, and membrane bioreactors exhibit the highest removal efficiencies, their energy consumption and operating costs are relatively high. Third, adsorption, bioremediation, and advanced oxidation processes have shown significant potential as effective, environmentally friendly alternatives for removing certain types of pollutants. Fourth, hybrid and integrated water purification systems provide more efficient and sustainable results than single technologies in removing multiple contaminants simultaneously. Finally, the combination of artificial intelligence, smart sensors, and circular water management will play a key role in making future coastal water treatment technologies more efficient, economical, and environmentally sustainable.

## RECOMMENDATION

Based on the results of the current study, the use of advanced water purification technologies needs to be expanded to effectively control coastal marine pollution. In particular, implementing hybrid water purification systems that combine membrane-based technology, adsorption, advanced oxidation processes, and biological treatment will enable more efficient removal of heavy metals, microplastics, and emerging pollutants. At the same time, priority should be given to the use of renewable energy, the development of environmentally friendly adsorbents, and the addition of artificial intelligence-based smart monitoring systems to reduce energy consumption and operating costs. In addition to laboratory-based testing, conducting long-term pilot studies in real coastal environments will provide more reliable information about the practical effectiveness, economic feasibility, and environmental sustainability of various technologies. In addition, effective policies need to be formulated and implemented through coordinated initiatives by the government, research institutions, industry, and environmental protection organizations. Future research should focus on developing more efficient, energy-efficient, and environmentally friendly technologies for the removal of emerging contaminants, including mercury, polyfluoroalkyl compounds, nanoplastics, pharmaceutical residues, and antibiotic-resistant microorganisms. If these initiatives are implemented, significant progress will be made in protecting coastal marine ecosystems, ensuring safe water reuse, and managing water resources sustainably.

## CONCLUSION

The current study comprehensively reviews the effectiveness, limitations, and future prospects of advanced water purification technologies for pollution mitigation in coastal marine ecosystems. The analysis found that industrialization, urbanization, and various human-induced activities are driving a continuous increase in the levels of heavy metals, microplastics, pharmaceutical residues, antibiotics, and other emerging pollutants, posing significant threats to marine biodiversity, ecological balance, and public health. In this context, membrane-based technologies, adsorption, advanced oxidation processes, bioremediation, and other advanced technologies have emerged as more effective alternatives to overcome the limitations of conventional water purification technologies. The study results also



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indicate that no single technology is equally effective in removing all types of contaminants. Rather, a hybrid water purification system consisting of multiple technologies can ensure greater removal efficiency, improved operational capability, and long-term environmental sustainability. At the same time, circular water management, resource recovery, renewable energy use, and artificial intelligence-based smart monitoring systems can play an important role in making future water treatment technologies more efficient, economical, and environmentally friendly.

Although significant progress has been made in advanced water purification technologies in recent years, several important challenges remain, including energy consumption, operating costs, membrane fouling, large-scale implementation, and the complete removal of emerging contaminants. As a result, future research needs to place greater emphasis on developing high-efficiency, low-cost, and environmentally friendly technologies, as well as evaluating long-term effectiveness in real coastal environments.

Overall, this study provides a comprehensive scientific understanding of the current progress, comparative performance, and future research potential of advanced water purification technologies for mitigating coastal marine pollution. The results of this study will serve as a useful reference for researchers, engineers, policymakers, and stakeholders involved in environmental management and will help lay the foundation for future research and technology development in sustainable coastal water management and marine environmental conservation.

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