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REMEDIATION OF WAR-RELATED CONTAMINANTS THROUGH GEOPOLYMER TECHNOLOGY: A CONSERVATION PERSPECTIVE

Dumitru Doru BURDUHOS-NERGIS[1], Petrica VIZUREANU[1,2*],
György DEÁK[3], Andrei Victor SANDU[2,4,5]

[1] Faculty of Materials Science and Engineering, “Gheorghe Asachi” Technical University of Iasi, 67 Prof. D. Mangeron Blvd., 700050 Iasi, Romania
[2] Technical Sciences Academy of Romania, 26 Dacia Blvd., 030167 Bucharest, Romania
[3] National Institute for Research and Development in Environmental Protection, 294 Splaiul Independenței, 6th District, 060031, Bucharest, Romania
[4] Romanian Inventors Forum, 3 Sf. Petru Movilă St., L11, III/3, 700089 Iași, Romania
[5] Academy of Romanian Scientists, 54 Splaiul Independenței St., Sector 5, 050094 Bucharest, Romania

Abstract

Pollution associated with armed conflicts poses a complex threat to marine environments, including heavy metals, hydrocarbons, persistent organic pollutants, plastic debris, and contaminated sediments. In this context, the article analyses the potential of geopolymer technology as a sustainable solution for remediating contaminants generated by military and industrial activities, with a focus on the conservation of marine ecosystems. Geopolymers, due to their aluminosilicate structure, controllable porosity, and capacity for adsorption, ion exchange, and encapsulation, can contribute to the retention and immobilization of hazardous pollutants. The paper highlights the main mechanisms through which geopolymeric materials can reduce the mobility of contaminants and limit their impact on biodiversity and water quality. The proposed approach supports the development of integrated decontamination and conservation solutions, in line with the current need to protect the marine environment affected by civil and military pollution.

Keywords*: military pollution; geopolymers; marine decontamination; heavy metals; hydrocarbons; adsorption; encapsulation; marine environmental conservation.*

Introduction

Marine pollution is one of the most significant challenges currently facing ecosystem conservation, as it simultaneously affects water quality, sediments, biodiversity, coastal habitats, and socio-economic activities that depend on marine resources [1]. In recent decades, pressure on marine ecosystems has increased significantly due to industrialization, maritime transport, resource exploitation, coastal urbanization, and poor waste management [2]. In addition to these conventional sources of pollution, armed conflicts have become an additional source of contamination, generating pollutants that are difficult to identify, monitor, and eliminate using conventional methods. In this context, protecting marine environments can no longer be addressed solely through preventive measures but requires the development of remediation technologies capable of limiting the mobility of contaminants and supporting the restoration of affected ecosystems [3].

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[*] Corresponding author: peviz2002@yahoo.com

The Black Sea region is particularly vulnerable to such pressures, due to both its geographical and ecological characteristics and the impact of human activities within its river basin. Inputs from major rivers, port activities, maritime transport, industrial areas, and urban agglomerations increase the risk of contamination. In the context of the conflict in Ukraine, risks to water resources and aquatic ecosystems have increased considerably, with reported impacts on water infrastructure, treatment systems, dams, port areas, and coastal regions [4]. Attacks on civilian and industrial infrastructure can lead to the release of toxic substances into soil, surface water, and groundwater, with the potential for subsequent transport to the marine environment [5]. Unlike contamination from conventional sources (industrial activities, maritime transport, etc.), contamination associated with armed conflicts is far more complex because it can include heavy metals, hydrocarbons, persistent organic pollutants, munitions remnants, petroleum products, plastics, nutrients, and contaminated sediments. These pollutants can originate from both direct sources, such as explosions, damaged military equipment, damaged ships, or fuel spills, and indirect sources, such as the destruction of water infrastructure, sewage systems, industrial storage facilities, or treatment plants. Furthermore, the effects of contamination are not limited to the immediate conflict zone, as pollutants can be transported via river systems, sediments, and ocean currents to distant coastal areas and ecosystems [4], [6]. An important characteristic of pollution caused by armed conflict is its mixed and unpredictable nature. Unlike situations where an industrial source generates a dominant type of pollutant, military actions can lead to the simultaneous presence of multiple classes of contaminants, each behaving differently in water, sediments, and biota [7]. Heavy metals can persist and bioaccumulate, hydrocarbons can affect oxygen exchange and marine organisms, and persistent organic compounds or plastic particles can contribute to the secondary transport of other pollutants. This complexity makes it difficult to apply a single remediation method and necessitates the development of integrated solutions tailored to multiple types of contamination.

Previous studies [3] on the remediation of marine environments have shown that conventional methods are generally effective for specific categories of pollutants. Bioremediation can be useful for certain organic substances, physical methods can help remove floating particles or debris, and chemical methods can facilitate the immobilization of certain metal species. However, in cases of contamination associated with armed conflict, these methods may be insufficient when applied in isolation. The study emphasized that marine pollution is complex and that reducing multiple contaminants requires combined methods capable of simultaneously addressing multiple transport and accumulation mechanisms.

In this context, geopolymer materials offer a promising avenue for developing sustainable remediation solutions. Geopolymers are inorganic materials obtained through the alkaline activation of aluminosilicate precursors, such as metakaolin, fly ash, slag, or other mineral wastes. Interest in these materials is driven by their sustainability, the potential to utilize secondary resources, and their ability to be engineered for functional applications, including the adsorption, filtration, and immobilization of contaminants [8]. Unlike conventional adsorbents, geopolymers can combine contaminant retention with their stabilization within an inorganic matrix, thereby reducing the risk of secondary contamination [9].

The relevance of geopolymers for the remediation of marine environments was also demonstrated by a previous study [10] that incorporated these types of materials into a filtration system for contaminated seawater. The results showed that metakaolin geopolymers can retain heavy metals, and the addition of zeolite aggregates can improve performance for certain classes of pollutants, including phosphates, petroleum hydrocarbons, and nitrogen compounds (Fig. 1). These results indicate that geopolymer technology can be adapted to mixed contamination scenarios; however, a more comprehensive analysis of the role of these materials is needed to better conserve marine environments affected by civil and military pollution.

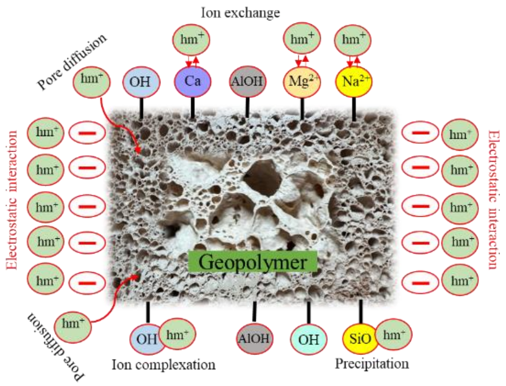

Fig. 1. Adsorption mechanism of heavy metals (hm$^+$) in geopolymer filter (reprinted from [10])

This paper evaluates the suitability of geopolymers technology for the restoration of marine environments affected by contaminants from armed conflict. Integrating geopolymer technology into remediation strategies can offer a solution that complements existing methods by combining functional performance with the principles of the circular economy and environmental conservation. Thus, geopolymers can be considered not merely adsorbent materials, but technological tools with the potential to reduce the impact of war contaminants and support the long-term recovery of marine ecosystems.

Contaminants associated with armed conflicts in marine environments

Marine contamination associated with armed conflicts represents a specific form of pollution because it does not typically originate from a single, controllable source but rather from a succession of destructive events. These events include explosions, ship damage, abandonment of military equipment, fuel spills, fires, destruction of industrial and port infrastructure, disruption of wastewater treatment systems, and resuspension of contaminated sediments [11]. Consequently, conflict-induced pollution is a mixed, discontinuous, and difficult-to-predict phenomenon, comprising inorganic and organic contaminants, solid particles, persistent compounds, and residues from destroyed infrastructure [11]. In the Black Sea, this problem is exacerbated by the basin's semi-enclosed nature, which can promote the accumulation and persistence of pollutants in water, sediments, and marine organisms [12], [13]. Fig. 2 summarizes the conceptual pathway of contaminants associated with armed conflicts, from pollution sources and transport routes to the affected marine compartments and ecological consequences. This diagram highlights the interconnected nature of contamination, in which pollutants can be transferred from affected areas to seawater, sediments, biota, and coastal habitats, generating persistent effects on ecosystems. Table 1 summarizes the main categories of contaminants and their main impacts on the marine environment.

An important category of contaminants is heavy metals. These can originate from ammunition, metal fragments, damaged military vehicles, damaged ships, electronic equipment, destroyed industrial infrastructure, or previously contaminated sediments remobilized by explosions, floods, or remediation work. Elements such as Pb, Cd, Cu, Zn, Ni, Cr, Mn, and As are of major concern because they are not biodegradable, can persist for long periods in sediments, and can be transferred to aquatic organisms [14]. Studies conducted in areas affected by military operations have indicated increases in the concentrations of certain metals and ecological risks associated with their accumulation in soils and aquatic systems, confirming that metal pollution can become a long-term problem rather than a temporary effect of the conflict [15]. The risk associated with heavy metals is amplified by their mobility between different environmental compartments. Once released into aquatic systems, metal species can remain dissolved, adsorb onto suspended particles, accumulate in sediments, or become bioavailable to organisms. Sediments can act as both a reservoir and a secondary source of contamination, especially when disturbed by currents, storms, dredging, explosions, or changes in pH and redox potential. In such situations, the mere physical removal of contaminated material is insufficient; methods capable of stabilizing or immobilizing contaminants are required to reduce the risk of re-release into the water and transfer to food chains [4], [12].

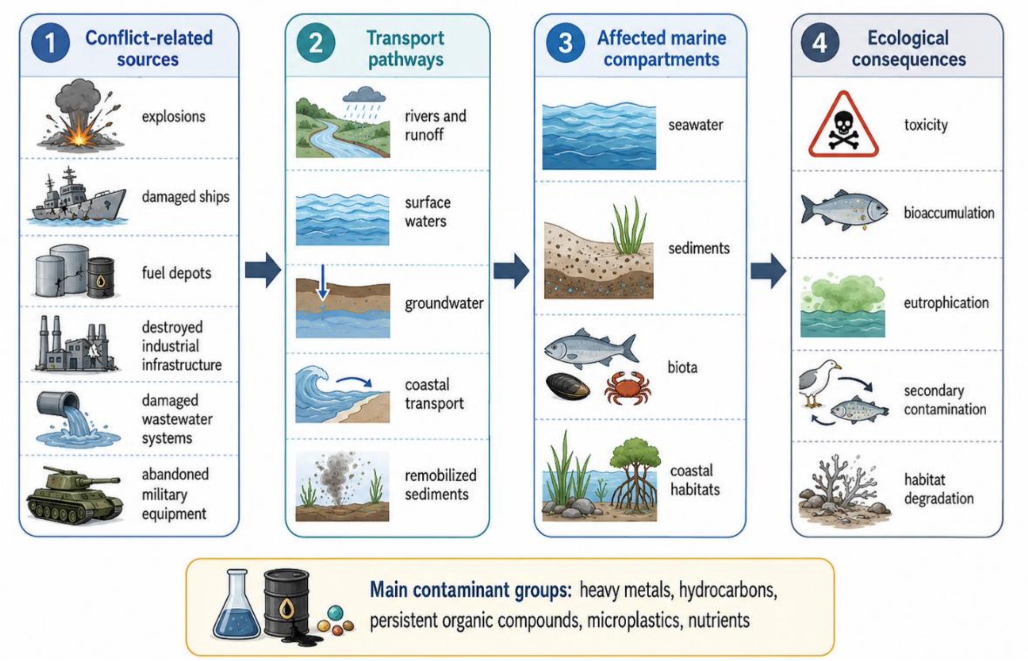

Fig. 2. Conceptual pathway of war-related contaminants from conflict-affected areas to marine ecosystems.

Table 1. Summary of the types of contaminants and their effects on marine environments

Contaminant category	Sources related to armed conflicts	Behavior in the marine environment	Main environmental impact
Heavy metals	ammunition, metal debris, military vehicles, damaged ships, destroyed industrial infrastructure	persist in water and sediments; they can be re-released and bioaccumulate	toxicity, bioaccumulation, impact on biodiversity
Petroleum hydrocarbons	fuel spills, damaged ships, destroyed oil storage facilities, fires	can form films, can bind to particles and sediments	toxicity to organisms, reduced oxygen exchange, sediment contamination
Persistent organic pollutants	fires, explosions, solvents, re-mobilized pesticides, PAHs, PCBs	persist in sediments and can enter food chains	chronic toxicity, bioaccumulation, long-term effects
Microplastics and synthetic fragments	equipment, packaging, synthetic textiles, cables, nets, composite materials	carries other pollutants; accumulates in water, sediments, and biota	ingestion, transport of metals and organic compounds
Nutrients and secondary pollutants	destroyed wastewater treatment plants, damaged sewer systems, and untreated wastewater	contributes to eutrophication and a decrease in dissolved oxygen	algal blooms, hypoxia, habitat degradation
Contaminated sediments	remobilization through explosions, flooding, dredging, and storms	acts as a reservoir and a secondary source of contaminants	long-term contamination, leaching into water

Another major category of contaminants consists of hydrocarbons and petroleum products. These can result from damage to military or commercial vessels, fuel spills, the destruction of fuel depots, fires, damage to port infrastructure, or the abandonment of military vehicles. Hydrocarbons can form films on the water's surface, reduce oxygen exchange, affect marine organisms, and facilitate the transport of other hydrophobic contaminants [11]. In addition, petroleum products can interact with suspended particles, microplastics, and sediments, generating complex mixtures of contaminants that are difficult to treat using methods targeting a single class of pollutants. For the Black Sea, oil pollution is relevant both due to routine maritime activities and the risks associated with conflicts, where damage to ships and coastal infrastructure can lead to acute contamination events [16].

Persistent organic pollutants are another category of concern for marine environments affected by armed conflicts. These may include residues from explosive materials, combustion products, solvents, industrial additives, remobilized pesticides, PCBs, polycyclic aromatic hydrocarbons, and other toxic substances released during fires, industrial accidents, or infrastructure destruction [12]. The persistence and toxicity of these compounds are important from a conservation perspective, as they can accumulate in sediments, be transported over long distances, and enter food chains. Recent assessments of the Romanian Black Sea region have highlighted the importance of persistent organic pollutants, polycyclic aromatic hydrocarbons, and organochlorine pesticides in assessing the marine environment's quality [13].

Microplastics and fragments from synthetic materials also constitute a significant component of contamination associated with armed conflicts. In war-affected areas, such particles can originate from packaging, protective gear, synthetic textiles, vehicle components, infrastructure debris, boats, cables, nets, ropes, and composite materials [17]. Explosions and mechanical fragmentation can accelerate the breakdown of large plastic materials into smaller particles. Microplastics are not merely physical pollutants; their surfaces can adsorb heavy metals, hydrocarbons, and persistent organic compounds, turning them into vectors for the transport of other contaminants into the water column, sediments, and marine organisms [18].

Nutrient contamination and secondary pollutants must also be considered in conflict scenarios. The destruction of wastewater treatment plants, damage to sewer systems, flooding of urban or industrial areas, and disruption of waste management systems can lead to the discharge of untreated or inadequately treated wastewater into rivers and coastal areas. This contamination can increase concentrations of nitrogen, phosphorus, ammonium, nitrites, and nitrates, promoting eutrophication, excessive algal growth, reduced dissolved oxygen, and the degradation of aquatic habitats [3].

Contaminated sediments represent a critical component of marine pollution associated with armed conflicts. They can accumulate heavy metals, hydrocarbons, organochlorine pesticides, polychlorinated biphenyls and polycyclic aromatic hydrocarbons, and other persistent substances. Once deposited, contaminants can remain in sediments for long periods, but can be remobilized by currents, storms, dredging, explosions, or changes in the water's physicochemical conditions. In the Black Sea, sediment vulnerability is particularly significant, as riverine inputs, port activities, industrial discharges, and conflict-related disturbances can contribute to the formation of accumulation zones [13], [19]. Thus, sediments should not be viewed as passive reservoirs, but as active environments that can control the long-term mobility of contaminants and the associated ecological risk.

The main challenge in remediating contamination associated with armed conflicts stems from the mixed nature of the pollution. Heavy metals, hydrocarbons, persistent organic pollutants, microplastics, nutrients, and contaminated sediments can coexist and interact, altering the mobility, bioavailability, and toxicity of the pollutants. Under these conditions, combined, adaptable remediation solutions are needed to limit the transfer of contaminants between water, sediments, and biota [10]. From this perspective, geopolymeric materials are relevant because they can integrate adsorption, ion exchange, precipitation, complexation, and encapsulation into a stable inorganic matrix [20]. Previous studies have shown that geopolymer systems and geopolymer–zeolite composites can retain heavy metals and reduce phosphates, petroleum hydrocarbons, and nitrogen compounds in seawater [3]. Thus, contaminants must be addressed as an interconnected pollution system, and the development of sustainable remediation technologies is essential to reduce contaminant mobility and protect marine ecosystems.

Geopolymer technology as a solution for remediation and conservation

Geopolymer technology represents a promising approach for the sustainable remediation of contaminated aquatic environments, particularly in cases of pollution associated with armed conflicts, where heavy metals, hydrocarbons, persistent organic pollutants, microplastics, nutrients, and contaminated sediments may coexist. In such scenarios, the materials used for decontamination must simultaneously fulfill several functions: enable effective contact with contaminated water, retain pollutants, reduce their mobility, and limit the risk of secondary contamination. Geopolymers meet these requirements through their aluminosilicate structure, controllable porosity, chemical stability, and adsorption, ion exchange, and immobilization capacities [21], [22].

Geopolymers are inorganic materials obtained through the alkaline activation of precursors rich in silicon and aluminum, such as metakaolin, fly ash, slag, red mud, or other mineral wastes [23], [24]. During geopolymerization, silicate and aluminate species form a three-dimensional network composed of [SiO_4] and [AlO_4] tetrahedra, which confer structural and chemical stability on the material and enable interaction with ionic species in contaminated solutions. Thus, geopolymers should not be viewed merely as alternatives to conventional cementitious materials, but also as functional materials for water treatment and contaminant immobilization [25].

Table 2. Mechanisms of geopolymers for the removal and immobilization of contaminants

Mechanism	Description	Target contaminants	Role in remediation	Relevance to conservation
Adsorption	Adsorption of contaminants onto the surface of the geopolymer gel or within its pores	Heavy metals, ionic compounds, certain organic molecules	Reduces the concentration of dissolved contaminants	Reduces organisms' exposure to pollutants
Ion exchange	Replacement of Na^+, Ca^{2+}, and Mg^{2+} ions in the matrix with toxic metal ions	Pb^{2+}, Cu^{2+}, Zn^{2+}, Cd^{2+}, Ni^{2+}	Binds metal cations	Reduces the bioavailability of metals
Surface complexation	Legarea ionilor metalici de grupări Si–O^-, Al–O^- sau –OH	Heavy metals	Increases the stability of retained contaminants	Limits the release into the water
Precipitation	The formation of poorly soluble hydroxides, carbonates, or silicates	Heavy metals	Converts contaminants into less mobile forms	Reduces toxicity and mobility
Diffusion through pores	Transport of pollutants to active domestic sites	Dissolved contaminants and fine particles	Increases the contact area	Improves the efficiency of the filtration system
Encapsulation	Trapping of contaminants in the hardened aluminosilicate matrix	Metals, contaminated particles, filter waste	Stabilizes contaminated material	Prevents secondary contamination
Functionalization	The addition of zeolites, biochar, or metal oxides	Phosphates, metals, hydrocarbons, organic compounds	Improves selectivity and performance	Allows for adaptation to mixed contamination

A key advantage of geopolymers is the possibility of obtaining tailored porosity. By selecting precursors, adjusting the solid-to-liquid ratio, modifying the alkaline activator, and employing structuring methods, it is possible to produce compact, granular, porous, or interconnected-porosity materials [10]. In remediation applications, open porosity allows contaminated water to penetrate the material, thereby increasing the contact surface area between pollutants and the active phases. Recent studies have shown that porous geopolymers can be used as adsorbents for inorganic and organic contaminants, including heavy metals, dyes, and other water pollutants [26]. Fig. 3 summarizes the general framework for the use of geopolymer materials in the remediation of marine contamination, spanning pollution sources and affected compartments, functional materials, remediation mechanisms, and environmental conservation effects. The diagram highlights the multifunctional nature of geopolymers and the role of continuous monitoring in optimizing remediation strategies.

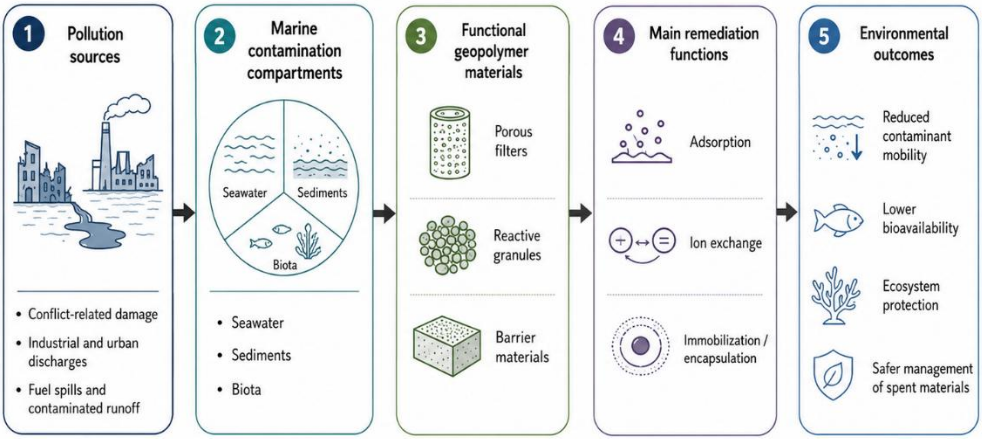

Fig. 3. General framework for geopolymer-based remediation of marine contamination.

In marine environments, porosity must be balanced with chemical and mechanical stability, as seawater contains high salinity, competing ions, organic matter, and suspended particles. These conditions can influence adsorption, ion exchange, pore flow, and the material's durability. Therefore, geopolymers intended for marine applications must combine permeability with resistance to saline environments and long-term functionality.

The ability of geopolymers to act as a remediation platform stems from the combined action of several mechanisms. The porous structure facilitates the transport of contaminants to active sites, while the aluminosilicate matrix enables adsorption, ion exchange, complexation, precipitation, and immobilization of hazardous species. In the case of heavy metals, these mechanisms can reduce the concentration of toxic ions and limit their mobility. Similar behaviors have been reported for porous geopolymeric materials used as reactive fillers in permeable barriers for lead removal from contaminated water [27], [28].

An important characteristic that distinguishes geopolymers from many conventional adsorbents is their capacity to immobilize contaminants within a solid matrix. Conventional adsorbents can retain pollutants on their surfaces, but they may be prone to desorption under varying pH, salinity, or ionic conditions. In contrast, geopolymers can stabilize contaminants by incorporating them into the aluminosilicate network, trapping them in pores, or forming poorly soluble phases. This property is relevant for contamination associated with armed conflicts, where the objective is not only to reduce pollutant concentrations but also to limit their long-term mobility [29]. From the perspective of marine environmental conservation, this stabilizing capacity is essential. A remediation solution must not transfer pollution from the water to other environmental compartments or generate unstable secondary waste. Through encapsulation and immobilization, geopolymers can reduce the risk of leaching, remobilization, and transfer of contaminants to sediments, organisms, and food chains. Thus, their role goes beyond that of a filtering material, becoming part of a strategy to reduce ecological risk and protect biodiversity.

From a sustainability perspective, geopolymers offer the advantage of utilizing local raw materials and mineral waste, such as fly ash, slag, red mud, or calcined clays. This approach reduces dependence on primary resources and supports the principles of the circular economy. In addition, geopolymer materials can have a lower environmental impact than conventional cement-based systems, especially when derived from industrial or mineral waste [30].

The versatility of the processing methods allows for the production of geopolymers in the form of granules, foams, porous monoliths, membranes, reactive layers, or 3D-printed structures. These forms can be integrated into filter cartridges, permeable reactive barriers, or modular treatment systems. Methods such as direct foaming, granulation, and 3D printing enable control over the pore architecture and optimization of contact between the contaminated water and the active material [31]. The incorporation of functional phases, such as zeolites, can improve the performance of geopolymers in mixed-contamination scenarios. Zeolites have a porous structure and high ion-exchange capacity, and their incorporation into a geopolymer matrix can combine the geopolymer's stability and encapsulation capacity with the zeolite's additional adsorption sites. Previous results have shown that adding zeolite aggregates to metakaolin-based geopolymers can improve the reduction of certain classes of pollutants, including phosphates, petroleum hydrocarbons, and nitrogen-containing species [10].

Therefore, geopolymer technology can be considered a remediation and conservation platform rather than merely a single-purpose adsorbent material. Its performance can be tailored by selecting precursors, controlling porosity, introducing functional phases, and choosing the final form of the material. This flexibility is important for marine environments affected by civil and military pollution, where contamination is mixed, variable, and difficult to treat with isolated solutions. Thus, geopolymers can help reduce pollutant concentrations, immobilize hazardous species, prevent secondary contamination, and support the restoration of marine ecosystems.

Challenges and Future Research Directions

Although geopolymers show great potential for remediating contaminants associated with armed conflicts, their application in real marine environments requires further validation. Unlike controlled laboratory conditions, seawater contains high salinity, competing ions, organic matter, suspended particles, and complex mixtures of pollutants, factors that can influence both the retention efficiency and the stability of the materials.

Future research should focus on testing geopolymers under dynamic conditions, including multiple contaminants, similar to those found in coastal, port, or lagoon areas. It is also necessary to assess durability after repeated cycles of use, control alkaline leaching, optimize material composition, including by introducing functional phases, and extend testing to microplastics and emerging pollutants.

Performance evaluation must be supplemented by ecotoxicity tests, leaching tests, and LCA analyses to confirm the technical efficiency, ecological safety, and environmental benefits of these materials. Furthermore, integrating sensors to monitor pH, turbidity, conductivity, heavy metals, hydrocarbons, or nutrients could enable remediation systems to adapt to actual variations in contamination levels. Thus, geopolymer technology can evolve from laboratory demonstrations to practical solutions for protecting and restoring marine ecosystems affected by mixed pollution.

Conclusions

This study highlights geopolymer technology as a sustainable remediation solution for marine environments affected by war-related contamination. Such pollution is typically complex, involving heavy metals, petroleum hydrocarbons, persistent organic compounds, nutrients, microplastics, and contaminated sediments, which may coexist and interact in saline and dynamic marine systems.

Geopolymers are suitable for these conditions due to their aluminosilicate structure, controllable porosity, chemical stability, and capacity to retain hazardous species through adsorption, ion exchange, surface complexation, precipitation, pore diffusion, and encapsulation. These mechanisms not only remove pollutants but also reduce contaminant mobility and limit secondary pollution.

From a conservation perspective, the main value of geopolymer-based remediation lies in the long-term stabilization of contaminants within an inorganic matrix. This can reduce leaching, remobilization, bioaccumulation, and transfer of hazardous species from water to sediments or biota, supporting biodiversity protection and ecosystem recovery.

The incorporation of zeolitic aggregates or other functional phases can further improve performance in mixed-contamination scenarios. Previous studies showed that metakaolin-based geopolymers can retain heavy metals, while geopolymer–zeolite composites can enhance the reduction of phosphates, petroleum hydrocarbons, and nitrogen-containing species.

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