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REMEDIAL SOLUTIONS AND CONSERVATION OF MARINE ENVIRONMENTS: A REVIEW

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Abstract

In the context of the blue economy and sustainable development of the marine environment, there is currently a continuous concern about identifying the most efficient practices and methods to mitigate pollution. Therefore, the current research in this field focuses on identifying remedial methods that can restore polluted environments and preserve those that haven't been affected significantly by the actions of humans. This study provides a comprehensive analysis of regional marine environmental pollution, including armed conflict-related contamination, and thoroughly assesses up-to-date principles and technologies regarding remedial solutions for marine pollution. Also, the best practices for remedial solutions have been identified and included in the available methodologies. Accordingly, it has been concluded that marine pollution is complex and suggests that combined methods should be used to address the multiple types of contaminants that reach marine environments.

Keywords*: marine pollution; armed-conflict pollution; remedial solutions; oil spills; heavy metals; plastic waste.*

Introduction

The pollution of marine environments has become a pressing problem worldwide due to its biodiversity, complex interaction with other environments, and challenges related to reductions of current pollutants [1,2]. Moreover, marine pollution dramatically affects the health of the oceans due to increasing industrialization, growing population, lack of sustainable waste management, armed conflicts, etc. [3,4]. Accordingly, the pollutants that reach the marine environment are vast (oil, pharmaceutical chemicals, chemicals from armed conflict, heavy metals, plastics, pesticides, etc.) and challenging to remove through conventional methods [5]. Therefore, marine pollution must be addressed through a multi-faceted process that considers a combination of technical and political principles; in other words, it combines filtration technologies (aimed at reducing current pollution) with international policies (aimed at reducing or eliminating future pollution). This report provides a combination of principles, best practices, and technologies that could be applied to ensure the remediation of the marine environment. This comprehensive overview aims to guide future efforts focused on pollution mitigation.

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The Black Sea basin faces ongoing environmental concerns, especially regarding the protection of the marine and coastal environment [1]. A strong collaboration among the Black Sea littoral entities can tackle this, which should aim to guide future efforts focused on the remediation of marine environments. Güneroğlu et al. [6] have highlighted the importance of several conventions (such as the Convention on the Protection of the Black Sea against Pollution and the Ministerial Declaration on the Protection of the Black Sea) and regional initiatives (like the Strategic Action Plan on the Rehabilitation and Protection of the Black Sea). Once the methods and action plan for protecting and rehabilitating the Black Sea are established, administrative entities should commit to reduce pollution in the region [6]. At the Romanian level, one of the most essential entities is The Commission on the Protection of the Black Sea Against Pollution, also known as The Black Sea Commission. The mission of The Black Sea Commission is to implement the provisions of the Convention on the Protection of the Black Sea Against Pollution and the Black Sea Strategic Action Plan.

The contamination related to the armed conflict requires innovative solutions, particularly due to the complexity of the pollutants combined with the diversity of the ecosystems (Fig. 1). Although conventional de-pollution methods have shown promising results in removing specific contaminants, only tailored solutions will work effectively in this area. One promising approach, known as bioremediation, consists of using microorganisms and fungi to transform the toxic compounds into unharmful products. In the case of marine environments, i.e., high-salinity environments, the bioremediation method is very efficient, especially in reducing pharmaceutical and organic pollutants [7].

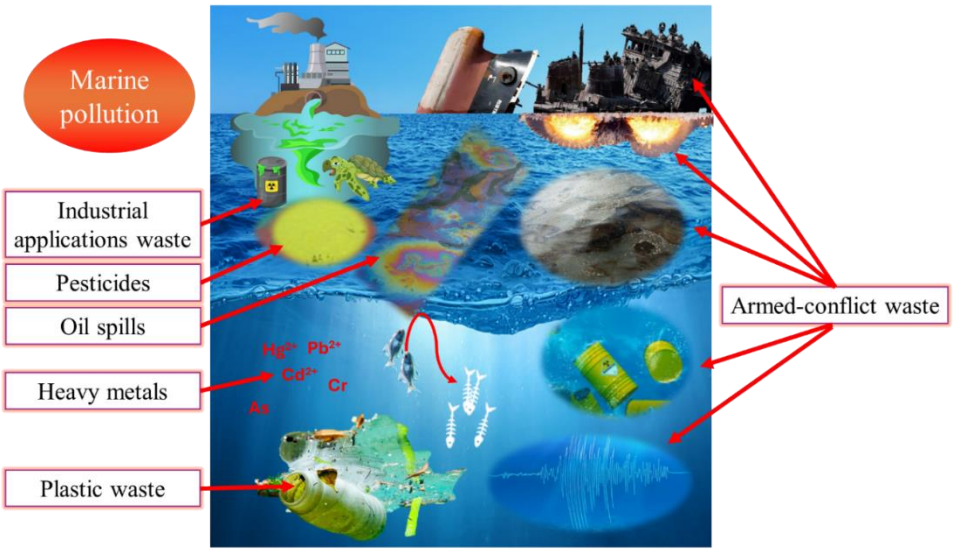

Fig. 1. Sources of marine pollution

Biodegradation exploits the capability of these contaminants to be degraded into these environments naturally, therefore being one of the most cost-effective and sustainable solution technologies [8]. Another advantage that makes this method preferable in many situations is its high versatility since almost any type of waste can be eliminated by using the right type of bacteria. For example, biosurfactants are suitable for hydrocarbon degradation in areas contaminated with oil products [9]. However, the main limitations of this method are related to the strict conditions in which the microorganisms are viable; therefore, if any condition changes, these microorganisms may die, and the de-pollution process will be stopped. Also, the decontamination speed is strongly dependent on the ability of the microorganisms or fungi

to reproduce. The marine environments also contain many contaminants that cannot be degraded using biodegradation since no microorganisms can consume those products [10].

Another advanced technique for the remediation of marine environments is known as electrokinetic. This method consists of applying an electric field that can mobilize heavy metals and organic compounds from sediments into products that can be recovered [11]. Pasciucco et al. [12] demonstrated the viability of this method for the decontamination of coastal areas by successfully using it to reduce toxic substances from marine sediments. However, its main limitation is related to the lack of adaptability to other types of contaminants, being viable only for treating marine sediments.

Currently, with the emergence of nanotechnologies as cutting-edge solutions in marine environment decontamination, different types of nanoparticles have been identified as suitable for adsorption, catalyzation, or detection of pollutants. Therefore, the job of developing tailored remedial solutions is much simpler while improving process efficiency and reducing the environmental footprint related to decontamination [13]. One successful pair contaminant-decontaminant is the example of polycyclic aromatic hydrocarbons-titanium dioxide; in this case, a common pollutant related to industrial activities could be reduced by using TiO_2 nanoparticles [14].

As also emphasized in the San Remo Manual on International Law, there is a crucial need to develop measures and methods that can mitigate the issues related to pollution and armed conflicts. Although the measures are mainly related to the legal frameworks and regulations, the methods are fundamentally connected to the evolution of decontamination techniques. Therefore, both sides should be approached in order to find the intersections between laws and technology that can ensure the safeguarding of coastal ecosystems against the negative impact of warfare on the environment [15]. In a balanced manner, since armed conflicts are already ongoing, suitable options should be sought to address the contaminants already present in the environment, facilitating the access of authorities to intervene and remove them [16]. These strategies for improving coastal management must also be developed to meet principles of sustainable practices. For example, the environment will not be remedied by removing one contaminant but affected by another, i.e., moving the contaminants from the water to the land. Strategies such as identifying and protecting essential areas and setting limits for exploiting marine resources will preserve marine diversity [17]. In order to develop the comprehensive strategies necessary to meet the current challenges of marine pollution, scientists, local communities, and policymakers should work together to address both the local and international consequences of this contamination.

The prevention of marine pollution is a key focus of EU environmental policy, aimed at managing all aquatic ecosystems. The EU Water Framework Directive emphasizes achieving “good ecological and chemical status” in waters. A unified mechanism is needed to monitor and curb pollution at its source. The Marine Strategy Framework Directive aligns with the EU’s "blue growth" agenda, promoting sustainable growth in the marine sector. To combat pollution, the EU has introduced the Zero Pollution Action Plan and the mission "Restore our Ocean and Waters," which focuses on reducing harmful emissions and enhancing ocean health. Additionally, “Healthy marine and coastal ecosystems” is a primary goal of the Common Maritime Agenda [17–21].

Maritime transportation, which increases during armed conflicts, is a major source of marine pollution, necessitating adherence to the MARPOL 73/78 Convention. On June 1, 2023, the European Commission proposed five legislative measures to modernize EU maritime safety and sustainability rules and prevent water pollution from ships. The proposals aim to align EU regulations with international standards and expand coverage to include illegal discharges of harmful substances, sewage, waste, and residues from exhaust gas cleaning systems.

In this context, marine pollution resulting from armed conflicts significantly threatens ecosystems, livelihoods, and human health. Several international conventions and agreements have been established to address these risks and promote environmental protection:

- United Nations Convention on the Law of the Sea (1982) [18] mandates states to prevent and control pollution from various sources, including armed conflict, focusing on Articles 192-237.
- Geneva Conventions (1949) and Additional Protocols (1977) emphasize the responsibility of conflict parties to protect the natural environment, including marine ecosystems.
- Hague Convention IV (1907), while primarily concerned with land warfare, influences international humanitarian law regarding environmental protection during conflicts.
- Customary International Law obligates states to refrain from causing unnecessary environmental damage, including to marine ecosystems during conflicts [11].
- International Law Commission's "Draft Principles on Protection of the Environment in Relation to Armed Conflicts" (2022), particularly Principles 13 and 14, prohibit warfare methods that cause severe environmental damage and apply humanitarian law principles to environmental protection [10].

Regional agreements, such as the **Barcelona Convention (1976)**, address specific marine pollution challenges in areas like the Mediterranean. The effects of pollution include oxygen depletion, reduced biodiversity, and health risks from contaminated seafood, threatening local economies dependent on fisheries and tourism.

With ongoing geopolitical tensions in the northern Black Sea, there is a growing need for biomonitoring of the marine environment due to concerns like acoustic pollution and toxic contamination from resource exploitation.

Assessment of up-to-date principles and technologies regarding the remedial solutions for marine pollution

In order to remediate marine pollution, a number of directions and principles (Figure 1) need to be developed simultaneously, such as prevention and protection, sustainable waste management (recycling, selective collection, etc.), integrated coastal zone management, development of the blue economy, biological remediation, international cooperation and legislative alignment, public awareness/education and business involvement, continuous monitoring and development of new/innovative remediation solutions for pollution affected areas. A number of guiding principles underlie the efforts aimed at addressing marine pollution [22]. These principles create a structure for adopting decisions, ensuring that the solutions implemented are effective, sustainable, and fair [23]. The principles outlined in Figure 2 are essential in influencing contemporary remedial approaches.

The principle of *prevention and precaution* focuses on eliminating pollution before it occurs. This is done by implementing strict regulations and limits on emissions from any machines (such as ships and barges) operating in coastal zones, as well as on waste disposal and land-based activities that could result in marine pollution.

The principles of *coastal zone management* can be put into action through a holistic approach that includes involving stakeholders. This approach encompasses the comprehensive management of coastal areas to attain a balance between social, ecological, and economic factors, ultimately leading to the reduction of marine pollution. Engaging all relevant parties, such as local communities, industry representatives, and government, is essential for effectively cleaning up the environment.

The *sustainable waste management* principle encourages the use of technologies and industries that already implemented all circular economy principles. Therefore, the disposed waste is very reduced or inexistent since it is used as raw material for other industries or processes. Moreover, all remaining waste, if any, should be treated correspondingly to ensure prevention from reaching the marine environment. Furthermore, the existing waste should be reduced or eliminated by involving innovative decontamination technologies, which should focus on recycling and reusing the collected waste or the polluted environment.

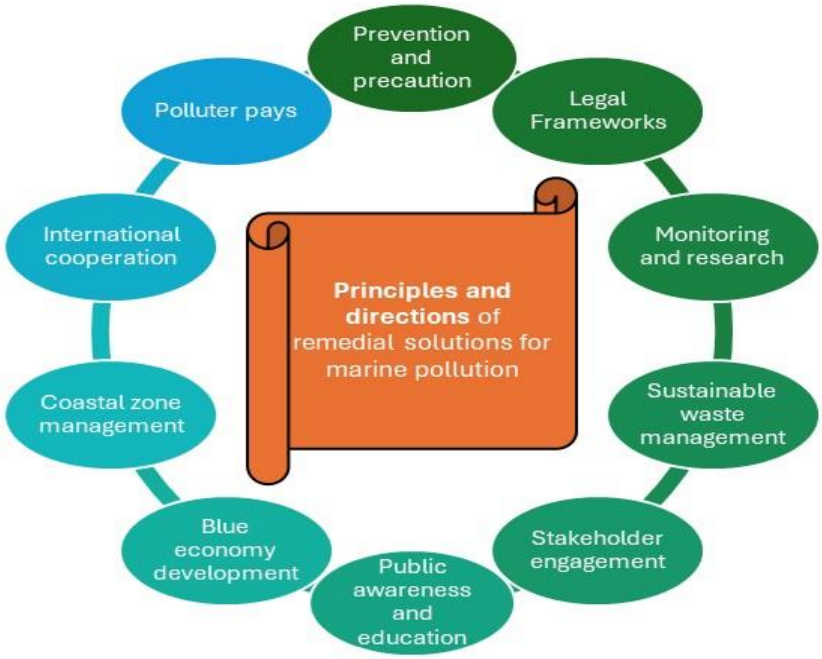

Fig. 2. The main principles and directions that could be applied to reduce marine pollution

The *blue economy* principle aims to encourage decontamination through bioremediation methods over conventional methods, which usually conduct other types of pollution due to using different natural resources (fuel, electrical energy, natural minerals, etc.) in the decontamination technologies. However, although this method is very effective against oil and heavy metals, which are challenging to remove through other methods, its main limitations are related to the dilution of bacteria in the marine environment. Also, the blue economy further encourages reducing the destabilization of ecosystems due to intensive fishing by developing sustainable fish farms with limited negative impact on the environment.

The changes in *legal frameworks* remain the strongest and most effective solution in combating pollution, especially in coastal zones by implementing strict regulations regarding how waste should be managed and pollution limits, the marine environment could be protected against pollution. When the policymakers *cooperate internationally* and manage to harmonize legislation, the entire region can be preserved. Some good practice examples are the UN's Vision 2030, which encourages sharing knowledge and resources at a Mondial scale to reduce pollution, and MARPOL, which specifies the regulations related to pollution from ships. Moreover, the legal framework should also include serious liability for polluters (*polluter pays*) that will result in increased care for the environment, especially when it comes to industrial activities. Nevertheless, some parties could afford any financial penalty. Therefore, the obligations should also include restoring the environment to its original state.

Although different remedial solutions for marine pollution have been developed and used, the current political context from some regions has conducted new types of pollutants that are challenging to eliminate, reduce, or even identify (noise pollution). These new pollutants are usually related to armed conflict events and the lack of collaboration from some states. In this context, marine pollution should be constantly *monitored and researched* in order to identify solutions suitable for the reduction/removal of these new contaminants. Data gathering regarding hot spot pollution will ensure informed decisions and reactions that will contribute to the elimination of intensive polluters.

Among the most important directions that could be conducted in marine protection for long periods of time is the increase in *public awareness and education* along with *stakeholder engagement*. Without educating the future generations and the representatives of the industries that affect the marine environment, no measure will be efficient. These measures should focus on promoting sustainable consumption habits as well as reducing the possibility of land-sourced pollutants. Moreover, the educational campaigns will impact local communities and empower representatives who will take the lead in organizing cleanup campaigns and sustainable practices at the regional level.

The principles guiding remedial solutions for marine pollution emphasize a proactive and integrated approach that combines prevention, innovative technologies, international cooperation, and community engagement. By adhering to these principles, stakeholders can effectively address the challenges of marine pollution in the Black Sea and beyond.

Identifying the best available practices for remedial solutions and including them in available methodologies

The evolution of technologies in the last decade offered efficient solutions for mitigating pollution problems. Most of the decontamination methods are designed for a specific pollutant [24,25]. Therefore, there are no decontamination solutions that can be used to solve all of these problems. Generally, the most suitable methods are sought and applied depending on the type of pollutant and the limitations related to the contaminated environment. In the case of marine pollution, decontamination technologies target well-known pollutants such as plastics, heavy metals, oil products, and wastes resulting from industrial applications. This study summarizes the most valuable methods used for the remediation of marine environments.

Decontamination methods for oil spills

One of the most destructive forms of pollution in marine environments is the contamination of oil products. The source of oil spills is related to many activities, such as extraction, transportation, or even ship explosions due to armed conflict [26]. Because the consequences of oil presence in marine environments are severe, many researchers focused on finding solutions to this problem. Therefore, the current literature presents mechanical, chemical, and biological methods for reducing contamination with oil. Due to their simplicity, cost-effectiveness, and high efficiency, skimmers and booms reduce oil from the water surface through mechanical methods. Also, when chemical methods are necessary, different dispersants and solidifiers can be introduced into the contaminated zone to break down the oil products and make them easier to degrade naturally. However, this method requires rigorous control to ensure the dispersants don't become polluters. Bioremediation is a much more "biocompatible" method that consists of introducing microparticles or microbacterials into the environment [27]. This technology will ensure the degradation of oil products in a much eco-friendlier manner.

Decontamination methods for plastic waste

Although different programs aimed at plastic reductions have been implemented in the last decade, the pollution of these products in the marine environment is still a pressing, growing problem. Plastic waste significantly affects the health of ecosystems due to the toxicity of the products resulting from degradation [28,29]. Some products made of plastics may become real death traps for marine life. Therefore, the need to develop suitable technologies to mitigate the impact of plastic pollution remains a priority worldwide. As in the case of oil spills, the plastic pollutants can be removed through a variety of methods (Figure 3), depending on the plastic size, shape and composition.

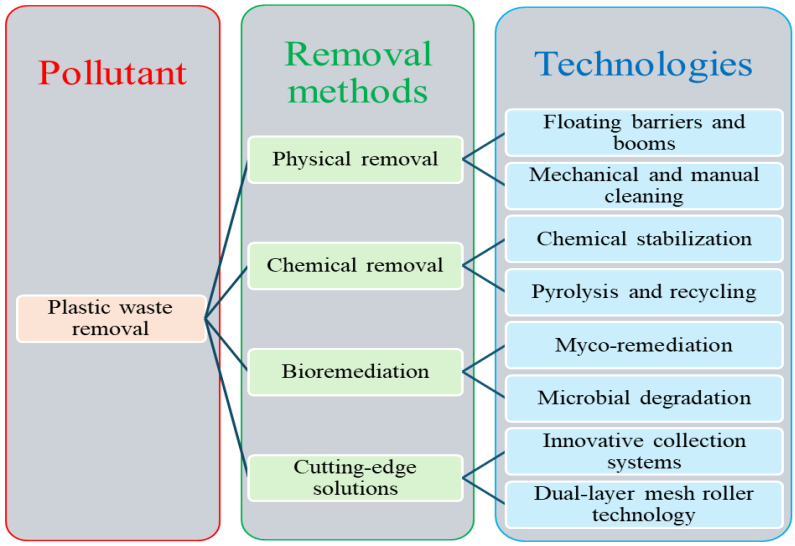

Fig. 3. Classification of plastic waste removal methods

In the case of plastic waste, the suitability and efficiency of each method depend on the type and location of plastic in the marine environment. The floating barriers and booms are mainly efficient for floating plastic waste by concentrating the contaminants using passive systems. While the main advantage of this method is related to the fact that the equipment used does not need any kind of energy to operate, the main disadvantage is related to the fact that the collected products must be transported to land for further processing. Mechanical and manual cleaning is mainly based on human effort; therefore, in this case, the local communities and authorities must be actively involved in decontamination by organizing and participating in campaigns to gather plastic products from the environment. The main advantage of physical removal is the minimum disturbance to the environment. However, its main limitation is related to the necessity of active involvement of people to collect the waste or to distribute the floating barriers and booms into the most relevant zones, and the further processing of the collected waste.

Myco-remediation and microbial degradation are effective methods for the bioremediation of environments contaminated with plastics. For example, species of the Aspergillus fungus can effectively degrade polyethylene and other types of plastics. This method relies on the ability of fungi to produce hydrolytic enzymes that break down polymer bonds [29].

The chemical method involves chemical stabilization and pyrolysis combined with recycling. The thermal degradation of plastics in oxygen-free environments allows for converting end-of-life plastic products into raw materials without releasing toxic byproducts into the atmosphere. This method can also enhance the efficiency of physical decontamination by incorporating elastomers, which can capture plastic microparticles from marine environments [30].

Due to the significant impact of plastic pollution on the marine environment, there is an urgent need to address this issue. This urgency has led to the development of new technologies, such as the dual-layer mesh roller method, which uses induction heating to separate plastic microparticles from water. Additionally, by integrating smart materials into physical removal systems, we can sustainably capture plastics without harming the marine ecosystem.

Decontamination methods for eutrophication and removing nutrients

Similar to removing plastics and oil, this environmental issue has been addressed through various methods to find the most suitable solution based on each environment's specific conditions that need treatment. In some cases, aeration and hypolimnetic oxygenation systems

have proven to be the most effective, while in others, using bio-filters and artificial wetlands has been more practical [31]. Of course, targeted solutions for phosphorus removal could be implemented in environments where high phosphorus concentrations are the main problem.

The high concentration of nutrients from aquatic systems that reach the marine environment due to wastewater discharge and agricultural runoff leads to the rapid development of algae. This phenomenon is known as eutrophication, which is responsible for decreasing oxygen levels in the water and releasing toxins associated with the decomposition of algae. The main chemical elements typically present in these marine environments are nitrogen and phosphorus, which contribute to hypoxic conditions. Several mitigation strategies can be implemented to reduce the harmful effects of eutrophication [32].

The restoration of water quality and environmental balance can be achieved through three main approaches: physical, chemical, and biological methods (Figure 4).

The restoration through physical methods includes aeration and sediment removal. They have the primary advantage of minimal impact on marine life; however, they tend to be less efficient and can incur high operational costs.

The restoration through chemical methods involves nutrient precipitation using flocculants and coagulants. They rely on physical methods for the actual removal of the coagulated nutrients, which can limit their effectiveness.

The restoration through biological methods uses microorganisms and aquatic plants to promote natural restoration, such as the growth of plants in marine environments. While beneficial, these plants may sometimes be incompatible with native species, potentially disrupting the local ecosystem.

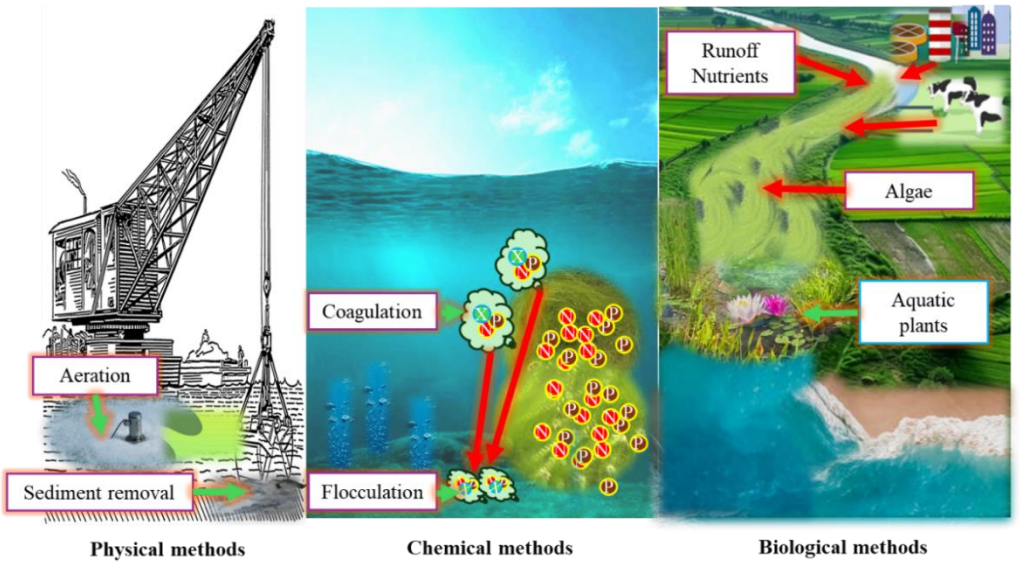

Fig. 4. Eutrophication and nutrients removal methods

As shown, none of the existing methods will be effective when used separately. Therefore, it is essential to develop and implement an integrated solution that combines all available techniques to reduce the causes of this type of pollution [33].

Decontamination methods for heavy metals and chemical pollution

One of the most persistent problems related to marine pollution is contamination by heavy metals/emergent pollutants. This issue can be addressed through various physical, chemical, biological, and technological methods. Among these, phytoremediation and

bioremediation show particularly promising results, especially in rivers and coastal areas. However, in environments where growing specific plants is challenging, nanotechnologies or advanced oxidation processes may be more suitable alternatives [34,35]. By combining these approaches, it is possible to effectively remove heavy metals/emergent pollutants or convert them into less toxic compounds, while also promoting natural restoration.

In the context of heavy metal contamination, sediment dredging and the use of sorbent materials are among the most commonly employed physical restoration methods [28]. While this approach is quite effective, the main challenge lies in managing the contaminated material that has been extracted, as it often results in transferring the problem from one environment to another.

Chemical methods can immobilize heavy metals into complex compounds that are non-toxic to the environment. For instance, using phosphates or electrocoagulation, or a combination of both, can transform these contaminants into products that are less harmful to aquatic life.

Similar to nutrient removal, bioremediation methods also utilize microorganisms to degrade or incorporate pollutants. Biostimulation and bioaugmentation involve introducing nutrients and specific microbial strains to facilitate the removal of targeted heavy metals.

Phytoremediation involves the use of plants to absorb heavy metals into their tissues or transform them into less toxic substances [36]. Aquatic plants, particularly water hyacinth, have demonstrated significant effectiveness in reducing levels of cadmium and lead in marine environments.

The use of nanotechnologies is highly effective in transforming heavy metals by introducing various reagents and nanoparticles into contaminated environments [37,38]. For example, the Fenton reagent can reduce both organic chemicals and heavy metals in marine ecosystems. Additionally, nZVI nanoparticles, which have high reactivity and a large surface area, can convert these toxic substances into non-toxic compounds [39].

Although each type of waste has different suitable technologies for removing it, the most useful method that will ensure the reduction of future pollution remains the education and engagement of the public and policymakers. By fostering the involvement of communities and setting international laws and regulations, the protection of the environment, especially the marine environment, can be assured. Moreover, different educational programs can be developed to target the young generation, empowering individuals who will further promote and lead to the employment of decontamination and waste reduction methods.

Marine pollution due to the armed conflict

The armed conflucts have a significant impact on the environment in various regions of both involved and neighbouring countries [40]. One growing concern is marine pollution in the Black Sea region. This ecosystem's biodiversity has been adversely affected by both bombings and industrial activities related to the production and transportation of war-related products. The ecological damage caused by debris and chemical pollutants in the Black Sea needs to be addressed and restored as soon as possible to prevent these effects from becoming permanent and irreversible [41]. However, tackling this type of pollution is very challenging due to its complexity and the restrictions from multiple zones, with a priority on addressing high-pollution hotspots.

The factors affecting the marine environment due to armed-conflict in the Black Sea region are [42–44]:

- Naval combat and explosion (noise pollution, heavy metals pollution, plastic pollution, chemical pollution, and debris);
- Oil spills and fuel leaks (oil pollution; chemical pollution);
- Chemical and radioactive pollution (heavy metals pollution; chemical pollution; radioactive pollution);

- Destruction of marine habitats (physical change of the environment: destruction of coral reefs, destruction of seagrass beds);
- Disruption of waste management (the wastewater treatment and solid waste management have been affected in the cities where the conflict was is taking place, therefore these contaminants will reach the marine environments);
- Disruption of fishing activities (unbalance of fish exploitation: overfishing in some areas, lack of fishing in other areas).

Addressing the marine pollution caused by the armed conflict requires complex methods that should involve cutting-edge technologies, policymakers, and local communities.

Political measures are the most effective way to combat this type of pollution, as they can be approached through methods that reduce pollution on an international level. Moreover, many international conventions and commitments, such as MARPOL, are already established and can be effective only if countries are convinced to adhere to their principles and regulations [45]. Essentially, these measures can help avoid further damage by prohibiting the use of weapons that significantly harm the environment, especially in marine areas. It is essential to implement fighting restrictions in areas requiring utmost protection. In regions where pollution could have irreversible consequences, all forms of bombing and attacks on fleets, such as ships or submarines, should be strictly prohibited.

First and foremost, political measures that can halt pollution related to armed conflict, such as implementing ceasefires, are crucial. Following this, the solution for decontamination lies in emergency response and cleanup operations. Specialized teams should be deployed to locate and eliminate contaminants using buoys with sensors or other efficient methods that can be controlled remotely [46]. These teams must be prepared to dispatch the necessary resources immediately to the polluted "red zones" in order to capture pollutants before they spread into the marine environment.

The reduction or removal of contaminants related to armed conflict should involve methods specific to each type of pollution [39]. Consequently, tailored restoration strategies should be developed and implemented for each area based on the specifics of the contamination. Furthermore, post-war reconstruction should be designed and carried out with the principles of sustainable development in mind. Coastal and port infrastructure should be constructed using sustainable, marine-friendly materials and machinery that produce low to zero pollutants while operating in the ports.

Conclusions

This report highlights the significant findings that underscore the importance of marine environment remediation strategies. The data collected demonstrates that marine pollution is complex and suggests that combined methods should be used to address the multiple types of contaminants that reach marine environments. Moving forward, it is essential to consider these insights to enhance the restoration of the environment. Therefore, continued research and monitoring are recommended to ensure sustained progress and adaptation.

To summarize, the analysis presented in this report sheds light on the sources of pollution in marine environments and the up-to-date principles and technologies regarding remedial solutions for marine pollution. The evidence indicates an urgent need to develop decontamination technologies, especially for armed-conflict-related contamination, and reveals the best practices for remedial solutions. Therefore, stakeholders must take action based on these findings, ensuring that the lessons learned are implemented effectively to foster improvement in the prevention and restoration of marine environments.

Ultimately, this report has addressed the contamination of marine environments due to the armed conflicts, and immediate action should be taken to reduce further pollution of the environment. The implications of these findings are profound, suggesting that policy measures

are among the most effective, but new technologies should also be developed to improve decontamination efficiency. The international community must reflect on these insights and collaborate towards finding a solution to the cease-fire between the involved countries. Through targeted actions and ongoing evaluation, we can pave the way for a sustainable rebuild of the Black Sea shore and worldwide restoration of the marine environment.

Acknowledgments

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