INTERNATIONAL JOURNAL
OF
CONSERVATION SCIENCE

ISSN: 2067-533X Volume 16, Issue 4, 2025: 1993-2002 www.ijcs.ro

DOI: 10. 36868/IJCS.2025.04.26

INTELLIGENT FILTRATION METHOD FOR MARINE POLLUTION DECONTAMINATION

Dumitru Doru BURDUHOS NERGIS[1], Petrica VIZUREANU[1,2*],
György DEÁK[3], Georgeta TUDOR[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 (AORS), 54 Splaiul Independenței St., Sector 5, 050094 Bucharest, Romania

Abstract

Marine pollution represents a major challenge for conservation science, as it threatens the integrity of marine ecosystems, associated coastal heritage, and biodiversity at both local and global scales. The degradation of marine environments is intensified by complex contamination sources, including hydrocarbons, plastics, heavy metals, and persistent chemicals originating from industrial activities and, increasingly, from armed conflicts. Current remediation approaches often lack adaptability, being designed to address isolated categories of pollutants rather than the multifactorial nature of marine contamination. This limitation reduces their effectiveness in conservation and post-impact restoration strategies. In this context, there is a critical need for integrated decontamination solutions capable of supporting ecosystem recovery and long-term environmental preservation, particularly in conflict-affected marine regions. This study proposes the development of an advanced filtration-based remediation approach aimed at the simultaneous reduction of multiple contaminant classes, contributing to sustainable conservation practices and supporting evidence-based decision-making for marine restoration and protection.

Keywords: *marine ecosystem conservation; armed-conflict pollution; remedial solutions; intelligent filtration.*

Introduction

Marine ecosystems represent some of the most dynamic and vulnerable environments on Earth, providing vital ecological, economic, and social services [1]. However, over the past decades, anthropogenic activities such as industrial discharge, shipping, oil exploration, and urban coastal development have intensified the introduction of pollutants into marine waters and sediments. Among the most persistent contaminants are heavy metals, petroleum hydrocarbons, synthetic dyes, nutrients, and microplastics, all of which can accumulate and persist in the marine food chain [2]. These pollutants threaten aquatic biodiversity, disrupt biogeochemical cycles, and impair water quality, ultimately posing significant risks to human health and socio-economic sectors dependent on clean marine environments, including fisheries, aquaculture, and tourism [3,4].

* Corresponding author: peviz2002@yahoo.com

Conventional remediation technologies such as activated carbon adsorption, ion exchange, chemical precipitation, and membrane separation have been extensively employed for the decontamination of aquatic systems [5]. While effective under controlled conditions, these methods are constrained by limitations such as high energy demands, expensive operational costs, short service lifetimes, and the generation of toxic secondary wastes that require further treatment [6]. For large-scale and long-term applications in marine environments, where salinity, pH, and contaminant concentrations are highly variable, such approaches are often unsustainable or economically unfeasible [7]. Consequently, research efforts have increasingly focused on developing sustainable materials and technologies that can mitigate pollution while minimizing environmental impact.

Geopolymers have emerged as a promising class of materials for environmental applications due to their unique combination of sustainability, versatility, and durability. Geopolymers are inorganic binders formed through the alkali activation of aluminosilicate precursors such as fly ash, metakaolin, or blast furnace slag [8]. Unlike Portland cement, their synthesis does not rely on high-temperature calcination, thereby significantly reducing energy consumption and carbon dioxide emissions. In fact, geopolymer production is frequently associated with the valorization of industrial by-products, offering a circular economy pathway that transforms waste streams into high-performance materials [9]. The environmental advantages, combined with their excellent chemical resistance, thermal stability, and mechanical strength, have established geopolymers as low-carbon alternatives to conventional cementitious binders [10].

One of the most notable features of geopolymers for pollution mitigation is their porous architecture, which can be tailored through techniques such as direct foaming, 3D printing, and templating methods [11]. Porous geopolymers provide high surface area and interconnected pore networks that facilitate adsorption and immobilization of contaminants, including toxic metal ions like Pb^{2+}, Cd^{2+}, and Cr^{6+} [8,12]. Copper (Cu^{2+}) is one of the heavy metals most commonly found in high concentrations in water environments. The significant levels of contamination are largely attributed to its widespread use in algicide processes within agriculture and industrial applications. Consequently, when contaminated water reaches the soil, it can spread through rivers and torrents, ultimately affecting marine ecosystems as well as drinking water [13,14]. Despite the fact that copper is essential for the human body within certain limits, an excess of copper can lead to toxicity and subsequently impair the function of various organs [15]. Excessive amounts of copper can result in copper poisoning, which may manifest as vomiting, stomach pain, rashes, liver and kidney damage, and nausea. The potential for copper to cause oxidative damage may be a key factor in its toxicity, as it induces oxidative harm to biological systems, affecting the peroxidation of lipids and other macromolecules [16]. To enhance water quality and safeguard public health, the copper content in wastewater effluents must be reduced in compliance with relevant legislation before any discharge into the environment. Moreover, surface modification with metals such as silver further enhances their functionality by introducing antimicrobial or catalytic properties, thereby extending their potential applications in water purification [17]. These characteristics make porous geopolymers highly suitable for deployment in complex and variable marine conditions, where multifunctional materials are essential to address multiple classes of pollutants simultaneously.

The most common and widely used methods for treating Cu^{2+} ions from aqueous environments are filtration, electrochemical processing, and ion exchange [18–20]. However, these technologies are impractical due to several drawbacks, including high costs and significant sludge generation. In contrast, adsorption offers key advantages: it is cost-effective, easy to implement, and highly effective for treating contaminated water. Therefore, it is essential to explore alternative technologies or absorbents that are more effective in removing Cu^{2+} ions from wastewater. Consequently, various types of adsorbents, including activated carbon, biochar, zeolite, clay minerals, geopolymer, and carbon nanotubes, have been utilized in wastewater treatment [21,22]. Among the various adsorbents, zeolites stand out as exceptional materials for removing metallic species from polluted water [23–25]. Zeolite is a crystalline aluminosilicate with a three-dimensional framework of $[SiO_4]^{4-}$ and $[AlO_4]^{5-}$ linked by oxygen atoms. Its synthesis occurs in a supersaturated aluminosilicate solution, involving dissolution, nucleation, and crystallization at high temperatures. A key concern is the energy-intensive thermal treatment required for synthesis, which can have a negative impact on the environment and production costs.

Beyond adsorption, geopolymers are also capable of stabilizing and encapsulating hazardous elements, thereby preventing their leaching and long-term release into aquatic environments [26]. This dual role—combining pollutant removal with permanent immobilization—offers an advantage over conventional adsorbents, which often face challenges related to desorption and regeneration. Additionally, their intrinsic durability in aggressive saline environments ensures that their structural and functional performance remains stable over extended periods, a crucial factor for marine applications [27].

The application of porous geopolymers to marine decontamination not only addresses environmental challenges but also aligns with broader global sustainability and decarbonization goals. Life cycle assessments (LCA) have consistently shown that geopolymers contribute to lower greenhouse gas emissions compared to traditional cementitious systems [28]. Furthermore, advances in processing technologies, such as 3D printing, open the possibility of designing geopolymer-based filters and structures with optimized pore architectures for targeted pollutant capture [29]. Such innovations enhance the role of geopolymers as a green technology at the intersection of materials science, environmental engineering, and marine sustainability.

Despite these promising attributes, several research gaps remain [2]. Most experimental studies on porous geopolymer adsorbents are conducted under laboratory conditions with simplified aqueous systems. Marine environments, however, present far more complex chemistry, including fluctuating ionic strength, competing species, and biological activity, all of which can influence adsorption performance and material stability. Therefore, there is a clear need in environmental engineering for the development of filtration methods that use these innovative adsorbent materials with low synthesis costs for the restoration of polluted aquatic environments.

This article aims to provide a filtration method that effectively integrates geopolymers as filtration materials in order to simultaneously reduce multiple types of contaminants from the marine environment.

Designing the Filtration Method

In this research, we designed an innovative filtration method aimed at reducing the concentration of pollutants in marine environments. This method involves a two-stage, multi-layer filtration system (see Fig. 1).

In the first stage, contaminants are removed from the polluted water using gravel and sand. These materials were chosen for their low cost and natural availability. Additionally, they can be utilized as aggregates in geopolymer concrete without the need for prior treatment to remove impurities, since geopolymers possess excellent encapsulation properties. This means that the impurities captured on the surfaces of the gravel or sand will be encapsulated within the geopolymeric matrix. Additionally, following the sand layer, a 50-micron multi-use, washable polypropylene & nylon mesh sediment filter cartridge was installed to retain any sand particles that can be carried by the water to the second stage of filtration.

In the second stage of filtration, the heavy metal pollutants are removed from the water using an intelligent cartridge. The intelligent cartridge uses multiple layers of geopolymers that possess tailored porosity and encapsulation capacity. Additionally, a 50-micron multi-use, washable sediment filter cartridge, made of polypropylene and nylon mesh, was installed to capture any geopolymer particles that may be carried away by the water during the filtration process. Moreover, this filter cartridge is designed to reduce the velocity of the water passing through the system, thereby increasing the interaction time between the contaminants in the water and the surface of the geopolymers.

Obtaining the Porous Geopolymers

Geopolymers can be created from various aluminosilicate sources, including metakaolin, fly ash, slag, rice husk, and red mud. Metakaolin is often favoured due to its high reactivity and purity, which lead to strong mechanical properties and low permeability. It is also utilized to produce geopolymer-based adsorbents with unique adsorption capabilities. Due to the complexity of pollution in marine environments, the design of the filtration method must incorporate multiple filtration stages and a multilayered, tailored filter to effectively reduce pollution in a sustainable manner.

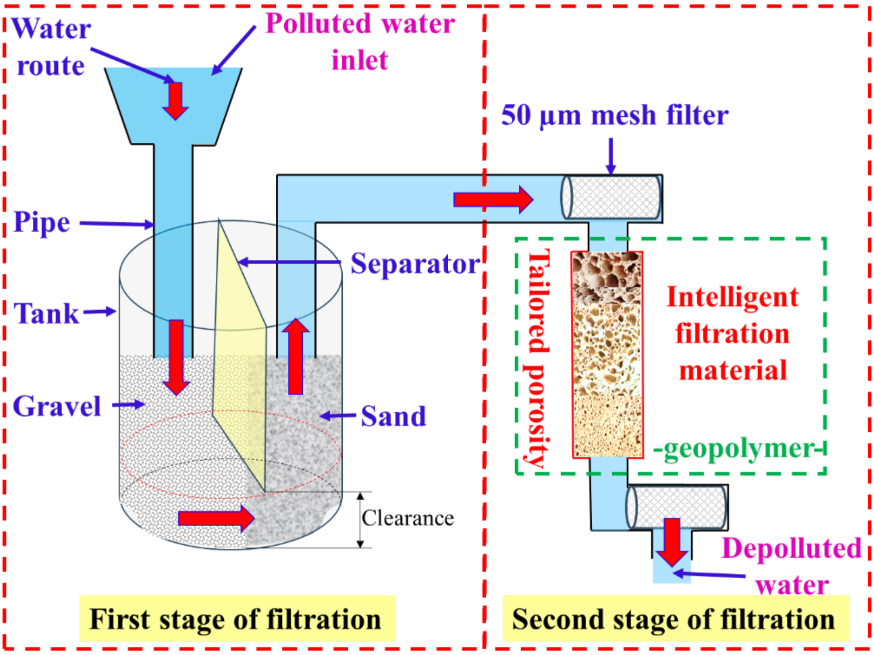

Fig. 1. The design of the filtration method that includes geopolymers for water decontamination

The raw materials used in this study were metakaolin (MK), sodium silicate (Na_2SiO_3), sodium hydroxide (NaOH), and hydrogen peroxide (H_2O_2). MK was obtained by calcining kaolin collected from Parva, Romania, at low temperatures (700 °C for 1 h). Sodium silicate (Na_2SiO_3) is obtained by melting sand (SiO2) with sodium carbonate (Na2CO3) at high temperatures, followed by condensation of the product from a vapor state into a semi-viscous liquid. A commercially available Na_2SiO_3 solution (Kynita S.R.L., Vâlcea, Romania) with a density of 1.52 g/cm^3 and a pH of about 11.5 will be utilized. This solution contains a minimum of 44.8% sodium silicate, 31.10% SiO_2, and 13.70% Na_2O. The concentration of sodium hydroxide (NaOH) significantly affects the properties of geopolymers, with higher concentration leading to increased early resistance and enhanced stability in acidic or sulfate environments. The NaOH solution, prepared by dissolving 98% pure NaOH flakes in water, was mixed with Na_2SiO_3 and solid components. To create the geopolymers, a 10M NaOH solution was used. Hydrogen peroxide

(H_2O_2), with a concentration of 35%, is used as a foaming agent in geopolymers, decomposing into water and oxygen to create pores.

First, metakaolin (MK) was weighed and mixed with the alkaline activator. The alkaline activator was prepared by premixing 10 M sodium hydroxide (NaOH) one day before sample molding to allow for heat release. Following that, NaOH and Na_2SiO_3 were combined in a 1:1 mass ratio and homogenized for 1 minute. This mixture was then gradually added to the dry component, followed by thorough mixing using a mechanical stirrer at a solid-to-liquid (S/L) ratio of 0.58. The low S/L ratio was chosen to enhance the geopolymerization process, as the reaction between the alkaline activator and the aluminosilicate materials is more significant at this ratio.

Once a homogeneous mixture of metakaolin and the alkaline activator was achieved, a foaming agent was added to the mixture at a concentration of 1% by mass of the metakaolin.

Subsequently, the resulting geopolymer paste was placed in a high-density polyethylene (HDPE) mold and left to cure at room temperature. Curing can also be conducted at slightly elevated temperatures, such as 60 °C, for 24 hours. Curing at these higher temperatures accelerates both the curing and foaming processes, resulting in improved porosity.

In addition, literature had previously addressed the leaching of alkalis from geopolymer. Accordingly, Novais et al. [30] indicated that the non-washed geopolymer had significant OH^- leaching. A high pH solution would cause metal hydroxide to precipitate, limiting the adsorption performance of the geopolymer adsorbent. The hardened geopolymer paste was crushed into small particles and washed with distilled water to reduce its alkalinity. The geopolymer particles were then sieved into four distinct size classes: 2-4 mm, 4-8 mm, 8-12 mm, and 12-20 mm. A filtration cartridge with tailored porosity was created by layering the geopolymer particles in ascending order based on their size. The first layer contained particles in the 2-4 mm range, the second layer included particles in the 4-8 mm range, and so on. All layers contained an equal mass of material.

Results and discussions

Filtration performances

To evaluate the filtration performance of the developed technology, water samples were collected from four different regions of the Black Sea (see Table 1).

Table 1. Coordinates of water sampling location

Water sampling location	Longitude	Latitude
Location 1 - Corbu area	N44°22.53391'	E28°42.66064'
Location 2 - Midia Cap area	N44°20.51829'	E28°41.40670'
Location 3 - Pescărie (Cherhana) Constanța	N44°12.93307'	E28°38.70671'
Location 4 - Tuzla area	N43°59.76471'	E28°39.85018'

The tests were conducted on-site to minimize any disturbances related to water storage and transportation. For each location, samples of both untreated water and filtered water were collected, then transported to the laboratory and stored at 4 °C until the testing day.

The removal efficiency of heavy metals (hm^+) by the synthesized geopolymer adsorbents varies depending on the initial concentration of these metals in the filtered water. At location 1, the concentration of copper (Cu) decreased by 99.91%, while the concentration of zinc (Zn) decreased by 54.36%. At location 2, the Cu concentration decreased by 42%, while the Zn concentration remained nearly unchanged. In location 3, Cu decreased by 58.31%, and Zn decreased by 49%. Finally, at location 4, Cu decreased by 49% and Zn decreased by 13%. These results indicate that the removal efficiency is influenced by the characteristics of the filtered water. At location 2, a minimum reduction of 42% in Cu concentration was achieved, while location 1 had the highest removal efficiency, where Cu was almost completely eliminated.

The filtration performance of geopolymers is strongly related to their chemical composition and porous morphology. The calcium atom in the raw material dissolves more easily than silicon and aluminum atoms and can quickly react with the sodium silicate solution [31]. The rapid dissolution of calcium (Ca) leads to a reaction between Ca^{2+} ions in the mixture and the Si-O-Al structure of the geopolymer gel. This reaction produces C-(A)-S-H gel. When water infiltrates the structure, it prevents water evaporation, which in turn facilitates the formation of the C-(A)-S-H phase with a low calcium-to-silicon ratio. This low ratio can result in a shorter setting time [32]. The aluminosilicate gel serves as the primary binding phase, enhancing interparticle bonding, improving macroscopic strength, and controlling the strength-gain behavior of geopolymer paste [33]. The adsorption mechanisms of heavy metal ions (hm^+) by the porous geopolymer used in this study are illustrated in Fig. 2. The 3D interconnected open pore structure of geopolymers serves as an effective adsorbent material, facilitating easy access for hm^+ ions to the adsorption sites within the material. Additionally, an ion exchange mechanism occurs within the geopolymer structure, where hm^+ ions are replaced by Na^+, Mg^{2+}, and Ca^{2+} ions. This mechanism is also involved in the adsorption process of Cu^{2+}, Zn^{2+} or any other heavy metals that will be present in the filtered solution.

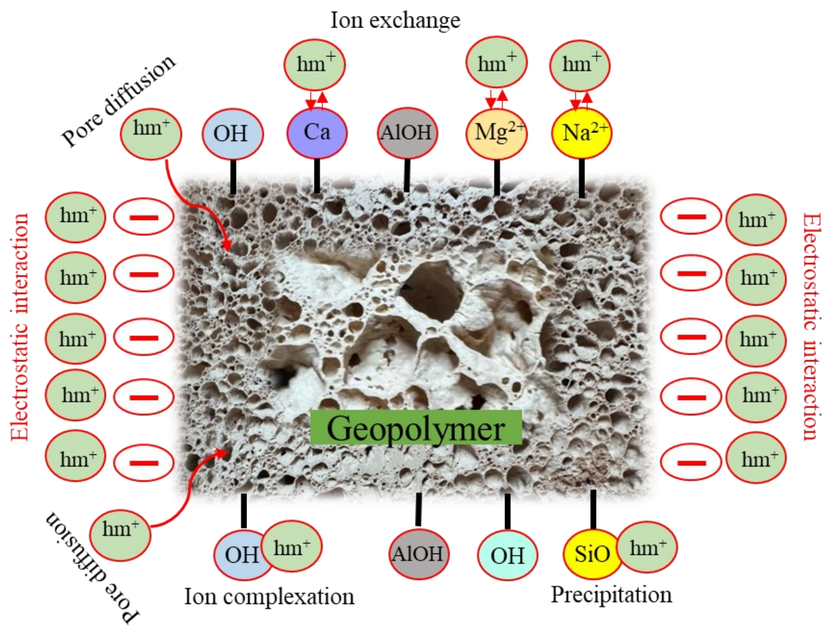

Fig. 2. Adsorption mechanism of heavy metals in geopolymer filter

Ion exchange interactions are not a single mechanism; rather, other removal mechanisms, such as surface complexation, surface precipitation, and electrostatic interactions, occur alongside this adsorption process. In addition, in the case of geopolymers, heavy metals are being trapped in the three-dimensional [SiO_4] or [AlO_4] tetrahedron structures. Thus, the developed materials can effectively adsorb Cu^{2+}, Zn^{2+} ions, and other metals that contaminate the marine environment through the combined contributions of ion exchange, precipitation, ion complexation, pore diffusion, and electrostatic interactions with heavy metals. However, a slight increase in iron content was observed in all analyzed samples. To avoid this issue, raw materials with low iron content should be used for the manufacture of geopolymers.

In addition to heavy metals, the filtration method demonstrated promising results in reducing nitrogen compounds, such as nitrites, nitrates, and ammonium, as well as chlorides and phosphorus content. However, due to the complexity of pollution in marine environments, metakaolin-based geopolymers appear to be insufficient for effective sustainable pollution reduction. Therefore, the geopolymer matrix itself does not seem to possess the required stability and efficiency in a marine environment to effectively remove these contaminants. To improve performance, an innovative composite geopolymer was developed, consisting of the original matrix with the addition of 20% zeolite aggregates. This method of including zeolites as aggregates, rather than in powder form, offers significant advantages by creating a composite that possesses the beneficial properties of both natural zeolites and metakaolin-based geopolymers. The combination of geopolymers and zeolites offers both environmental and economic advantages [34]. The production of geopolymer is simpler and requires less water and energy compared to zeolites. As a result, the combination of zeolite aggregates and the amorphous geopolymer gel forms a self-supporting structure. This leads to the development of a more stable filtration system. The presence of zeolite crystals in the geopolymeric product contributes to the creation of a stable zeolitic structure, enhancing the properties of the geopolymer [35]. Natural zeolite and metakaolin geopolymers can effectively adsorb heavy metal ions through ion exchange, precipitation, and complexation mechanisms, creating a composite suitable for the depollution of marine water.

Using this innovative composite material, the phosphate content was reduced to non-detectable levels at Locations 1 and 2. At Location 3, the reduction reached 91.37%, while at Location 4, it was decreased by 89.36%. Additionally, at the first three locations, a decrease of up to 45.45% in the concentration of total petroleum hydrocarbons was achieved. However, at Location 4, the value remained unchanged, likely due to the low initial concentration of just 0.03 mg/L. The efficiency of the filtration was also tested for the chlorine reduction, where a slight decrease was observed at all four locations. Similar results were obtained for other factors such as NH_4, NO_2^-, and NO_3^- content. Moreover, the same structure is capable of retaining oil pollution [36], as well as microplastic [37] and other types of contaminants from the marine environment. Using geopolymers for decontamination in marine environments is both energy-efficient and sustainable. This technology can effectively remove multiple pollutants, and the contaminated materials, such as filters, can be repurposed as raw materials for building products.

Conclusions

This paper demonstrates that a two-stage filtration method, consisting of mechanical filtration with natural aggregates and intelligent filtration using a metakaolin-based geopolymer filter, can effectively reduce pollution in marine environments. The chemically active structure of geopolymers effectively retains heavy metals and various pollutants from saltwater collected around the Black Sea. The filtration efficiency depends on the initial concentration of the pollutants, reaching 99% in the case of Cu in some locations. However, in the case of phosphates, petroleum products, and N compounds, the geopolymers with zeolite addition showed better performances.

By utilizing a composite material composed of a geopolymer matrix combined with zeolite aggregates, it is possible to achieve a reduction in phosphate content of up to 100% under certain conditions. Therefore, the developed filtration method demonstrates promising results for creating filtration systems that can be applied in coastal areas, as well as in regions affected by military or industrial activities.

The synthesized metacaolin-based geopolymer adsorbent used in this study should be further examined through batch adsorption experiments involving microplastics and pharmaceutical pollutants. These experiments should be conducted at various pH levels and contact times to analyze the adsorption interactions in detail, including adsorption isotherms, kinetics, and thermodynamics.

Acknowledgments

This work has been carried out through the project Black Sea SIERRA Harnessing complementary curricular preparedness via sustainable management in response to civil and military pollution on the coastline, tributaries and lagoons in Black Sea's North, West, South zone, funded through the call EMFAF-2023-PIA-FLAGSHIP by the European Climate, Infrastructure and Environment Executive Agency (CINEA).

Co-funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

References

[1] C. Riisager-Simonsen, G. Fabi, L. van Hoof, N. Holmgren, G. Marino, D. Lisbjerg, *Marine nature-based solutions: Where societal challenges and ecosystem requirements meet the potential of our oceans*, **Mar Policy**, **144**, 2022, p. 105198. https://doi.org/10.1016/J.MARPOL.2022.105198.

[2] P. Vizureanu, G. Deák, D.D. Burduhos Nergis, A.V. Sandu, *Remedial solutions and conservation of marine environmnets: a review*, **International Journal of Conservation Science**, **15**, 2024, pp. 1841–1854. https://doi.org/10.36868/IJCS.2024.04.16.

[3] Y. Ettahiri, B. Bouargane, K. Fritah, B. Akhsassi, L. Pérez-Villarejo, A. Aziz, L. Bouna, A. Benlhachemi, R.M. Novais, *A state-of-the-art review of recent advances in porous geopolymer: Applications in adsorption of inorganic and organic contaminants in water*, **Constr Build Mater**, **395**, 2023, p. 132269. https://doi.org/10.1016/J.CONBUILDMAT.2023.132269.

[4] X. Zhang, X. Zhang, X. Li, Y. Liu, H. Yu, M. Ma, *Porous geopolymer with controllable interconnected pores-a viable permeable reactive barrier filler for lead pollutant removal*, **Chemosphere**, **307**, 2022. https://doi.org/10.1016/J.CHEMOSPHERE.2022.136128.

[5] J. Ayach, W. El Malti, L. Duma, J. Lalevée, M. Al Ajami, H. Hamad, A. Hijazi, *Comparing Conventional and Advanced Approaches for Heavy Metal Removal in Wastewater Treatment: An In-Depth Review Emphasizing Filter-Based Strategies*, **Polymers (Basel)**, **16**, 2024, p. 1959. https://doi.org/10.3390/POLYM16141959.

[6] T. Luukkonen, J. Yliniemi, H. Sreenivasan, K. Ohenoja, M. Finnilă, G. Franchin, P. Colombo, *Ag- or Cu-modified geopolymer filters for water treatment manufactured by 3D printing, direct foaming, or granulation*, **Sci Rep**, **10**, 2020. https://doi.org/10.1038/S41598-020-64228-5.

[7] V. Ramesh, B. Muthramu, D. Rebekhal, *A review of sustainability assessment of geopolymer concrete through AI-based life cycle analysis*, **AI in Civil Engineering**, **4**, 2025, pp. 1–29. https://doi.org/10.1007/S43503-024-00045-3/FIGURES/15.

[8] F. Genua, I. Lancellotti, C. Leonelli, *Geopolymer-Based Stabilization of Heavy Metals, the Role of Chemical Agents in Encapsulation and Adsorption: Review*, **Polymers**, **17**, 2025, p. 670. https://doi.org/10.3390/POLYM17050670.

[9] S. Sbahieh, G. McKay, S.G. Al-Ghamdi, *Comprehensive Analysis of Geopolymer Materials: Properties, Environmental Impacts, and Applications*, **Materials**, **16**, 2023, p. 7363. https://doi.org/10.3390/MA16237363.

[10] D. Awalluddin, M.A.M. Ariffin, M.M. Al Bakri Abdullah, N.F. Zamri, H.S. Lee, J.S. Kumar, *A review of the developments in geopolymer technology*, **Recent Developments of Geopolymer Materials: Processing and Characterisations**, 2025, pp. 3–32. https://doi.org/10.1016/B978-0-443-24068-3.00001-7.

[11] T. Luukkonen, A. Heponiemi, H. Runtti, J. Pesonen, J. Yliniemi, U. Lassi, *Application of alkali-activated materials for water and wastewater treatment: a review*, **Rev Environ Sci Biotechnol**, **18**, 2019, pp. 271–297. https://doi.org/10.1007/S11157-019-09494-0.

[12] S. V. Siva Shankari, M. Sivasakthi, *A State-of-the-Art Review on Effectiveness of Geopolymer Technology Toward Dye Degradation, Heavy Metal Encapsulation and Its Future Prospects on Environmental Remediation*, **Environmental Quality Management**, **34**, 2025. https://doi.org/10.1002/TQEM.70054.

[13] M. Bagheri, S. Azizian, B. Jaleh, A. Chehregani, *Adsorption of Cu(II) from aqueous solution by micro-structured ZnO thin films*, **Journal of Industrial and Engineering Chemistry**, **20**, 2014, pp. 2439–2446. https://doi.org/10.1016/j.jiec.2013.10.024.

[14] N. Bakhtiari, S. Azizian, *Adsorption of copper ion from aqueous solution by nanoporous MOF-5: A kinetic and equilibrium study*, **J Mol Liq**, **206**, 2015, pp. 114–118. https://doi.org/10.1016/j.molliq.2015.02.009.

[15] M. Kaur, P. Sharma, S. Kumari, *Equilibrium studies for copper removal from aqueous solution using nanoadsorbent synthesized from rice husk*, **SN Appl Sci**, **1**, 2019, pp. 1–9. https://doi.org/10.1007/s42452-019-1024-0.

[16] A.O. Dada, D.F. Latona, O.J. Ojediran, O.O. Nath, *Adsorption of Cu (II) onto bamboo supported manganese (BS-Mn) nanocomposite: effect of operational parameters, kinetic, isotherms, and thermodynamic studies*, **Journal of Applied Sciences and Environmental Management**, **20**, 2016, pp. 409–422. https://doi.org/10.4314/jasem.v20i2.24.

[17] I. Luhar, S. Luhar, M.M.A.B. Abdullah, R.A. Razak, P. Vizureanu, A.V. Sandu, P.-D. Matasaru, *A State-of-the-Art Review on Innovative Geopolymer Composites Designed for Water and Wastewater Treatment*, **Materials**, **14**, 2021, p. 7456. https://doi.org/10.3390/ma14237456.

[18] Y. Li, H. Yu, L. Liu, H. Yu, *Application of co-pyrolysis biochar for the adsorption and immobilization of heavy metals in contaminated environmental substrates*, **J Hazard Mater**, **420**, 2021, p. 126655. https://doi.org/10.1016/j.jhazmat.2021.126655.

[19] S.A. Razzak, M.O. Farooque, Z. Alsheikh, L. Alsheikhmohamad, D. Alkuroud, A. Alfayez, S.M.Z. Hossain, M.M. Hossain, *A Comprehensive Review on Conventional and Biological-Driven Heavy Metals Removal from Industrial Wastewater*, **Environmental Advances**, **7**, 2022, p. 100168. https://doi.org/10.1016/j.envadv.2022.100168.

[20] F.Y. Aljaberi, *Studies of autocatalytic electrocoagulation reactor for lead removal from simulated wastewater*, **J Environ Chem Eng**, **6**, 2018, pp. 6069–6078. https://doi.org/10.1016/j.jece.2018.09.032.

[21] M. qin Jiang, X. ying Jin, X.Q. Lu, Z. liang Chen, *Adsorption of Pb(II), Cd(II), Ni(II) and Cu(II) onto natural kaolinite clay*, **Desalination**, **252**, 2010, pp. 33–39. https://doi.org/10.1016/j.desal.2009.11.005.

[22] A.S. Mestre, R.A. Pires, I. Aroso, E.M. Fernandes, M.L. Pinto, R.L. Reis, M.A. Andrade, J. Pires, S.P. Silva, A.P. Carvalho, *Activated carbons prepared from industrial pre-treated cork: Sustainable adsorbents for pharmaceutical compounds removal*, **Chemical Engineering Journal**, **253**, 2014, pp. 408–417. https://doi.org/10.1016/j.cej.2014.05.051.

[23] K. He, Y. Chen, Z. Tang, Y. Hu, *Removal of heavy metal ions from aqueous solution by zeolite synthesized from fly ash*, **Environmental Science and Pollution Research**, **23**, 2016, pp. 2778–2788. https://doi.org/10.1007/s11356-015-5422-6.

[24] L.R. Rad, A. Momeni, B.F. Ghazani, M. Irani, M. Mahmoudi, B. Noghreh, *Removal of Ni2+ and Cd2+ ions from aqueous solutions using electrospun PVA/zeolite nanofibrous adsorbent*, **Chemical Engineering Journal**, **256**, 2014, pp. 119–127. https://doi.org/10.1016/j.cej.2014.06.066.

[25] Y. Taamneh, S. Sharadqah, *The removal of heavy metals from aqueous solution using natural Jordanian zeolite*, **Appl Water Sci**, **7**, 2017, pp. 2021–2028. https://doi.org/10.1007/s13201-016-0382-7.

[26] L. Angelova, D.D. Burduhos-Nergis, A. Surleva, A.V. Sandu, D. Ilieva, G. Chernev, P. Vizureanu, *Study of Heavy Metal Encapsulation in Geopolymerized Industrial Waste by Sequential Extraction*, **JOM**, **77**, 2024, pp. 1385–1394. https://doi.org/10.1007/S11837-024-07049-5/TABLES/4.

[27] G. Kalyoncu Erguler, A. Dahi Taleghani, *Geopolymer applications in deep-sea energy and mining infrastructure: a review of properties, challenges, and future prospects*, **Environmental Earth Sciences**, **84**, 2025, pp. 1–26. https://doi.org/10.1007/S12665-025-12339-5.

[28] I. Bianco, B. Ap Dafydd Tomos, R. Vinai, *Analysis of the environmental impacts of alkali-activated concrete produced with waste glass-derived silicate activator – A LCA study*, **J Clean Prod**, **316**, 2021, p. 128383. https://doi.org/10.1016/j.jclepro.2021.128383.

[29] P. Arokiasamy, M.M.A.B. Abdullah, S.Z. Abd Rahim, M. Sadique, L.Y. Ming, M.A.A. Mohd Salleh, M.R.R. Mohd Arif Zainol, C.M.R. Ghazali, *Diverse material based geopolymer towards heavy metals removal: a review*, **Journal of Materials Research and Technology**, **22**, 2023, pp. 126–156. https://doi.org/10.1016/J.JMRT.2022.11.100.

[30] R.M. Novais, L.H. Buruberri, M.P. Seabra, D. Bajare, J.A. Labrincha, *Novel porous fly ash-containing geopolymers for pH buffering applications*, **J Clean Prod**, **124**, 2016, pp. 395–404. https://doi.org/10.1016/j.jclepro.2016.02.114.

[31] X. Wang, C. Zhang, H. Zhu, Q. Wu, *Reaction kinetics and mechanical properties of a mineral-micropowder/metakaolin-based geopolymer*, **Ceram Int**, **48**, 2022, pp. 14173–14181. https://doi.org/10.1016/j.ceramint.2022.01.304.

[32] L.H. Buruberri, D.M. Tobaldi, A. Caetano, M.P. Seabra, J.A. Labrincha, *Evaluation of reactive Si and Al amounts in various geopolymer precursors by a simple method*, **Journal of Building Engineering**, **22**, 2019, pp. 48–55. https://doi.org/10.1016/j.jobe.2018.11.017.

[33] P. Duan, C. Yan, W. Zhou, *Influence of partial replacement of fly ash by metakaolin on mechanical properties and microstructure of fly ash geopolymer paste exposed to sulfate attack*, **Ceram Int**, **42**, 2016, 3504–3517. https://doi.org/10.1016/j.ceramint.2015.10.154.

[34] A.H.J. Al-Rkaby, A.H.J. Al-Rkaby, *Performance of Zeolite-Based Soil–Geopolymer Mixtures for Geostructures under Eccentric Loading*, **Infrastructures**, **9**, 2024. https://doi.org/10.3390/INFRASTRUCTURES9090160.

[35] Y. Aygörmez, *Assessment of performance of metabentonite and metazeolite-based geopolymers with fly ash sand replacement*, **Constr Build Mater**, **302**, p. 2021. https://doi.org/10.1016/j.conbuildmat.2021.124423.

[36] F. da S. Maranhão, F. Gomes, S. Thode, D.B. Das, E. Pereira, N. Lima, F. Carvalho, M. Aboelkheir, V. Costa, K. Pal, *Oil Spill Sorber Based on Extrinsically Magnetizable Porous Geopolymer*, **Materials**, **14**, 2021, p. 5641. https://doi.org/10.3390/MA14195641.

[37] M.M. Madirisha, B.D. Ikotun, E.K. Onyari, *Turning the tide on microplastic pollution: Leveraging the potential of geopolymers for mitigation*, **Environ Res**, **272**, 2025, p.121182. https://doi.org/10.1016/J.ENVRES.2025.121182.

Received: September 20, 2025
Accepted: November 27, 2025