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Toward a comprehensive remediation of polluted waters using a compact composite layered material

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Abstract

This study proposes and conceptally develops a compact composite layered material for simultaneous removal of organic pollutants and heavy metals from contaminated waters. The objective is the evaluation of the adsorption performance of natural and modified clay minerals toward selected pesticides (atrazine, chlorpyrifos, glyphosate) and pharmaceuticals (azithromycin, paracetamol, ibuprofen), and to assess the heavy-metal uptake capacity of layered manganese oxides (birnessites and buserites), with the aim of integrating them into a multifunctional composite adsorbent. The methodology combines previously obtained experimental results on Albanian natural and activated clays and synthetic manganese oxides with an extensive quantitative literature analysis. Adsorption capacities were compared, and mechanisms were interpreted using well-known isotherm models.

Natural clays exhibit adsorption capacities up to 200 mg/g for atrazine, 150 mg/g for chlorpyrifos, 130 mg/g for glyphosate, 150 mg/g for azithromycin, 200 mg/g for paracetamol, and 100 mg/g for ibuprofen. After activation, capacities increased by approximately 40–60%, exceeding 300 mg/g for selected compounds. Layered manganese oxides demonstrated heavy-metal adsorption up to 400 mg/g in natural forms and above 600 mg/g in synthetic variants, particularly for Pb^{2+} and Hg^{2+}. Based on these findings, a compact clay - birnessite/buserite composite is proposed as a universal adsorbent capable of addressing complex pollutant mixtures. Preliminary energy and sustainability analysis indicates that thermal regeneration requires approximately 150-200 kWh per ton of exhausted composite, which could be feasibly supplied by a small wind turbine of 10 kW capacity running at 30% capacity or small-scale solar installations. The proposed material offers a scalable, low-cost and environmentally compatible solution for integrated water remediation.

Keywords*: Clays, birnessites/buserites, composite material, pollutants, water remediation*

1. Introduction

Water pollution constitutes one of the most pressing environmental and societal challenges worldwide, exacerbated by industrial growth, intensive agricultural practices, urbanization, and climate-change-driven water scarcity [1, 2]. Surface waters and groundwater resources are increasingly contaminated by complex mixtures of organic and inorganic pollutants, among which pesticides, pharmaceuticals, dyes, and heavy metals are particularly problematic due to their persistence, toxicity, and potential for bioaccumulation [3, 4]. Pesticides remain indispensable in modern agriculture, yet their extensive and often uncontrolled application has resulted in widespread contamination of soils and water bodies. Compounds such as atrazine, glyphosate, chlorpyrifos, metribuzin, methomyl, diuron, carbaryl, and alachlor are frequently detected in surface waters and aquifers. Their presence is often at locations distant from their application sites due to leaching, runoff, and atmospheric transport [5, 6, 7]. This widespread distribution poses significant risks to aquatic ecosystems and human health, including endocrine disruption, neurotoxicity, and carcinogenic effects. Similarly, pharmaceutical compounds have become ubiquitous environmental contaminants due to their extensive use and incomplete removal in conventional wastewater treatment plants. Substances such as the antibiotic azithromycin and the common analgesics paracetamol and ibuprofen are frequently detected in aquatic systems, raising concerns about antibiotic resistance and chronic ecological effects. Adsorption onto clay minerals has emerged as a promising mechanism for the removal of these pharmaceuticals from water, leveraging the charged surfaces and modifiable interlayer spaces of clays to capture a variety of organic molecules [8, 9, 10, 11, 12].

Conventional water treatment technologies like coagulation, flocculation, membrane filtration, and advanced oxidation processes are often inadequate or economically prohibitive for the removal of such micropollutants, particularly when present at low concentrations and in complex mixtures [13, 14]. In this context, adsorption-based remediation has emerged as a technically simple, cost-effective, and scalable alternative, capable of addressing a wide range of contaminants simultaneously [15].

Clay minerals represent one of the most extensively studied classes of natural adsorbents for organic pollutant removal. Their abundance, low cost, high specific surface area, and permanent negative charge make them particularly attractive for environmental applications [16]. Nu-

merous studies have demonstrated the ability of natural and modified clays to adsorb pesticides and pharmaceuticals through mechanisms such as cation exchange, hydrogen bonding, and hydrophobic interactions [5, 6, 17]. Recent reviews focusing on diuron, carbaryl, and alachlor adsorption have highlighted the critical role of clay type, surface modification, and solution chemistry in controlling adsorption efficiency [7]. Parallel to organic contamination, heavy metal pollution represents another major threat to water quality.

Metals such as Pb^{2+}, Cd^{2+}, Cu^{2+}, Zn^{2+}, and Hg^{2+} originate from industrial discharges, mining activities, and natural geochemical processes. Unlike organic pollutants, heavy metals are non-degradable and require immobilization or removal from the aqueous phase [18, 19]. Layered manganese oxides, particularly birnessite and its hydrated analogue buserite, have been identified as highly efficient adsorbents for heavy metals due to their ion-exchange capacity, redox activity, and structural flexibility [20, 21]. Previous research conducted by us and collaborators has demonstrated the effectiveness of Albanian natural and activated clays for the removal of metribuzin and methomyl from contaminated waters [22, 23, 24]. Complementary studies have shown that synthetic birnessites and buserites act as powerful traps for heavy metal cations, with adsorption capacities exceeding those of many conventional adsorbents [25].

Beyond these broad pollutant classes, this study specifically sheds light on the role of natural and modified clay minerals in adsorbing both widely used pesticides, such as atrazine, chlorpyrifos, and glyphosate, and a group of emerging pharmaceutical contaminants, including azithromycin, paracetamol, and ibuprofen. The co-occurrence of these substances in water bodies necessitates remediation strategies capable of addressing such diverse chemical groups simultaneously. This underpins the relevance of investigating clay-based adsorbents for this combined purpose. As a follow up of these findings and based on the extensive literature concerning pesticide adsorption on clays and metal uptake by manganese oxides, the present paper aims to propose and conceptually develop a compact composite layered material combining clays with birnessites/buserites. Such a composite is designed to function as a universal adsorbent, capable of simultaneously removing organic pollutants and heavy metals from polluted waters. This study integrates experimental insights from previous studies with enriched discussion based on recent literature, particularly focusing on pesticide, pharmaceutical-clay interactions, heavy metal-layered manganese oxides adsorption mechanisms, and environmental remediation strategies.

2. Study methodology

The present work is based on a synthesis of experimental data obtained in earlier investigations carried by us, complemented by an in-depth analysis of recent literature on adsorption-based water remediation. Particular attention was given to studies addressing the adsorption of pesticides (including atrazine, chlorpyrifos, glyphosate, azithromycin, paracetamol and ibuprofen) on natural and modified clays, as well as the uptake of heavy metal cations by layered manganese oxides such as birnessites and buserites.

The data presented in Figures 2, 3, and 5 were compiled from a comprehensive review of peer-reviewed literature. For figures 2 and 3, the adsorption capacities (mg/g) for each pollutant-clay combination were extracted from studies reporting equilibrium batch adsorption experiments. literature-reported values and experimental adsorption data obtained under the following representative laboratory conditions: Initial pollutant concentration: 50–200 mg/L, adsorbent dosage: 0.5–2 g/L, pH range: 5–7 for pesticides and pharmaceuticals, contact time: 24 h equilibrium, temperature: 298 ± 2 K, agitation speed: 150 rpm. The adsorption capacity (q_e) was calculated using the equation (1)

$$q_e = \frac{(C_0 - C_e)V}{m}$$

where C_0 and Ce are initial and equilibrium concentrations (mg/L), V is solution volume (L), and m is adsorbent mass (g).

Heavy-metal adsorption data presented in Figure 5 were obtained from both prior experimental work and literature under comparable equilibrium conditions, typically within pH 5–6 to prevent metal precipitation. Isotherm fitting was performed using Langmuir and Freundlich models. The values represent maximum adsorption capacities derived from Langmuir isotherm model fits. Where multiple values existed for a similar clay-pollutant pair, a representative range or maximum value was selected to illustrate the potential of the material.

Natural Albanian clays, previously characterized by X-ray diffraction, scanning electron microscopy, and chemical analysis, served as representative clay materials. Activation procedures reported in the literature include acid treatment, thermal activation, and cation exchange, all aimed at enhancing surface area, porosity, and adsorption capacity [26]. Birnessites and buserites were considered in both natural and synthetic forms, with emphasis on sodium-exchanged and hydrated variants known for their high ion-exchange capacity [20, 25]. Adsorption data reported in the literature were analyzed in terms of equilibrium capacities, kinetics, and controlling mechanisms. Where applicable, adsorption behavior was interpreted using classical isotherm models such as Langmuir and Freundlich, which remain widely employed for describing pollutant uptake on heterogeneous surfaces [27, 28].

3. Clays in organic pollutant removal

Clays are natural minerals made of thin layers. These layers consist of tetrahedral silica and octahedral alumina or magnesia sheets, stacked together and held by cations like sodium or calcium [16, 29]. This structure creates spaces between the layers that can expand to store water or capture pollutant molecules (**Fig. 1**). The most effective clays for adsorption have a 2:1 layer structure, which allows them to swell and host various molecules [5, 16]. These interlayer spaces and surfaces act as active sites where organic pollutants can be trapped. Pesticides, pharmaceu-

ticals, and dyes can attach to clay surfaces through different forces, such as cation exchange, hydrogen bonding, or van der Waals interactions [5, 30]. The natural negative charge of clays attracts positively charged organic molecules. Furthermore, clays can be modified with surfactants or acid to improve their ability to capture neutral or hydrophobic pollutants [14, 26].

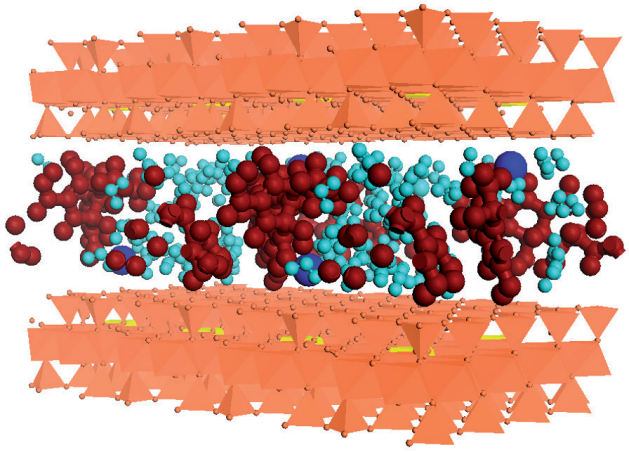

Fig. 1. Pollutant molecules trapped within clay nanopores and interlayer spaces [31].

The research in this area has shown the value of clays in cleaning water. Studies on Albanian clays demonstrated their effectiveness in removing pesticides like metribuzin and methomyl [22, 23]. Further work confirmed that these natural and activated clays can significantly reduce concentrations of various pesticides and antibiotics in water [32], as illustrated in **Fig. 2**. The adsorption process typically follows well-known scientific models, with a rapid initial uptake of pollutants that slows down as the clay surfaces become full [27]. In swelling clays such as smectites (e.g., montmorillonite), the typical interlayer spacing (basal spacing) is about 1.0-1.5 nm when dry. When water or organic molecules enter the interlayer space, this distance can expand significantly, often reaching 1.8-2.0 nm for small polar organics and up to 2.5-3.5 nm or more when larger organic pollutants (e.g., phenols, pesticides, hydrocarbons) are intercalated. In practice, clays can accommodate a wide range of organic pollutants within these nanometer-scale interlayer galleries. There are several factors which influence the adsorption capacity of organic pollutants onto clays, mainly related to the properties of the clay, the pollutant, and the solution environment.

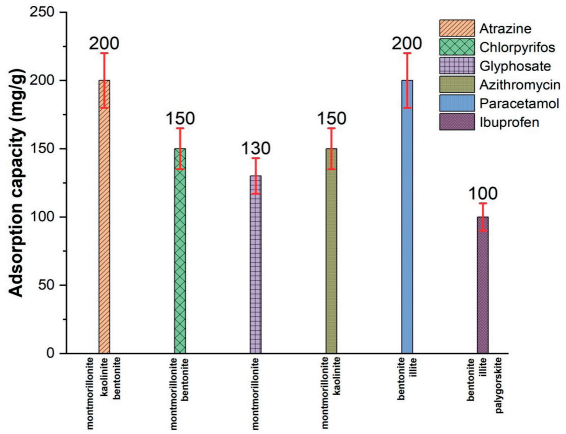

Fig. 2. Adsorption capacity versus clay type for different natural clays toward three pesticides and three pharmaceuticals.

Figure 2 shows the adsorption capacities of some natural clays toward three pesticides: Atrazine, Chlorpyrifos, Glyphosate and three pharmaceuticals mostly used during Covid 19 pandemic times, such as Azithromycin, Paracetamol, Ibuprofen. Natural clays such as montmorillonite, kaolinite, and bentonite have been reported to show adsorption capacities ranging up to 200 mg/g for atrazine, 150 mg/g for chlorpyrifos and approximately 130 mg/g for glyphosate [33, 34, 35, 36, 37]. Meanwhile, the adsorption capacities of azithromycin ranging up to 150 mg/g are reported for montmorillonite and kaolinite, 200 mg/g for paracetamol on bentonite, illite, and kaolinite and 100 mg/g for ibuprofen by bentonite, illite, and palygorskite [8, 9, 10,11,12].

Reviews of clay adsorption confirm its broad usefulness against a range of common pesticides [7]. A major advantage of clays is their global availability and low cost. They are found worldwide and can be processed inexpensively, making them ideal for large-scale water cleaning strategies [16, 22]. In order to increase the adsorbing capacities of natural clays, clay activation is performed. Clay activation refers to the physical, chemical, or thermal treatments applied to natural clays in order to improve their surface area, porosity, cation exchange capacity, and adsorption or catalytic properties. Since raw clays often have limited surface activity due to impurities, compact structure, or low reactivity, activation makes them more effective for applications in adsorption, catalysis, and environmental remediation. **Fig. 3** shows the influence of the adsorption capacity of three pesticides and three pharmaceuticals for the natural and activated clays. The increase of the adsorption capacities of all clays toward the selected organic pollutants with the clay activation has been observed. Activated clays have demonstrated maximal adsorption capacities exceeding 300 mg/g for atrazine and glyphosate; 200 mg/g for chlorpyrifos; 200 mg/g [38, 42] for azithromycin and ibuprofen and 300 mg/g for paracetamol [43, 44, 45, 46, 47. 48, 49]. These values are almost 50% higher compared to the adsorption capacities of the natural clays for the same analytes.

Modifying them with organic compounds can further enhance their selectivity and ability to capture specific pollutants like dyes [50, 51]. While clays are a powerful first step for removing organic pollutants, they are not sufficient on their own when the water is also contaminated with heavy metals. This is why they need to be combined with other materials, like manganese oxides, in composites.

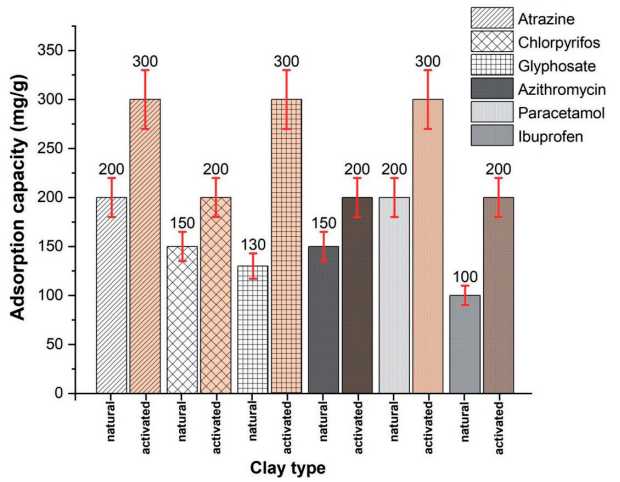

Fig. 3. The influence of the adsorption capacity of three pesticides and three pharmaceuticals for the natural and activated clays.

4. Birnessites, buserites, and heavy metal removal

While clays are excellent for organic pollutants, manganese oxides like birnessite (δ-MnO_2) and its hydrated form, buserite, are particularly effective for removing heavy metals [20, 19]. These minerals have a layered structure built from manganese-oxygen octahedra, with a high capacity for ion exchange and redox reactions [20, 18]. The layers in birnessite carry a negative charge, which is balanced by positively charged ions (e.g., Na^+, Ca^{2+}) and water molecules located between the layers [52]. The standard distance between these layers is about 7 Å. When water molecules enter this space, it expands to about 10 Å, transforming the material into buserite (**Fig. 4**). This hydration process is reversible and makes the material flexible, allowing it to accommodate large, hydrated metal ions [20].

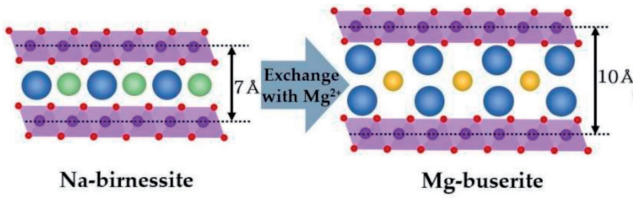

Fig. 4. Schematic structure of birnessite and buserite, showing the MnO_6 sheets, interlayer cations, and the expansion of the interlayer spacing upon hydration [53].

Heavy metals are captured through several mechanisms. These include ion exchange, where metal cations swap places with the ions in the interlayer space; surface complexation, where metals bind to oxygen atoms on the mineral surface; and sometimes redox reactions, where manganese changes oxidation state to trap the metal [19, 54]. Studies show that birnessite and buserite can effectively uptake toxic metals like lead, cadmium, copper, zinc, and mercury [21, 55, 56]. The hydration that creates buserite is especially important as it opens up the structure, improving the capture of these hydrated metal cations [20]. The adsorption capacity tends to be stronger for metals with larger hydrated ionic radii, such as lead and mercury, compared to smaller ones like cobalt [54] (**Fig. 5**).

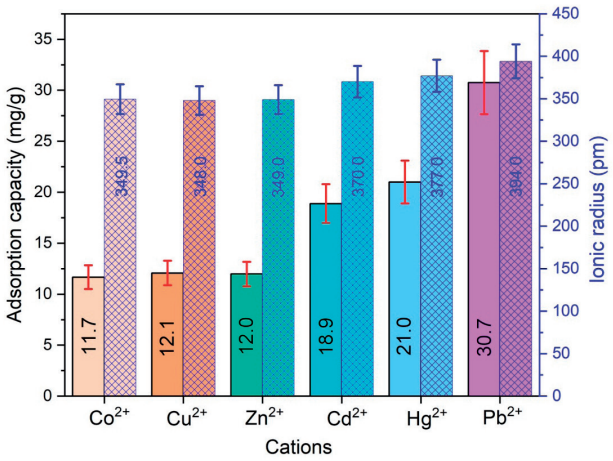

Fig. 5. Relationship between the adsorption capacity (left) of birnessites and the hydrated ionic radius (right) of various cations.

Early work on synthetic birnessites and buserites demonstrated their potential as remedies for environmental metal contamination [25]. Later research confirmed that the key to their effectiveness lies in the structural flexibility and mixed oxidation states of manganese, which control their selectivity and efficiency [57, 58]. This unique ability to change and adapt through hydration makes birnessites and buserites ideal partners for clays. Together, they can target the complex mixture of pollutants found in real-world water sources.

Regarding the ribbon graph of **Fig. 5** the adsorption capacity of Birnessites increases with the increase of the hydrated ionic radii. Thus Co^{2+} is less adsorbed compared to Cu^{2+}, Zn^{2+}, Cd^{2+}, Hg^{2+} and Pb^{2+}. This trend highlights the role of interlayer hydration and structural flexibility of Birnessites, where larger hydrated ions interact more strongly with the layered MnO_6 structure, leading to enhanced ion-exchange and adsorption efficiency.

5. Composite materials for universal water purification

In reality, polluted water rarely contains just one type of contaminant. It is often a complex mix of organic and inorganic substances. Combining clays and manganese oxides into a single composite material creates a mul-

tifunctional adsorbent that can handle this complexity [59]. In such a composite, the clays trap organic molecules through their interlayer spaces and surface interactions, while the manganese oxides remove toxic heavy metals through ion exchange and redox reactions [60, 61, 62]. The goal of this research is to propose a universal purification material, made of both, clays that birnessites/buserites as compact and efficient. Scientific models indicate that adsorption on these composites follows predictable patterns, with a fast initial removal rate that gradually slows as the material reaches its capacity [28, 27]. These composites can be manufactured into practical forms. For static applications, they can be shaped into spherical pellets or beads. This forms provide mechanical stability and a high surface area for contact [63]. This allows them to be used in fixed filters, packed columns, or simply dispersed directly into contaminated water bodies. For example, composites of montmorillonite clay and birnessite have been shown to simultaneously remove dyes and lead more effectively than either material alone [59]. Similarly, clay beads coated with manganese oxides have been used successfully in continuous-flow filter systems [30, 64].

The main advantage of these composites is their universality. A single material can target multiple classes of pollutants, simplifying the purification process and reducing the need for complex, multi-stage treatment plants. Their low cost, natural abundance and adaptability make them excellent candidates for a wide range of applications, from small household filters to large industrial wastewater treatment systems.

6. Static and dynamic remediation approaches

Two main approaches can be used to apply these composite materials for water purification: static and dynamic systems [65].

- In the static approach, the composite material is formed into spherical pellets or beads. These beads are then immersed directly into the polluted water body, where they remain stationary (**Fig. 6**).

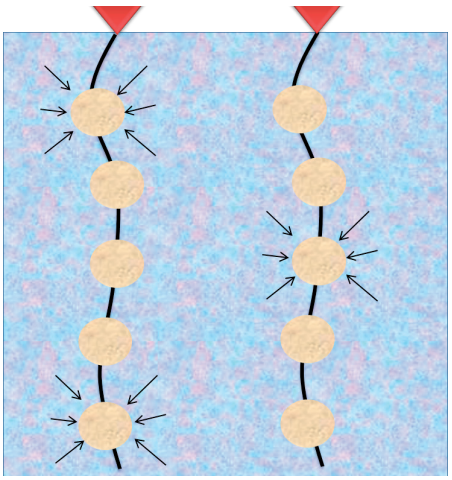

Fig. 6. Example of static composite spheres immersed in water, adsorbing pollutants.

Pollutants are removed through diffusion as the water moves around the beads. This spherical shape provides good mechanical stability, resistance to erosion, and a high surface area for contact with the water. The adsorption process follows a predictable pattern, with rapid initial clean-up that slows over time. This method is best suited for treating stagnant or slow-moving water, such as ponds, lakes, or reservoirs, though the clean-up speed can be limited by the rate of diffusion.

- In the dynamic approach (**Fig. 7**), the composite material is packed into a filter system. Polluted water is pumped or flows through a compact bed of the material. The filter is often designed in layers.

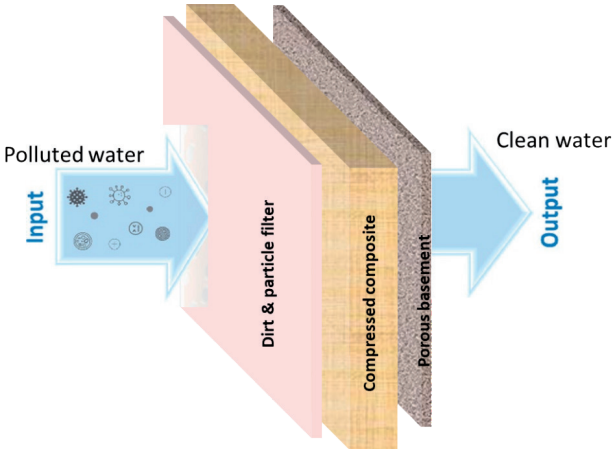

Fig. 7. Dynamic composite filter, showing a three-layer system with inflow of polluted water, a central composite layer for retention, and outflow of purified water.

A front layer might remove dirt and suspended particles, a central layer of the clay-manganese oxide composite adsorbs organic pollutants and heavy metals, and a final porous support layer ensures the filter remains stable and allows clean water to flow out steadily. This system is highly efficient for continuous-flow applications, like home water filters or industrial effluent treatment.

The main requirement is that the filter material must be replaced or regenerated once its adsorption sites are full.

7. Adsorbent management and sustainability

A critical aspect of any adsorption-based clean-up technology is managing the material after it has captured the pollutants. If not handled properly, used adsorbents can become a new source of contamination. For clay-birnessite composites, three main strategies are considered: (a) chemical regeneration and (b) thermal treatment [66], (c) integration with bioelectrochemical systems.

a) Chemical regeneration involves treating the saturated composite with specific aqueous solutions under controlled pH and temperature. Acidic or basic conditions can help to release (desorb) the organic pollutants and exchange the heavy metals back into the solution [65]. This process can restore some of the material's adsorption capacity, allow-

ing it to be reused. However, it has drawbacks: it can be costly, and it generates a secondary stream of liquid waste that itself requires careful treatment to avoid causing further pollution [67]. Additionally, the regeneration process can slowly damage the structure of the adsorbent, reducing its efficiency over multiple cycles [66].

b) Thermal treatment offers a more straightforward and often more sustainable solution, especially at a large scale. In this method, the exhausted composites are heated to a high temperature (typically 400-600°C). This process, known as calcination, burns off and destroys the organic pollutants through combustion. The heavy metals remain within the resulting ash, where they are converted into stable oxides or other mineral phases. To prevent these metals from leaching out, the metal-laden ash is typically mixed into a cementitious matrix, creating concrete blocks that can be safely stored in controlled facilities or even used in construction [68]. This method safely immobilizes the pollutants for the long term. The energy required for heating is a significant operational cost. For a large-scale water treatment plant treating millions of liters per day, the thermal treatment of spent adsorbent could require a significant energy input. A preliminary estimate suggests that heating 1 ton of composite to 500°C could require approximately 150-200 kWh of energy. If powered by a dedicated renewable source, this would require, a small wind turbine (e.g., 10 kW capacity running at 30% capacity factor) to treat about 10-15 tons of spent material per month. While this is an additional cost, it avoids the creation of a secondary liquid waste stream and provides a permanently stabilized final product. The sustainability of this approach is maximized when the required heat is sourced from renewable energy, such as solar thermal or biogas, aligning with circular economy principles.

c) Integration with Bioelectrochemical Systems (BES), an innovative and sustainable approach to manage the secondary waste stream from chemical regeneration is to treat it using bioelectrochemical systems, such as microbial fuel cells (MFCs). The concentrated eluate from chemical regeneration, containing both desorbed organic pollutants and heavy metals, is often toxic and difficult to treat with conventional methods. BES offer a unique solution. In an MFC, electroactive bacteria oxidize the organic pollutants (e.g., pesticides, pharmaceuticals) at the anode, releasing electrons and protons. The heavy metals in the eluate can be simultaneously reduced and deposited at the cathode, achieving their removal and recovery [69, 70]. This integration is particularly synergistic with the materials discussed in this paper. Many advanced MFCs utilize clay-based separators and membranes due to their low cost, ion-exchange properties, and structural stability [71, 72]. Furthermore, manganese oxides have been explored as low-cost cathode catalysts to enhance oxygen reduction or direct metal reduction reactions [73]. Therefore, the very materials that form the core of our composite adsorbent (clays and birnessites) could be repurposed to build the BES reactor that treats its own waste stream. This creates a closed-loop or integrated system where the secondary pollution problem is solved by a technology built from the same abundant, low-cost materials, simultaneously recovering energy (as electricity) and valuable metals.

From a sustainability perspective, thermal immobilization provides long-term stability and avoids creating liquid waste streams. Its main drawback is the energy required for heating, which should ideally come from renewable sources to minimize the environmental footprint. Chemical regeneration is less energy-intensive but is more practical for small-scale or decentralized systems where the secondary waste can be managed locally. The choice between methods depends on the scale of the operation and the types of pollutants involved. Worth to mention here is that the sustainability of these composites is especially related to their abundance and the low cost. Clays are widely available and inexpensive [16, 22], and manganese oxides can be synthesized from common precursors. This makes the composite technology an accessible and scalable solution, particularly valuable for regions that lack advanced water treatment infrastructure. Recent research has shown that local clays can be successfully shaped into pellets for pesticide removal, demonstrating the strong potential for integrating them into these kinds of composite systems [7, 17, 22, 23]. The availability of both static and dynamic methods makes these composites highly adaptable to different environmental needs and scales of operation.

8. Cost considerations for deployment

The proposed clay-birnessite composite offers several inherent cost advantages. The raw materials, natural clays and manganese precursors are abundant and inexpensive. Clay minerals are globally available and can often be sourced locally, significantly reducing transportation costs. Manganese is also a common element, and birnessites can be synthesized using relatively simple and low-energy wet chemistry methods [20, 25]. The manufacturing of the composite into pellets or beads, while adding a processing step, utilizes standard equipment from the ceramics and materials industry, keeping production costs moderate. When comparing the cost to conventional adsorbents like granular activated carbon (GAC), which can cost 1,500-2,500 USD/ton, the clay-based composite is projected to be significantly cheaper, potentially in the range of 300-500 USD/ton, together with an estimation of potential water treatment capacity per ton of adsorbent. This is calculated considering the following approximations: natural clays ~30-100 USD/ton, acid-activated clays ~150-300 USD/ton, and synthetic birnessite ~400-800 USD/ton at laboratory scale. Since GAC is primarily effective for organic compounds and requires thermal regeneration, the clay-birnessite composite targets both organics and inorganics. Its potential for low-cost chemical regeneration or its ability to be thermally treated and safely immobilized without the need for complex reactivation processes can offer long-term operational savings. The integration with BES for waste stream treatment, while requiring initial capital investment, offers the potential for energy recovery and metal recuperation, offsetting operational costs over the system's lifetime. A detailed life-cycle cost analysis, including raw material extraction, manufacturing, transportation, operation, and end-of-life management, would be the next step to fully quantify the economic benefits and optimize the design for specific applications.

9. Conclusions

This study sheds light on the strong potential of clay minerals, layered manganese oxides, and their composites as effective, low-cost materials for water remediation in the context of increasing global water pollution and scarcity. The synthesis of experimental evidence from previous work and an extensive review of the literature clearly demonstrates that natural clays, particularly montmorillonite, kaolinite, bentonite, illite, and palygorskite, are highly efficient adsorbents for a wide range of organic pollutants. Selected pesticides such as atrazine, chlorpyrifos, and glyphosate, as well as pharmaceutical contaminants including azithromycin, paracetamol, and ibuprofen, show substantial adsorption onto clay surfaces and interlayer spaces. Natural clays already exhibit significant uptake capacities, while activated and chemically modified clays display markedly enhanced adsorption, often reaching or exceeding 200-300 mg/g, confirming the crucial role of surface modification and interlayer chemistry in optimizing performance. In parallel, the study underlines the exceptional capacity of layered manganese oxides, such as birnessites and their hydrated form, buserites for the removal of toxic heavy metal cations from water. These materials efficiently capture metals such as Pb^{2+}, Cd^{2+}, Cu^{2+}, Zn^{2+}, and Hg^{2+} through ion exchange, surface complexation, and redox-driven mechanisms. Natural birnessites and buserites show adsorption capacities up to about 400 mg/g, while synthetic and sodium-exchanged variants can exceed 600 mg/g, with adsorption strength closely linked to interlayer hydration and the hydrated ionic radius of the metal cations.

The main conclusion of this study is that combining clays and birnessites/buserites into a single composite material represents a highly promising strategy for universal water purification. Such composites can simultaneously target organic pollutants and heavy metals, reflecting the complex mixtures typically present in real contaminated waters. Conceptual designs involving compact spherical pellets or filter-packed systems offer practical routes for both static and dynamic remediation applications.

Importantly, the abundance, low cost, and environmental compatibility of clays and manganese oxides make these composites particularly suitable for large-scale deployment, including in regions with limited access to advanced water treatment technologies. The long-term sustainability of this technology depends not just on adsorption performance, but also on the responsible management of the employed material. Both chemical regeneration and thermal immobilization offer viable pathways to ensure that the composites do not become secondary pollutants. Thermal treatment, in particular, which incorporates the metal-laden residue into concrete, aligns well with circular economy principles by creating a stable, safe end product. Furthermore, the innovative integration of chemical regeneration with bioelectrochemical systems presents a forward-thinking solution to manage secondary waste streams, potentially recovering energy and metals while utilizing the same family of low-cost clay and manganese materials. A preliminary cost analysis suggests the composite is economically competitive with conventional adsorbents, reinforcing its potential for widespread adoption. A follow up of this study should focus on pilot-scale testing of these composites in dynamic flow systems, optimizing the composite ratio for specific pollutant mixtures, and conducting a full life-cycle assessment to validate the sustainability and economic benefits outlined here.

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