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Heated aluminum oxide particles (HAOPs): From synthesis and mechanisms to applications and environmental aspects

Ladawan Mee-ngern, Muhammad Yaqub and Wontae Lee*

Department of Environmental Engineering, Kumoh National Institute of Technology, 61 Daehak-ro, Gumi, Gyeongsangbuk-do 39177, Republic of Korea

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Abstract. Heated Aluminum Oxide Particles (HAOPs) have emerged as a promising class of engineered adsorbents with unique physicochemical properties suited for water purification. Their ability to effectively remove a range of contaminants positions them as valuable materials in advancing water treatment technologies. This review summarizes current research on HAOPs covering their synthesis, chemistry, adsorption mechanisms, applications, comparative analysis, environmental aspects, and future research directions. The HAOPs were synthesized by neutralizing aluminum sulfate hydrate with sodium hydroxide to form aluminum hydroxide precipitates, which were then heated at 110°C for 24 hours. They have a well-organized microcrystalline structure with abundant surface hydroxyl groups, contributing to high adsorption efficiency, and demonstrate significant potential in removing natural organic matter, phosphorus, and uranium from water sources. Compared to other adsorbents such as powdered activated carbon and iron oxide particles, HAOPs offer improved contaminant removal and fouling mitigation. Environmentally, their moderate-temperature synthesis reduces energy consumption and production costs. Effective regeneration extends material life and reduces waste, but proper disposal and management of spent HAOPs are crucial to avoid secondary pollution. Comprehensive life-cycle cost assessments and advanced regeneration methods are needed to improve economic feasibility and sustainability. Future research should focus on developing HAOP composites and exploring sustainable disposal and regeneration options to optimize their application in water treatment systems.

Keywords: adsorption; heated aluminum oxide particles; natural organic matter; phosphorous, uranium

1. Introduction

Rapid industrialization and urbanization have caused water pollution to become a global concern (Jing *et al.* 2025). Each day, approximately 2 million tons of industrial, sewage, and agricultural wastewater are discharged worldwide, leading to serious health issues and resulting in the death of approximately 14,000 people daily (Yasasve *et al*. 2022). Various technologies, including membrane filtration (Tran *et al*. 2025*)*, chemical oxidation (Li *et al*. 2025), adsorption (Choi *et al*. 2024), ion exchange (IX) (Kim *et al*. 2023), and electrocoagulation (Wang *et al*. 2024), are used for water treatment (Zakir *et al*. 2025). Among these, adsorption is one of the most efficient and versatile methods owing to its simplicity and capability to remove a range of water pollutants (Satyam and Patra 2024). Adsorption is the accumulation of a substance at the surface or interface of a solid adsorbent and contaminated water through physical or chemical interactions (Alkhaldi *et al*. 2024, Mabalane *et al*. 2024). Physisorption involves reversible weak interactions between the adsorbate and adsorbent, such as van der Waals, electrostatic, hydrophobic (π–π), and hydrogen bonds (Sahu *et al*. 2024). Conversely, chemisorption is an irreversible process that involves complex formation, covalent bonding, proton displacement, chelation, and redox reactions between the adsorbent surface and adsorbate molecules (Ho *et al*. 2025). The adsorption efficiency differs according to the adsorbent's functional groups, capacity, selectivity, and cost (Murphy *et al*. 2023, Han and Chakraborty 2025).

The functional groups on the surface play a crucial role in the adsorption process because they determine the types of interactions that can occur with the adsorbate molecules (Xiang *et al*. 2025). The capacity of an adsorbent refers to the maximum amount of the target substance that it can adsorb and is influenced by factors such as surface area, porosity, and pore size distribution (Murphy *et al*. 2023). For example, zeolites often exhibit high adsorption capacities owing to their large surface areas and optimal pore size distributions (Wang *et al*. 2025). Selectivity is the ability of the adsorbent to preferentially adsorb the target substance, with high selectivity enhancing adsorption efficiency by limiting the capture of undesired compounds (Geng *et al*. 2023). It is often determined by the functional groups present and the size and shape of the adsorbent's pores (Giglio *et al*. 2024). The cost of an adsorbent includes factors such as raw material price, manufacturing, regeneration, longevity, and disposal. Adsorbents with higher efficiency often have higher production and usage costs than those with lower efficiency. Consequently, cost-effectiveness is a critical consideration in selecting an adsorbent, and the overall adsorption efficiency may vary

*Corresponding author, Professor,
E-mail: wtlee@kumoh.ac.kr

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depending on cost constraints (Eniola *et al*. 2023). The adsorbent synthesis process is crucial because it significantly influences the adsorption efficiency of the adsorbent. The specific techniques and parameters employed during the adsorbent preparation process can alter the physical and chemical properties, such as the surface area, pore structure, and functional groups (Ren and Liu 2023). Therefore, the chemical properties and adsorption mechanisms were studied to select the most suitable adsorbent for specific applications (Akhtar *et al*. 2024).

Various adsorbents have been utilized to remove pollutants and recover valuable species from water systems (Li *et al*. 2025), such as biosorbents (Zhao *et al*. 2025, Kim *et al*. 2025), activated carbon (AC) (Li *et al*. 2024, Zuo *et al*. 2023), biochar (BC) (Eniola and Sizirici 2023, Maharathi *et al*. 2025), clays and minerals *(*Muslim *et al*. 2024, Wang *et al*. 2025), polymers (Yu *et al*. 2024, Wang *et al*. 2023), and nanoparticles (NP) (Bhardwaj and Singh 2024, Deng *et al*. 2025) with high adsorption efficiency. Researchers have found heated aluminum oxide particles (HAOPs) to be effective potential adsorbents in the last decade because of their high capacity and cost-efficiency in hybrid adsorption/membrane systems for the adsorption of various contaminants, including natural organic matter (NOM), phosphorous (P), and uranium (U), at the laboratory scale (Liu *et al*. 2017, Ma *et al*. 2020, 2022, Cai *et al*. 2008, Malczewska *et al*. 2022, Malczewska and Benjamin 2016, Wang and Benjamin 2016a, Kim *et al*. 2008a, b 2010, 2024, Chun *et al*. 2021, Malczewska 2021). Few studies synthesized HAOPs and implemented them in fully automated pilot systems (Manamperuma *et al*. 2019). However, owing to the lack of comprehensive research consolidating information on HAOPs, researchers have not explored them in detail, including the synthesis process, chemistry, and adsorption phenomena. Thus, this review aims to gather the available literature on HAOPs to comprehensively understand their synthetic processes, chemistry, and adsorption phenomena. We also explore the applications of HAOPs, conduct a comparative analysis, consider environmental aspects, and suggest future research directions to benefit researchers interested in studying HAOP adsorbents.

2. Synthesis process

The synthesis of adsorbents directly influences adsorption efficiency, key properties such as pore structure and particle size, and cost-effectiveness for specific applications (Liu *et al*. 2024, Wang *et al*. 2025). Aluminum oxide-based (Al_2O_3) materials for water treatment applications can be prepared through various methods, such as sol-gel processes, combustion, and precipitation (Ravindhranath and Ramamoorty 2017). Sol-gel processes involve dissolving the precursor, such as aluminum isopropoxide, in a solvent to form a sol, then converting it into a gel and heating to obtain Al_2O_3 (Hosseini *et al*. 2011, Kim *et al*. 2007). The advantages of this method are low raw material costs, high thermal stability, high purity, and high surface area (Ziva *et al*. 2021). However, it has some disadvantages, including high energy demand for calcining above 1200 °C, and process complexity requiring strict control of hydrolysis and solvents (Carstens *et al*. 2019, Yepuri and Ramachandramurthy 2025). The solution combustion process for synthesizing Al_2O_3 begins with the preparation of a homogeneous aqueous solution of aluminum nitrate ($Al(NO_3)_3 \cdot 9H_2O$) and fuel (e.g., urea or glycine). The solution is then heated to a temperature range of 100-250°C, leading to dehydration and decomposition into intermediates, such as $Al(OH)(NO_3)_2$ and ammonia. An exothermic reaction is initiated upon reaching approximately 400–600°C, causing the temperature to rise to 1350°C. This rapid combustion (3–5 minutes) forms a fine, porous α-Al_2O_3 powder. Subsequently, additional calcination at 600–800°C ensures complete crystallization (Shea *et al*. 2000, Varma *et al*. 2016). This method offers advantages such as simple set-up and the production of high-quality α-Al_2O_3 NP with large surface areas (Zhuravlev *et al*. 2013). However, challenges include the potential for residual carbon from excess fuel and particle aggregation due to rapid combustion, which may require grinding to prevent clumping (Shea *et al*. 2000). Precipitation methods involve the formation of aluminum hydroxide ($Al(OH)_3$) precipitates, which are then subjected to further processing, such as aging, washing, and calcination, to achieve the desired phase and particle characteristics (Egzar *et al*. 2022, Sivasenthil *et al*. 2023). The literature reported that this method is the most efficient method for synthesizing Al_2O_3. It is the simplest compared to other methods, scalable, and low-cost, making it accessible for large-scale production. They also operate at relatively low temperatures, providing a more energy-efficient approach. They offer reasonable control over particle size, morphology, and homogeneity, ensuring consistency in the final product. Moreover, the high surface area achieved through this method is critical for applications such as adsorption in water treatment (Ziva *et al*. 2021).

This review focuses specifically on heated aluminum oxide, which is a method developed from the precipitation process, involving heating freshly precipitated (unheated) $Al(OH)_3$ (Lee *et al*. 2019). HAOPs were developed to study their effectiveness in removing NOM and membrane fouling (Kim *et al*. 2008). The synthesis process begins with the precipitation of aluminum sulfate hydrate ($Al_2(SO_4)_3 \cdot xH_2O$), which is neutralized with sodium hydroxide (NaOH) to form $Al(OH)_3$ residues. The resulting $Al(OH)_3$ suspension is then heated in a closed environment at approximately 110 °C for 24 hours to yield the desired particles. Previous studies reported that HAOPs synthesized using this method contain approximately 24–30% aluminum (Al) by weight (Chun *et al*. 2021, Kim and Jang 2008a, b Cai *et al*. 2008, Manamperuma *et al*. 2019, Lee *et al*. 2019, Lee and Lee 2021, Wang and Benjamin 2016b, Shi and Benjamin 2008). The particle size distribution gradually decreases with heating because this step partially dehydrates them, leading to a reduction in size, with almost all particles becoming smaller than 50 μm, and the small size of HAOPs enhances pollutant removal efficiency (Liu *et al*. 2017, Lee *et al*. 2019). In summary, the heating process in the synthesis of HAOPs causes partial structural transformation of $Al(OH)_3$,

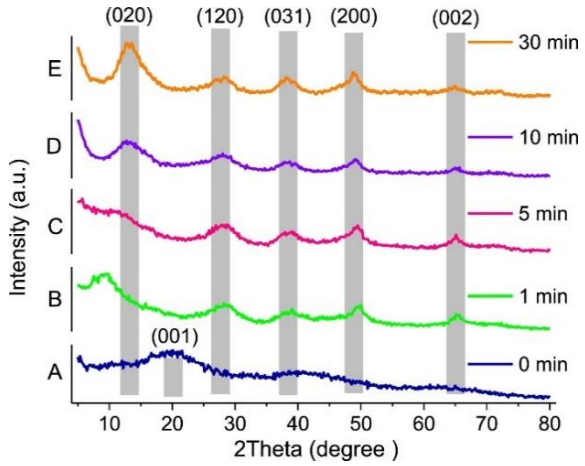

Fig. 1 XRD patterns of HAOPs with different heating times: (A) 0 min, (B) 1 min, (C) 5 min, (D) 10 min, (E) 30 min (Liu *et al*. 2017)

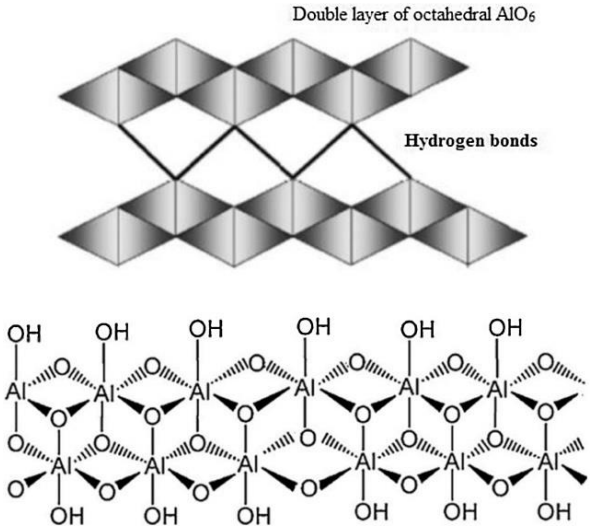

Fig. 2 Structure of boehmite layers (Mohammadi *et al*. 2021)

obtained from the precipitation step, through dehydration. This process results in a significant reduction in particle size, which in turn enhances the specific surface area and improves the adsorption efficiency for pollutants. This highlights the importance of selecting appropriate synthesis techniques to produce high- quality adsorbents with enhanced functional properties.

3. Chemistry and adsorption phenomenon of HAOPs

Understanding the chemical properties of adsorbents is essential, as they are directly related to the adsorption mechanisms and significantly influence their performance (Pellenz *et al*. 2023, Alkhaldi *et al*. 2024). The adsorption phenomenon is crucial for selecting appropriate and efficient adsorbents to adsorb specific substances, as the type of mechanism depends on the nature of both the adsorbent and adsorbate (Wang *et al*. 2020, Alsharif 2025). This section describes the chemistry and adsorption phenomenon of HAOPs synthesized by heating the suspension of Al $(OH)_3$ obtained from the $Al_2(SO_4)_3{\cdot}xH_2O$ and NaOH reaction. The thermal treatment of Al $(OH)_3$ to produce HAOPs involves a complex series of phase transformations that significantly influence the resulting material's properties (Lamouri *et al*. 2017). The Al $(OH)_3$ initially exists in an amorphous phase before heating. During the heating, as the temperature increases, this phase gradually transitions into a more organized phase with a well-defined structure (Kim *et al*. 2024). Extended heating led to further changes in the crystallinity and microstructure of the particles, as evidenced by the X-ray Diffraction (XRD) result of Liu *et al*. (2017) shown in Fig. 1, where the increasing intensity and sharpening of peaks with the increase of heating time suggested that crystallization of the particles occurred. The XRD pattern, the positions, and relative intensities align closely with those of the boehmite (γ-AlOOH) crystal phase. Fig. 2 shows γ-AlOOH structure, which crystallizes in a layered structure composed of AlO_6 octahedra. The layers are held together by hydrogen bonds between hydroxyl (OH) groups (Mohammadi *et al*. 2021). In terms of the functional groups present on HAOPs surface, Fourier-transformed infrared spectroscopy analysis revealed a band near 3380 cm^{-1}, corresponding to the asymmetric stretching vibrations (ν_{as} (Al)O–H) of OH groups, while a band at 1640 cm^{-1} was attributed to the bending vibrations of H–O–H in weakly bound molecular water (Liu *et al*. 2017). The broad peaks observed at 1101 and 611 cm^{-1} were assigned to aluminum-based functional groups, also present in the spectra of Al $(OH)_3$ species (Lee and Lee 2021).

The adsorption capacity of HAOPs depends on these surface properties, particularly the acidity of the surface and the hydroxylation. The surface acidity of HAOPs is primarily attributed to the Lewis acid sites on the Al atoms within the structure. These acid sites act as active centers for adsorption, especially for basic compounds. This acidity facilitates the adsorption of negatively charged or electron-rich species (Lundie *et al*. 2005). The hydroxylation of HAOPs' surface is another critical factor affecting its adsorption properties. The OH groups, present as a result of the surface chemistry of the γ-AlOOHstructure, are capable of forming hydrogen bonds with adsorbates, which enhances the material's ability to retain molecules. In addition, the OH groups can enhance the acidity of the Al sites by strengthening the acid-base interaction between the Lewis acidic Al and the basic adsorbates (Ma *et al*. 2024). This dual mechanism of surface acidity and hydroxylation is particularly evident in the adsorption of P onto the surfaces of HAOPs. In the process, phosphate ions (PO_4^-) replaces the OH groups, facilitating strong binding to the adsorbent (Peinemann and Helmy 1977). Moreover, the OH groups of HAOPs can form hydrogen bonds with various functional groups in NOM molecules, such as carboxyl (-COOH) and OH groups (Liu *et al*. 2017). Overall, HAOPs represent a significant advancement in adsorbent technology, offering exceptional performance in environmental applications, particularly water treatment. Their unique chemistry, involving phase transformations, plays a key role in their adsorption properties. The adsorption phenomenon in HAOPs is primarily governed by their surface chemistry,

Table 1 Performance of HAOP pre-deposited on various membranes for NOM removal

Membrane types/ Batch test	Pollutants	Water sources	Eff. (%)	Reference
UF membranes	P	MBR	99	(Lee *et al*. 2019)
PES membranes	P	SW	88–98	(Malczewska 2021)
Batch test	P	MBR	97	(Kim *et al*. 2008)
Batch test	U	SW	98	(Lee and Lee 2021)
Batch test (Fe-HAOPs combined)	U	Sim. W	100	(Xie *et al*. 2017)
Batch test	Phenol	Sim. W	92	(Safwat *et al*. 2022)

Eff: Efficiencies; Fe: Iron; MBR: Membrane bioreactor; P: Phosphorus; PES: Polyethersulfone; Sim.W: Simulated water; SW: Surface water; U: Uranium; UF: Ultrafiltration

including acidity and hydroxylation. These properties can be tailored through synthesis conditions and thermal treatments to optimize performance for specific applications. Future developments in HAOPs technology may focus on enhancing their selectivity for specific contaminants, improving their regeneration capabilities, and exploring their combination with other materials to expand their applications to address other environmental remediation challenges.

4. Applications of HAOPs and Al oxide-based adsorbent

4.1 Application of HAOPs

The unique properties of HAOPs, such as the high density of OH groups, have revealed great potential as adsorbents for removing pollutants from water sources, attracting attention for both research and practical use. This section consolidates information regarding the use of HAOPs in water treatment and their performance in such applications, with a focus specifically on HAOPs prepared by heating an $Al(OH)_3$ suspension of $Al_2(SO_4)_3{\cdot}xH_2O$ and NaOH. Most of the literature focuses on using HAOPs pre-deposited on membranes to remove NOM from natural water sources and membrane bioreactor (MBR) effluents. Beyond NOM, recent investigations have expanded to explore the capability of HAOPs in adsorbing other pollutants such as P, U, and phenol, showcasing their broad applicability.

To illustrate the effectiveness of HAOPs in NOM removal, Table 1 summarizes various studies utilizing HAOPs pre-deposited on different membrane types. The literature reported that using HAOPs pre-deposited on polyacrylonitrile electrospun nanofibrous membranes achieved 91% NOM removal in terms of total organic carbon (TOC) and minimized fouling problems (Malczewska *et al*. 2022). Similarly, when applied to ultrafiltration (UF) membranes, HAOPs were able to remove 88, 90, and 90% of humic acid (HA), bovine serum albumin (BSA), and sodium alginate (SA), respectively, which are representative of NOM (Liu *et al*. 2017). Another study reported that this system removed 70–80% of NOM as Ultraviolet at 254 nm (UV_{254}), and 45–60% as dissolved organic carbon (DOC) and resulting in decreased fouling (Wang and Benjamin 2016a, Malczewska and Benjamin 2016, Liu and Benjamin 2016). HAOPs on micro granular membranes displayed NOM removal efficiencies ranging from 40–67% for DOC and 75–82% for UV_{254}, which slowed the increase in transmembrane pressure (TMP) compared to bare membranes, indicating efficacy in preventing membrane fouling (Cai *et al*. 2008, Kim *et al*. 2008). Moreover, when utilized as the adsorbent layer in a micro granular adsorptive filtration (μGAF) system, it presented 65% NOM removal efficiency in DOC and 65–80% for UV_{254}, along with a delayed fouling rate (Modarresi and Benjamin 2019, Cai *et al*. 2013, Cai and Benjamin 2011).

The polyethersulfone (PES) membrane was pre-deposited with HAOPs and indicated significantly improved NOM removal, with 72–92% efficiency compared to less than 2% with the bare PES membrane (Kim *et al*. 2010). HAOPs on ceramic (CE) membranes removed 70% of NOM from surface water and decreased it to 55% for DOC and 60% for UV_{254} when applied to remove effluent organic matter (EfOM) (Kim and Jang 2018, Chun *et al*. 2021). Some studies have utilized HAOPs in a fully automated pilot system to remove NOM from surface water sources at the UniVann water treatment plant in Ullensaker County, Norway. The pilot-plant treatment involved passing water through a thin layer of HAOPs deposited on a mesh support. The treatment consistently achieved >85% NOM removal, with turbidity <0.01 NTU and non-detectable suspended solids in the permeate (Manamperuma *et al*. 2019). In summary, the pre-deposition of HAOPs onto various membrane types has been shown to significantly improve the removal efficiency of NOM. HAOPs act as a thin coating layer on the membrane surface, enhancing the adsorption of both low- and high-molecular-weight (HMW) NOM compounds, compared to uncoated membranes. The large NOM molecules are primarily adsorbed onto the surface of the HAOPs layer, involving the presence of functional groups commonly found in NOM, particularly -COOH and OH groups, which play a crucial role in forming chemical interactions, such as hydrogen bonding and electrostatic attractions with Al ions present on the surface of HAOPs. Since NOM is a major contributor to membrane fouling (Taniguchi *et al*. 2003), the ability of HAOPs to adsorb these compounds not only enhances NOM removal but also helps mitigate membrane fouling. As a result, membrane performance is improved, enabling longer operation times and higher overall efficiency.

Expanding on their demonstrated effectiveness in NOM removal, HAOPs have also shown excellent performance in removing other challenging contaminants. As shown in Table 2, their application extends to P, U, and phenol, either through pre-deposition on membranes or in batch adsorption tests. HAOPs pre-deposited on UF and PES membranes achieved P removal from MBR effluents of 99% and 98%, respectively. Similarly, showing high P removal in the batch test (97%). This impressive performance is attributed

Table 2 Performance of HAOPs for P, U, and phenol removal

Membrane types	NOM species	Water sources	AE (%)	Reference
PAN electrospun nanofibrous membranes	TOC	SW	91	(Malczewska *et al*. 2022)
UF membranes	BSA	SW	90	(Liu *et al*. 2017)
	SA	SW	90	
	HA	SW	88	
	UV_{254}	SW	70–80	(Wang and Benjamin 2016a, Malczewska and Benjamin 2016, Liu and Benjamin 2016)
	DOC	SW	45–60	
MF membranes	UV_{254}	SW	75–82	(Kim *et al*. 2008, Cai *et al*. 2008)
	DOC	SW	40–67	
μGAF systems	UV_{254}	SW	65–80	(Cai *et al*. 2013, Cai and Benjamin 2011)
	DOC	SW	65	(Modarresi and Benjamin 2019)
PES membrane	UV_{254}	SW	72–92	(Kim *et al*. 2010, Malczewska 2021)
Ceramic membranes	UV_{254}	MBR	60	(Chun *et al*. 2021)
	DOC	SW	70	(Kim and Jang 2018)
		MBR	55	(Chun *et al*. 2021)
Pilot systems	UV_{254}	SW	85	(Manamperuma *et al*. 2019)

AE: Adsorption efficiency; BSA: Bovine serum albumin; DOC: Dissolved organic carbon; HA: Humic acid; MBR: Membrane bioreactor; MF: Microfiltration; NOM: Nature organic matter; PAN: Polyacrylonitrile; PES: Polyethersulfone; SA: Sodium alginate; SW: Surface water; TOC: Total organic matter; UF: Ultrafiltration; μGAF: Microgranular adsorptive filtration UV_{254}: Ultraviolet at 254 nm

to the adsorption mechanisms of HAOPs, which involve strong chemical interactions between PO_4^- and the reactive OH groups on the HAOPs surface. These interactions lead to the formation of stable surface complexes, enabling selective and efficient phosphate capture (Lee *et al*. 2019, Malczewska 2021, Kim *et al*. 2008). A few studies reported that HAOPs showed 98% U removal efficiency from surface water, which increases to 100% when combined with iron (Fe). The U adsorption involved HAOPs possessing negatively charged surfaces due to the presence of OH groups, enabling strong electrostatic interactions with UO_2^{2+} ions and positively charged U complexes such as $UO_2(OH)^+$ (Lee and Lee 2021, Xie *et al*. 2017). Moreover, the literature revealed that HAOPs can adsorb 92% of phenol. This high efficiency is attributed to chemisorption, where the adsorption of phenol occurs through the exchange or sharing of electrons between phenol and the surface of HAOPs (Safwat *et al*. 2022). Overall, the application of HAOPs demonstrates considerable potential as highly effective adsorbents for water treatment processes, particularly for addressing natural NOM contamination. This efficiency has been observed in various configurations, including HAOPs pre-deposited on membranes, which have remarkably enhanced NOM removal and mitigated membrane fouling. Moreover, the application of HAOPs in removing radioactive substances, such as U, underscores their broader applicability in treating various water sources. However, the development of composite adsorbents that incorporate HAOPs into other functional materials can create highly efficient multifunctional adsorbents. In the future, these composites can be tailored to target specific contaminants or achieve broader spectrum removal capabilities.

4.2 Application of Al oxide-based adsorbents synthesized from other materials

$(SO_4)_3 \cdot xH_2O$, this section expands on the applications of Al oxide-based adsorbents synthesized from a range of other precursors, including $AlCl_3 \cdot 6H_2O$, $Al(NO_3)_3$, and their composites. This highlights the diversity of options for selecting materials suitable for different types of pollutants. Considering these various precursors allows for developing properties tailored to treat water contaminated with a wide range of pollutants effectively. The data in Table 3 compiles the use of Al oxide-based adsorbent from the past five years that are not derived from the precursor $Al_2(SO_4)_3 \cdot xH_2O$. The literature removed several pollutants such as heavy metals, radioactive compounds, P, fluoride (F), and dyes. Many studies focus on the removal of heavy metal, indicating that highly porous Al_2O_3 membrane and its combination with Fe oxide displayed high arsenic adsorption efficiencies (>99%), whereas anchoring with magnetic BC and AC resulted in 90% and 94% adsorption, respectively (Ahmad *et al*. 2022, Shen *et al*. 2021, Al-Gaashani *et al*. 2021). Biosorbent Al NP, Al-functionalized graphene oxide (GO), and the integration of graphitic carbon nitride and Al composites resulted in 87, >95, and >99% cadmium adsorption, respectively (Chaudhuri *et al*. 2021, Sawaf-Barros *et al*. 2020, Momin *et al*. 2023) Moreover, Al-Fe oxide and core-shell nanorods adsorbed 99 and 86% of selenium and chromium, respectively (Jadhav *et al*. 2022, Madhusudan *et al*. 2023), whereas doping with magnesium (Mg) indicated 90% adsorption efficiency for antimony (Zhang *et al*. 2020). Magnetic γ-Al_2O_3 NP, Al-doped with AC and biosorbents Al NP displayed 88, 97 and 81% for copper, molybdenum, and nickel (Ni) adsorption, respectively

Table 3 Overview of Aluminum oxide-based adsorbents for pollutant removal and adsorption efficiencies

Adsorbent	Pollutants	AE (%)	References
Al_2O_3 membrane and Al-Fe_2O_3 composite	As	>99	(Ahmad *et al*. 2022, Muedi *et al*. 2021)
Al Mag BC and AC	As	90,94	(Shen *et al*. 2021, Al-Gaashani *et al*. 2021)
BS-Al NP, GCN-Ca-Al, and GO-Mn-Al NC	Cd	87,>99, >95	(Chaudhuri *et al*. 2021, Herrera-Barros *et al*. 2020, Momin *et al*. 2023)
Al-Fe core-shell NR	Cr	86	(Madhusudan *et al*. 2023)
Mag γ-Al_2O_3 NP	Cu	88	(El-Sawaf *et al*. 2024)
Al-Fe-Mg oxide	Sb	90	(Zhang *et al*. 2020)
Al-AC	Mo	97	(Al-Gaashani *et al*. 2021)
BS Al NP	Ni	81	(Herrera-Barros *et al*. 2020)
Al-Fe oxide	Se	99	(Jadhav *et al*. 2022)
Al_2O_3 and Al-V MS	U	>93	(Liao and Zhang 2020, Luo *et al*. 2022)
AlS/PVA/SA	U	>90	(Yang *et al*. 2020)
Al KNF and Mag BC	F	92,99	(Shen *et al*. 2021, Choi *et al*. 2022)
Al-Fe oxide with Mg, Ni oxide, and CS	F	>90,96	(Murambatsvina and Mahamadi 2019, Zhang *et al*. 2020, Sun *et al*. 2021, Jing *et al*. 2020)
Al-HCIX and TiO_2/ /MgAl-LDH	F	99,85	(Tangjitjaroenkit *et al*. 2021, Wang *et al*. 2024)
Al combined Zn/CaO, Mn-Mg, and Ni oxide	F	67–94	(Gao *et al*. 2022, Gao *et al*. 2020, Alterary 2024)
Al combined Co and Ni LDH	I	>95	(Kang *et al*. 2022)
Al combined Ce NC and Ca LDH	P	>99	(Nakarmi *et al*. 2020, Xie *et al*. 2024)
Al_2O_3 and its combined Fe oxide	Dyes	>96	(Jiang *et al*. 2021, Lou *et al*. 2024)
CH-Al	Dyes	81–98	(Li *et al*. 2023)

AC: Activated carbon; AE: Adsorption efficiencies; Al: Aluminum; AlS; Aluminum sludge; Al_2O_3: Aluminum oxide; As: Arsenic; BC: Biochar; BS: Biosorbents; Ca: Calcium; CaO: Calcium oxide; Cd: Cadmium; Ce: Cerium; CH: Composite hydrate; Cr: Chromium; Co: Cobalt; CS: Carbonized sludge; Cu: Copper; F: Fluride; Fe: Iron; GO: Graphene oxide; GCN: Graphitic carbon nitride; HCIX: Hybrid cation exchanger; I: Iodine; KNF: Kenaf; LDH: Layered double hydroxides; Mag: Magnetics; Mg: Magnesium; Mn: Manganese; Mo: Molybdenum; MS: Microspheres; NC: Nanocomposites; Ni: Nickel; NP: Nanoparticles; NR: Nanorod; P: Phosphorus; PVA: Polyvinyl alcohol; SA: Sodium alginate; Sb: Antimony; Se: Selenium; TiO_2: Titanium dioxide; U: Uranium; V: Vanadium; Zn: Zinc

(El-Sawaf *et al*. 2024, Al-Gaashani *et al*. 2021, Herrera-Barros *et al*. 2020). A few studies utilized Al_2O_3 and its combination with vanadium microspheres for U adsorption. The results showed an efficiency of >93%, which decreased to 90% when using Al sludge/polyvinyl alcohol/SA composites (Liao and Zhang 2020, Luo *et al*. 2022, Yang *et al*. 2020). While many studies concentrated on the adsorption of heavy metals, Al oxide-based has also proven effective for F adsorption. For instance, Al-anchored Kenaf BC adsorbed 99% of F, which declined to 92% when using magnetic BC (Shen *et al*. 2021, Choi *et al*. 2022). Moreover, Hydrous Al-Fe oxide mixed with Mg and Ni oxide also displayed >90% F adsorption efficiencies, while impregnated with carbonized sludge could improve to 96% (Murambatsvina and Mahamadi 2019, Zhang *et al*. 2020, Sun *et al*. 2021, Jing *et al*. 2020). In addition, a hybrid cation exchanger and porous Mg-Al/Titanium dioxide doped with Al_2O_3 showed 99 and 85% F adsorption, respectively (Tangjitjaroenkit *et al*. 2021, Wang *et al*. 2024). Simultaneously, Al combined with zinc/calcium oxide, Manganese-Mg, and Ni oxide displayed 67-94% (Gao *et al*. 2022, Gao *et al*. 2020, Alterary 2024). Some works presented that >95% of iodine is adsorbed using the layered double hydroxides (LDH) Cobalt-Al and NiAl (Kang *et al*. 2022), while >99% of P could be adsorbed by LDH Calcium-Al and Cerium-Al (Nakarmi *et al*. 2020, Xie *et al*. 2024). A few studies reported that using Al_2O_3 and its combination with Fe oxide can adsorb >96% of dye, whereas the composite hydrated Al revealed 81–98% (Jiang *et al*. 2021, Lou *et al*. 2024, Li *et al*. 2023). Overall, Al oxide-based adsorbents demonstrated significant potential for environmental remediation, particularly in water treatment processes.

Materials such as Al_2O_3, Al-Fe composites, and Al-functionalized nanomaterials showed excellent efficiency in removing various pollutants, including heavy metals, F, dyes, and P. Their high adsorption efficiencies, often exceeding 90%, highlighted the promise for sustainable environmental management. These materials' versatility and ability to be tailored for specific pollutants offer valuable insights for developing more efficient and cost-effective water treatment technologies.

5. Comparative analysis

Comparing the effectiveness of HAOPs with other materials is essential for understanding their benefits and drawbacks. This analysis highlights the performance of adsorbents under similar conditions and provides insights into their applications and potential limitations. The following section discusses the advantages and limitations

Table 4 Comparison of NOM adsorption efficiency and interaction energy between HAOPs and PAC

Parameters	NOM species	Adsorbents		Reference
		HAOPs	PAC	
Adsorption efficiency (%)	DOC	35	35	(Chun *et al*. 2021)
	UV_{254}	55	45	
	HMW	81	38	
	LMW	17–39	57–63	
Interaction energy (kcal/mol)	HMW	-114.8	-75.3	(Ma *et al*. 2022)
	LMW	-75.0	-85.0	
	HMW	-115	-110	(Ma *et al*. 2020)
	LMW	-10	-25	

DOC: Dissolved Organic Carbon; NOM: Natural organic matter; HAOPs: Heated aluminum oxide particles; HMW: High molecular weight; LMW: Low molecular weight; PAC: Powdered activated carbon; Ref: References; UV_{254}: Ultraviolet at 254 nm

Table 5 Comparison of HAOPs and HIOPs performance in DM systems (Kim *et al*. 2024)

Parameters	HAOPs	HIOPs
HA Removal Efficiency	90%	82%
Layer Density	Less dense	Denser
Water Flux Improvement	Similar to virgin membranes	Lower than virgin membranes
Membrane Fouling	70%–80% irreversible fouling	80%–90% reversible fouling
Regeneration Ability	Requires replacement after use	Reuse is possible after chemical cleaning

HA: Humic acid; HAOPs: Heated aluminum oxide particles; HIOPs: Heated iron oxide particles

Table 6 Comparison of NOM adsorption performance and fouling characteristics between HAOPs and FAO

Parameters	Adsorbents		Reference
	HAOPs	FAO	
NOM Adsorption efficiency (%)	HA = 46	HA = 90	(Kim and Jang 2017)
	BSA = 68	BSA = 70	
	SA = 18	SA = 70	
Maximum Adsorption capacity (mg/g)	HA=79.6	HA=17.2	
	BSA = 217.6	BSA = 461.3	
	SA = 101.1	SA = 84.6	
Surface Area (m^2/g)	1.59	70.3	
Flux Reduction	Less severe	More severe	(Kim and Jang 2018)
Fouling Type	External cake layer fouling	Cake layer fouling and pore-blocking	

BSA: Bovine serum albumin; FAO: Fe-Al oxide; HA: Humic acid; HAOPs: Heated aluminum oxide particles; NOM: Natural organic matter; SA: Sodium alginate

of HAOPs over powdered activated carbon (PAC), heated iron oxide particles (HIOPs), Fe-Al oxide (FAO), alum, ferric chloride ($FeCl_3$), and IX resin.

PAC was selected for comparison benchmark due to its well-established role as a conventional adsorbent in water treatment, particularly effective in removing NOM (Liu *et al*. 2014). Widespread industrial use and extensive research background make it an ideal reference point for evaluating the adsorption performance and fouling mitigation capacity of emerging materials like HAOPs. Table 4 provides a detailed comparison of the efficiencies and interaction energies of the HAOPs and PAC adsorbents for the adsorption of different NOM species, where interaction energy refers to the interaction energy between the foulants and adsorbents. More negative interaction energy values indicate stronger adsorption. The results showed that both had comparable effectiveness in DOC removal, achieving a maximum reduction of 35%. However, the HAOPs exhibited higher efficiency in UV_{254} absorbance, with 55% and 45% adsorption rates for PAC. This suggests that HAOPs are more effective at targeting UV-absorbing organic compounds, typically HMW substances that contribute significantly to membrane fouling (Chun *et al*. 2021). These results align with other studies that reported HAOPs were more effective in adsorbing HMW NOM fractions, achieving 81% efficiency and negative interaction energy of 114.8–115 kcal/mol compared to PAC, 38% and 75–110 kcal/mol, respectively. On the other hand, HAOPs were less effective in adsorbing low-molecular-weight NOM, as evidenced by an adsorption efficiency of 17–39% and negative interaction energy of 10–75 kcal/mol (Ma *et al*. 2020, Modarresi and Benjamin 2019). These findings highlight the higher performance of HAOPs in HMW NOM, which causes major membrane fouling, as demonstrated by their higher adsorption efficiency and more negative interaction energies compared with PAC. Overall, they offer a more robust solution for applications in which reducing membrane fouling caused by HMW NOM is critical.

HAOPs and HIOPs, both used as adsorbents deposited onto a dynamic membrane (DM), were compared to investigate the effect of the adsorbent material. Fe and Al salts are commonly used as coagulants to remove NOM, but a major limitation is that both can cause membrane fouling. However, HIOPs have shown effective NOM removal comparable to Fe salts without causing membrane fouling, which is a significant advantage. For this reason, there is interest in studying whether HAOPs, which have similar basic properties, can produce the same positive results as HIOPs. The results presented in Table 5 revealed that HAOPs achieved a higher NOM removal efficiency of 90% compared to HIOPs (82%). Although HIOPs form a denser dynamic layer, which can improve filtration but reduce water flux, HAOP-deposited membranes maintained a water flux similar to that of virgin membranes, indicating minimal impact on permeability. However, it resulted in 70–80% irreversible fouling, requiring membrane replacement, whereas HIOPs resulted in 80–90% reversible fouling (Kim *et al*. 2024). These findings suggest that although HAOPs demonstrate better NOM removal efficiency, their tendency to cause irreversible fouling limits their suitability for long-term use, making them more appropriate for applications where membrane replacement is feasible or expected. In contrast, HIOPs, despite forming a denser dynamic layer

that may slightly reduce the water flux, offer a more sustainable option for prolonged operation because of their higher reversible fouling rate, which can be effectively managed through regular cleaning. Therefore, the choice between HAOPs and HIOPs should be guided by the filtration system's operational requirements and maintenance capabilities.

A few studies have explored the comparative adsorption performance of NOM between iron–aluminum binary metal oxides (FAO) and single-metal oxides such as HAOPs The comparison between HAOPs and FAO provides insight into whether the modification of adsorbent materials through the incorporation of Fe and Al can enhance the efficiency of NOM removal from water, which is beneficial for the design and development of adsorbents in water treatment systems. The results shown in Table 6 revealed that FAO outperformed HAOPs, with higher adsorption efficiencies of 90% for HA and over 70% for BSA and SA compared to 46, 68, and 18% for HAOPs, respectively. It also exhibited greater maximum adsorption capacities of 79.6 mg/g for HA, 217.6 mg/g for BSA, and 101.1 mg/g for SA, along with a larger surface area of 70.3 m^2/g compared to HAOPs, which presented 17.2, 461.3, 84.6 mg/g, and 1.59 m^2/g, respectively. These findings suggest that FAO was a more effective adsorbent for NOM removal during batch tests (Kim and Jang 2017). However, another study reported that when both adsorbents were applied to the CE membrane surface as an adsorbent cake layer, FAO caused more cake layer fouling, pore blocking, and flux reduction owing to its smaller particle size, allowing easier penetration of the membrane pores, which can lead to more significant fouling and resistance over time. In contrast, HAOPs, with their larger particle sizes, primarily cause external fouling because they do not penetrate pores as easily (Kim and Jang 2018). In conclusion, the FAO performed better than the HAOPs in NOM removal. However, the smaller particle size of the FAO leads to more severe membrane fouling, including pore blocking and flux reduction. The choice between FAO and HAOPs should weigh their adsorption benefits against the potential fouling impacts on membrane performance.

In addition to the adsorbents mentioned above, the performance of the HAOPs was also compared with that of other common adsorbents, such as alum, $FeCl_3$, and IX resin. These materials were selected because alum and $FeCl_3$ are conventional coagulants widely used in water treatment for removing NOM, while IX resin represents a more modern technology that efficiently removes negatively charged NOM fractions such as humic substances. The findings indicated that HAOPs had a higher NOM removal efficiency than alum and $FeCl_3$, achieving 80% NOM removal efficiency, suggesting that HAOPs offer higher performance for NOM removal than traditional coagulants (Cai *et al*. 2008). In μGAF systems, a thin layer of HAOPs or IX resin was pre-deposited to investigate membrane fouling mitigation. The results revealed that HAOPs achieved 80% UV_{254} removal, while IX resin showed only 70% (Cai and Benjamin 2011). Overall, HAOPs are promising alternatives to traditional adsorbents for water treatment, particularly for applications requiring high adsorption efficiencies and fouling mitigation. These outperformed PAC in the removal of HMW NOM. While FAO has a higher adsorption efficiency and HIOPs exhibit more reversible fouling properties, HAOPs have the advantage of causing less severe membrane fouling and maintaining a higher water flux. This information provides valuable insights into the strengths and weaknesses of HAOPs compared with other materials used in water treatment, aiding in the selection of appropriate materials for specific applications.

6. Economics and environmental aspects

The economic feasibility of HAOPs as adsorbents in water treatment is influenced by both their synthesis process and practical application. The synthesis of HAOPs in each step requires careful control of raw material quality, energy input, and processing time, all contributing significantly to the overall production cost. HAOPs may have higher synthesis costs due to chemical reagents and controlled heating conditions than other adsorbents, such as BC or activated clays derived from agricultural waste (Kilic 2020). However, the relatively moderate heating temperature reduces energy consumption compared to high-temperature processes, offering economic and environmental advantages. Efforts to optimize synthesis parameters and explore alternative, low-cost precursors could further improve the cost-effectiveness of HAOP. Moreover, the potential for recycling and regenerating HAOPs after adsorption cycles can lower lifecycle costs by reducing the need for fresh material production and disposal expenses. In practical applications, HAOPs demonstrate high adsorption efficiency and selectivity for removing contaminants, leading to a reduction in required dosage and frequency of adsorbent replacement, thereby lowering operational costs (Kim and Jang 2018). Nonetheless, the economic benefit also depends on contaminant concentration and diversity, influencing the adsorbent demand. Additionally, managing spent HAOPs, especially when laden with toxic pollutants, poses economic and environmental challenges related to disposal or regeneration processes.

From an environmental perspective, the synthesis method employing moderate temperature and aqueous- based chemistry reduces greenhouse gas emissions and hazardous waste generation compared to more energy- intensive adsorbent production techniques. This inherent sustainability can be further enhanced through the adoption of circular economy principles, such as using industrial by- products as feedstock and developing efficient regeneration protocols, which can enhance sustainability by minimizing waste and maximizing resource utilization (Liu *et al*. 2024). Integrating HAOPs with advanced water treatment technologies, such as membrane filtration, holds great potential to improve pollutant removal efficiency and reduce operational costs (Kim and Jang 2018). By combining adsorption with physical separation processes, these hybrid systems enhance overall contaminant removal while mitigating common issues like membrane fouling (Malczewska *et al*. 2022). This synergy can decrease the required amount of adsorbent

and limit the generation of secondary pollutants. In addition, the reduced adsorbent dosage needed due to HAOPs' efficiency also lowers the potential for residual waste generation, contributing to a cleaner and more sustainable water treatment operation. Advanced evaluation methods, such as Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA), play a vital role in ensuring the sustainability of such integrated systems (Kumari *et al*. 2024). LCA allows comprehensive quantification of environmental impacts throughout the entire lifecycle, from raw material sourcing and HAOP synthesis to application, regeneration, and disposal, helping identify areas where improvements can be made (Odey *et al*. 2021). Meanwhile, TEA offers a structured framework to compare economic costs with environmental and social benefits, providing decision-makers with balanced insights for selecting appropriate treatment strategies (Meramo-Hurtado and González-Delgado 2020). Moreover, applying modelling and optimization techniques, including surrogate- based optimization, aids in balancing treatment effectiveness and cost constraints, increasing the feasibility of deploying HAOP-based technologies in real- world settings. These evaluation tools and technological integrations accelerate the advancement of HAOP research toward practical, market-ready solutions, fostering more sustainable and cost-effective water treatment.

In summary, the economic and environmental sustainability of HAOPs depends on balancing synthesis costs, energy consumption, and adsorbent performance in real-world applications. Continued advancements in synthesis optimization, regeneration technologies, and system integration will be crucial to enabling HAOPs as a viable, sustainable solution for water treatment.

7. Future research direction

HAOPs have many applications and benefits, particularly in water treatment processes. Nevertheless, this field is still full of progress and possibilities for enhancement. Future studies should focus on the following key areas to achieve the full potential of HAOPs. Most current research has focused primarily on the use of HAOPs to remove NOM, with only a few studies targeting other contaminants. Therefore, future research should focus on developing HAOPs synthesized using different materials to improve their adsorption capabilities and broaden their applicability for the removal of other contaminants beyond NOM. Further research should focus on regeneration to ensure that its utilization does not contribute to environmental degradation. This is a critical consideration because improper management of these spent adsorbents can introduce harmful substances into the environment, potentially causing further contamination. Moreover, the process of regenerating HAOPs is vital for minimizing the environmental impacts and has significant cost implications. Effective regeneration techniques can help reduce the need to frequently replace these materials, leading to lower overall operational costs (Jia *et al*. 2024). More research is required to comprehensively evaluate the cost-effectiveness of HAOPs, considering the full spectrum of associated expenses, including manufacturing, application, regeneration, transportation, and disposal costs. A study that thoroughly examines all these aspects would provide a more accurate understanding of the total economic impact of HAOPs. This comprehensive evaluation will lead to more knowledgeable decisions regarding their practical application, ensuring a balanced consideration of both environmental and economic factors for sustainable applications.

8. Conclusions

HAOPs have emerged as highly effective adsorbents, distinguished by their unique synthesis method that produces particles with a well-defined microcrystalline structure, abundant surface OH groups, and optimized particle size, all of which contribute to enhanced adsorption performance. The distinctive surface chemistry of HAOPs, characterized by prominent Lewis acid sites and extensive hydroxylation, facilitates selective and efficient adsorption of contaminants, particularly NOM, P, and U, underscoring their suitability for advanced water treatment applications.

Key advantages of HAOPs include their superior adsorption capacity for high molecular weight organic compounds, which are primary contributors to membrane fouling, as well as their ability to substantially mitigate fouling when pre-deposited on membranes, thereby improving membrane lifespan and operational efficiency. Compared to conventional adsorbents such as PAC, alum, and ferric chloride, HAOPs demonstrate enhanced contaminant removal and fouling control. Although Fe–Al binary oxides exhibit higher adsorption efficiencies, HAOPs offer the advantage of causing less severe membrane fouling and present simpler regeneration or replacement options.

Economically, their moderate-temperature synthesis lowers energy demands and production costs. Their potential for regeneration and integration into hybrid systems further supports sustainability. Future research should focus on developing HAOP composites and improved regeneration methods to enhance efficiency and expand applications. Emphasizing sustainable disposal and life cycle assessments is essential for ensuring feasibility and environmental safety, enabling broader use in water treatment.

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References

Ahmad, H., A.R.A. Abdulwahab, B.H. Koo and R.A. Khan. (2022), "Selective extraction of trace arsenite ions using a highly porous aluminum oxide membrane with ordered nanopores", *ACS Omega*, **7**(3), 3044-51.

https://doi.org/10.1021/acsomega.1c06133.
Akhtar, M.S., S. Ali and W. Zaman. (2024), "Innovative adsorbents for pollutant removal: exploring the latest research and applications", *Molecules*, **29**(18). https://doi.org/10.3390/molecules29184317.
Al-Gaashani, R., D. Almasri, B. Shomar and V. Kochkodan. (2021), "Preparation and properties of novel activated carbon doped with aluminum oxide and silver for water treatment", *J. Alloys Compd*., **858**, 158372. https://doi.org/10.1016/j.jallcom.2020.158372.
Alkhaldi, H., S. Alharthi, S. Alharthi, H.A. AlGhamdi, Y.M. AlZahrani, S.A. Mahmoud, L.G. Amin, … and S.F. Abaza (2024), "Sustainable polymeric adsorbents for adsorption-based water remediation and pathogen deactivation: a review", *RSC Advances*, **14** (45), 33143-90. https://doi.org/10.1039/D4RA05269B.
Alsharif, M.A. (2025), "Understanding adsorption: Theories, techniques and applications", IntechOpen, London, U.K. https://doi.org/10.5772/intechopen.1008865.
Alterary, S.S. (2024), "Potent and versatile biogenically synthesized alumina/nickel oxide nanocomposite adsorbent for defluoridation of drinking water", *ACS Omega*, **9**(22), 23220-40. https://doi.org/10.1021/acsomega.3c09076.
Bhardwaj, A. and A.K. Singh (2024), "Biogenic synthesis, characterization and photocatalytic activity of cerium nanoparticles for treatment of dyes contaminated water", *Biocatal. Agric. Biotech*., **57**, 103075. https://doi.org/10.1016/j.bcab.2024.103075.
Cai, Z. and M.M. Benjamin (2011), "NOM fractionation and fouling of low-pressure membranes in microgranular adsorptive filtration", *Environ. Sci. Tech*., **45**(20), 8935-40. https://doi.org/10.1021/es202219e.
Cai, Z., J. Kim and M.M. Benjamin (2008), "NOM removal by adsorption and membrane filtration using heated aluminum oxide particles", *Environ. Sci. Tech*., **42**(2), 619-23. https://doi.org/10.1021/es7021285.
Cai, Z., C. Wee and M.M. Benjamin (2013), "Fouling mechanisms in low-pressure membrane filtration in the presence of an adsorbent cake layer", *J. Membr. Sci*., **433,** 32-38. https://doi.org/10.1016/j.memsci.2013.01.007.
Carstens, S., C.Splith and D. Enke (2019), "Sol-gel synthesis of α-Al_2O_3 with enhanced porosity via dicarboxylic acid templating", *Sci. Rep*., **9**(1), 19982. https://doi.org/10.1038/s41598-019-56294-1.
Chaudhuri, S., R. Chatterjee, S.K. Ray and C. Majumder (2021), "Removal of cadmium ions from water by using aluminum functionalized graphene oxide", *J. Indian Chem. Soc*., **97**(Apr 2020). https://doi.org/10.5281/zenodo.5638487.
Choi, H., Y. Jang, J. Choi, H. Choi, H. Oh and S. Chung (2024), "Adsorption of phosphate and mitigation of biofouling using lanthanum-doped quorum quenching beads in MBR", *Membr. Water Treat*., **15**(2), 51-57. https://doi.org/10.12989/mwt.2024.15.2.051.
Choi, M.Y., C.G. Lee and S.J. Park (2022), "Enhanced fluoride adsorption on aluminum-impregnated kenaf biochar: adsorption characteristics and mechanism", *Water Air Soil Pollut*., **233**(11), 435. https://doi.org/10.1007/s11270-022-05906-0.
Chun, Y., T. Hua, A. Anantharaman, J.W. Chew, N. Cai, M. Benjamin and R. Wang (2021), "Organic matter removal from a membrane bioreactor effluent for reverse osmosis fouling mitigation by microgranular adsorptive filtration system", *Desalination*, **506**, 115016. https://doi.org/10.1016/j.desal.2021.115016.
Deng, B., M. Zhou, X. Li, J. Tong, Y. Gao, T. Sun, P. Liu, Y. Zhang, D. Li and X. Cheng (2025), "Developing regenerable levodopa/ε-polylysine magnetic nanoparticles for rapid selective adsorption of anionic dyes", *Chem. Eng. Res. Des*., **218**, 718-28. https://doi.org/10.1016/j.cherd.2025.05.042.
Egzar, H.K., E.H. Sahap, A.M. Juda and N.A.S. Ridha (2022), "Co-precipitation synthesis and characterization of aluminum oxide nanoparticles as catalyst for the removal of reactive blue 4 dye from aqueous solutions", *Eur. Chem. Bull*., **11**(6), 101-6. https://doi.org/10.31838/ecb/2022.11.06.015.
El-Sawaf, A.K., S.R. El-Dakkony, M.A. Zayed, A.M. Eldesoky, A.A. Nassar, A. El Shahawy and M.F. Mubarak. (2024), "Green synthesis and characterization of magnetic gamma alumina nanoparticles for copper ions adsorption from synthetic wastewater", *Results Eng*., **22**, 101971. https://doi.org/10.1016/j.rineng.2024.101971.
Eniola, J.O. and B. Sizirici (2023), "Investigation of biochar-modified biosand filter performance for groundwater treatment for drinking water purposes: a laboratory and pilot scale study", *J. Water Proc. Eng*., **53**, 103914. https://doi.org/10.1016/j.jwpe.2023.103914.
Eniola, J.O., B. Sizirici, Y. Fseha, J.F. Shaheen and A.M. Aboulella (2023), "Application of conventional and emerging low-cost adsorbents as sustainable materials for removal of contaminants from water", *Environ. Sci. Pollut. Res*., **30**(38), 88245-71. https://doi.org/10.1007/s11356-023-28399-8.
Gao, M., W. Wang, M. Cao, H. Yang and Y. Li (2020), "Hierarchical hollow manganese-magnesium-aluminum ternary metal oxide for fluoride elimination", *Environ. Res*., **188**, 109735. https://doi.org/10.1016/j.envres.2020.109735.
Gao, R., Y. Huang, J. He, W. Shi, S. Huang, L. Pan, Z. Pan and G. Li (2022), "Preparation of MgAl layered double oxides and its adsorption kinetics for ciprofloxacin hydrochloride in water", *Environ. Prog. Sust. Energy*, **41**(6), e13899. https://doi.org/10.1002/ep.13899.
Geng, C., R. Lin, P. Yang, P. Liu, L. Guo, B. Cui and Y. Fang (2023), "Highly selective adsorption of Hg (II) from aqueous solution by three-dimensional porous N-doped starch-based carbon", *Environ. Sci. Pollut. Res*., **30**(18), 52107-23. https://doi.org/10.1007/s11356-023-26002-8.
Giglio, V., C. Zagni, E.T. Spina, F. Cunsolo and S.C. Carroccio (2024), "Polyvinylimidazole-based cryogel as an efficient tool for the capture and release of oleuropein in aqueous media", *Polymers*, **16**(16), 2339. https://doi.org/10.3390/polym16162339.
Han, B. and A. Chakraborty (2025), "Machine learning optimized adsorption heat transformations from adsorbents screening to enhanced performances", *Energy Convers. Manage*., **344**, 120272. https://doi.org/10.1016/j.enconman.2025.120272.
Herrera-Barros, A., C. Tejada-Tovar, A. Villabona-Ortíz, A.D. González-Delgado and J. Benitez-Monroy. (2020), "Cd (II) and Ni (II) uptake by novel biosorbent prepared from oil palm residual biomass and Al_2O_3 nanoparticles", *Sust. Chem. Pharm*., **15**, 100216. shttps://doi.org/10.1016/j.scp.2020.100216.
Ho, K.L., S.P. Yeap and K.M. Lee (2025), "A critical review of microplastics and nanoplastics in wastewater: Insights into adsorbent-based remediation strategies", *Environ. Pollut*., **382**, 126658. https://doi.org/10.1016/j.envpol.2025.126658.
Hosseini, Z., M. Taghizadeh and F. Yaripour (2011), "Synthesis of nanocrystalline γ-Al_2O_3 by sol-gel and precipitation methods for methanol dehydration to dimethyl ether", *J. Natural Gas Chem*., **20**(2), 128-34. https://doi.org/10.1016/S1003-9953(10)60172-7.
Jadhav, A.S., P. Ramteke, S.K. Singh and N.K. Labhasetwar (2022), "Sustainable selenium remediation from water using aluminium-iron mixed oxide: Batch and column adsorption studies", *J. Water Proc. Eng*., **48**, 102824. https://doi.org/10.1016/j.jwpe.2022.102824.
Jia, L., M. Yang, X. Shen, J. Li, Xi. Chen, F. Zhang and H. Yang (2024), "Humid-air regeneration of microporous adsorbents at ambient temperature for cyclic dynamic adsorption of volatile organic compounds: a comparison with thermal regeneration",

Ind. *Eng*. *Chem*. *Res*., **63**(33), 14786-800. https://doi.org/10.1021/acs.iecr.4c01472.

Jiang, Y., Q. Mao, T. Ma, X. Liu, Y. Li, S. Ren and J. Sun (2021), "Facile preparation of Fe_2O_3 Al_2O_3 composite with excellent adsorption properties towards congo red", *Ceram*. *Int*., **47**(10), 13884-94. https://doi.org/10.1016/j.ceramint.2021.01.255.

Jing, F., B. Hui, X. Yudan, Z. Rui, Z. Puli, B. Duo, D. Zeng, L. Wei and L. Xuebin (2020), "Recycling of iron and aluminum from drinking water treatment sludge for synthesis of a magnetic composite material (ALCS-Fe-Al) to remove fluoride from drinking water", *Groundwater Sust*. *Develop*., **11**, 100456. https://doi.org/10.1016/j.gsd.2020.100456.

Jing, Z., Y. Zhang, X. Liu, Q. Li, Y. Hao, Y. Li and H. Gao (2025), "Identifying human activities causing water pollution based on microbial community sequencing and source classifier machine learning", *Environ*. *Int*., **195**, 109240. https://doi.org/10.1016/j.envint.2024.109240.

Kang, J., F. Cintron-Colon, H. Kim, J. Kim, T. Varga, Y. Du, O. Qafoku, W. Um and T.G. Levitskaia (2022), "Removal of iodine (I^- and IO_3^-) from aqueous solutions using CoAl and NiAl layered double hydroxides", *Chem*. *Eng*. *J*., **430**, 132788. https://doi.org/10.1016/j.cej.2021.132788.

Kilic, M.Y. (2020), "A comparative treatability study for textile wastewater: agricultural waste adsorbent versus activated carbon", *Polish J*. *Environ*. *Stud*., **29**(6), 4131-37. https://doi.org/10.15244/pjoes/120770.

Kim, J., Z. Cai and M.M. Benjamin (2008a), "Effects of adsorbents on membrane fouling by natural organic matter", *J*. *Membr*. *Sci*., **310**(1), 356-64. https://doi.org/10.1016/j.memsci.2007.11.007.

Kim, J., Q. Deng and M.M. Benjamin (2008b), "Simultaneous removal of phosphorus and foulants in a hybrid coagulation/ membrane filtration system", *Water Res*., **42**(8), 2017-24. https://doi.org/10.1016/j.watres.2007.12.017.

Kim, J., Z. Cai and M.M. Benjamin (2010), "NOM fouling mechanisms in a hybrid adsorption/membrane system", *J*. *Membr*. *Sci*., **349**(1), 35-43. https://doi.org/10.1016/j.memsci.2009.11.017.

Kim, K.J. and A. Jang (2017), "Evaluation of natural organic matter adsorption on Fe-Al binary oxide: Comparison with single metal oxides", *Chemosphere*, **185**, 247-57. https://doi.org/10.1016/j.chemosphere.2017.07.007.

Kim, K.J. and A. Jang (2018a), "Presence of Fe-Al binary oxide adsorbent cake layer in ceramic membrane filtration and their impact for removal of HA and BSA", *Chemosphere*, **196**, 440-52. https://doi.org/10.1016/j.chemosphere.2018.01.011.

Kim, K.J. and A. Jang (2018b), "Effect of heated aluminum oxide particles dynamic membranes on polymeric and ceramic microfiltration membrane", *Desalin*. *Water Treat*., **135**, 314-22. https://doi.org/10.5004/dwt.2018.22698.

Kim, N., J.W. Lee, T. Jang, S. Yoon, J.H. Choi, E. Hong and J.A. Park (2025), "Adsorption of cationic dyes using Sargassum horneri and Ulva australis biosorbent", *Desalin*. *Water Treat*., **323**, 101351. https://doi.org/10.1016/j.dwt.2025.101351.

Kim, S.K., D.M. Shin and J.W. Rhim (2023), "Cation exchange membrane and anion exchange membrane aided electrolysis processes for hypochlorite generation", *Membr*. *Water Treat*., **14**(2), 55-63. https://doi.org/10.12989/mwt.2023.14.2.055.

Kim, S.M., Y.J. Lee, K.W. Jun, J.Y. Park and H.S. Potdar (2007), "Synthesis of thermo-stable high surface area alumina powder from sol-gel derived boehmite", *Mater*. *Chem*. *Phys*., **104**(1), 56-61. https://doi.org/10.1016/j.matchemphys.2007.02.044.

Kim, Y., S. Lee, C.M. Kim and A. Jang (2024), "Evaluation of various factors influencing dynamic membrane formation and performance using metal oxide adsorbent", *Desalination*, **572**, 117117. https://doi.org/10.1016/j.desal.2023.117117.

Kumari, S., J. Chowdhry, M. Kumar and M.C. Garg (2024), "Zeolites in wastewater treatment: a comprehensive review on scientometric analysis, adsorption mechanisms and future prospects", *Environ*. *Res*., **260**, 119782. https://doi.org/10.1016/j.envres.2024.119782.

Lamouri, S., M. Hamidouche, N. Bouaouadja, H. Belhouchet, V. Garnier, G. Fantozzi and J.F. Trelkat (2017), "Control of the γ-alumina to α-alumina phase transformation for an optimized alumina densification", *Boletín de La Sociedad Española de Cerámica y Vidrio*, **56**(2), 47-54. https://doi.org/10.1016/j.bsecv.2016.10.001.

Lee, G. and W. Lee (2021), "Adsorption of uranium from groundwater using heated aluminum oxide particles", *J*. *Water Proc*. *Eng*., **40**, 101790. https://doi.org/10.1016/j.jwpe.2020.101790.

Lee, G., S. Modarresi and M.M. Benjamin (2019), "Efficient phosphorus removal from MBR effluent with heated aluminum oxide particles (HAOPs)", *Water Res*., **159**, 274-82. https://doi.org/10.1016/j.watres.2019.05.010.

Li, K., B. Zhang, R. Ma and S. Li (2025), "Magnetic composite adsorbents for radioactive Cs^+/Sr^{2+} removal: Progress in material design and enhanced performance", *Sep*. *Purif*. *Tech*., **374**, 133683. https://doi.org/10.1016/j.seppur.2025.133683.

Li, S., H. Chen, Y. Li, Z. Du, L. Bin, W. Li, F. Fu, P. Li and B. Tang (2023), "Efficient removal of refractory dyestuffs from textile wastewater by composite hydrated alumina derived from waste aluminum polishing solution", *J*. *Environ*. *Chem*. *Eng*., **11**(3), 109859. https://doi.org/10.1016/j.jece.2023.109859.

Li, W., C. Dong, Z. Hao, X. Wu, D. Ding and J. Duan (2024), "The effectiveness and feasibility of ball-milled powdered activated carbon (BPAC) for removal of organic pesticides in conventional drinking water treatment process", *Chemosphere*, **359**, 142229. https://doi.org/10.1016/j.chemosphere.2024.142229.

Li, Y., Z. Ma, Y. Yang, X. Li, E. Gao, Q. Zhao, X. Chen and H. Zhang (2025), "K-Modified cyano-rich carbon nitride for photocatalytic production of water treatment agent - hydrogen peroxide in two-phase system", *J*. *Water Proc*. *Eng*., **73**, 107627. https://doi.org/10.1016/j.jwpe.2025.107627.

Liao, J. and Y. Zhang (2020), "Effective removal of uranium from aqueous solution by using novel sustainable porous Al_2O_3 materials derived from different precursors of aluminum", *Inorg*. *Chem*. *Front*., **7** (3), 765-76. https://doi.org/10.1039/C9QI01426H.

Liu, J. and M.M. Benjamin (2016), "Effect of water chemistry and operational conditions on MGAF process performance", *Water Res*., **105**, 76-84. https://doi.org/10.1016/j.watres.2016.08.048.

Liu, J., H. Chu, B. Dong, J. Wang, Y. Sheng and H. He (2014), "Effect of PACs pretreatment on uf performance for NOM removal", *Desalin*. *Water Treat*., **52**(37), 6878-85. https://doi.org/10.1080/19443994.2014.886294.

Liu, T., B. Yang, N. Graham, Y. Lian, W. Yu and K. Sun (2017), "Mitigation of NOM fouling of ultrafiltration membranes by pre-deposited heated aluminum oxide particles with different crystallinity", *J*. *Membr*. *Sci*., **544**, 359-67. https://doi.org/10.1016/j.memsci.2017.09.048.

Liu, Y., B. Biswas, M. Hassan and R. Naidu (2024), "Green adsorbents for environmental remediation: Synthesis methods, ecotoxicity and reusability prospects", *Processes*, **12**(6), 1195. https://doi.org/10.3390/pr12061195.

Lou, B., H. Shen, B. Liu, J. Zhang, X. Zhang, J. Liu and S. Zhang (2024), "In-Situ preparation of porous metal-ceramic composite from secondary aluminum dross and red mud for adsorption of organic pollutant", *J*. *Alloys Compd*., **986**, 174135. https://doi.org/10.1016/j.jallcom.2024.174135.

Lundie, D.T., A.R. McInroy, R. Marshall, J.M. Winfield, P. Jones, C.C. Dudman, S.F. Parker, C. Mitchell and D. Lennon (2005), "Improved description of the surface acidity of η-alumina", *J*.

Phys. Chem. B, **109** (23), 11592-601. https://doi.org/10.1021/jp0405963.

Luo, J., J. Chen, J. Chen, J. Ma, S. Liu, X. Tong and J. Xiong (2022), "Aluminum vanadate microspheres is a simple but effective material for uranium extraction: performance and mechanism", *J. Solid State Chem*., **312**, 123237. https://doi.org/10.1016/j.jssc.2022.123237.

Ma, Y., F. Tang, Z. Liu, J. Li, H. Wang, F. Wu, D. Wang and A. Lu (2024), "A thermodynamic model of the surface hydroxylation of γ-Al_2O_3", *Phys. Chem. Chem. Phys*., **26** (28), 19543-53. https://doi.org/10.1039/D4CP01968G.

Ma, Y., T. Hua, T.A. Trinh, R. Wang and J.W. Chew (2022), "Molecular dynamics simulation of the competitive adsorption behavior of effluent organic matters by heated aluminum oxide particles (HAOPs)", *Sep. Purif. Technol*., **292**, 120961. https://doi.org/10.1016/j.seppur.2022.120961.

Ma, Y., S. Velioğlu, M.B. Tanis-Kanbur, R. Wang and J.W. Chew (2020), "Mechanistic understanding of the adsorption of natural organic matter by heated aluminum oxide particles (HAOPs) via molecular dynamics simulation", *J. Membr. Sci*., **598**, 117651. https://doi.org/10.1016/j.memsci.2019.117651.

Mabalane, K., N.D. Shooto and P.M. Thabede (2024), "A novel permanganate and peroxide carbon-based avocado seed waste for the adsorption of manganese and chromium ions from water", *Case Stud. Chem. Environ. Eng*., **10**, 100782. https://doi.org/10.1016/j.cscee.2024.100782.

Madhusudan, P., C. Lee and J.O. Kim (2023), "Synthesis of Al_2O_3@Fe_2O_3 core-shell nanorods and its potential for fast phosphate recovery and adsorption of chromium (VI) ions from contaminated wastewater", *Sep. Purif. Technol*., **326**, 124691. https://doi.org/10.1016/j.seppur.2023.124691.

Maharathi, P., S.L. Lo, K.K. Eripogu and H.F. Wu (2025), "Engineered graphene oxide-modified biochar for enhanced adsorption in livestock wastewater treatment: nanoporous confinement and chemisorption mechanisms for soil and water purification", *Sep. Purif. Technol*., **376**, 134044. https://doi.org/10.1016/j.seppur.2025.134044.

Malczewska, B. and M.M. Benjamin (2016), "Efficacy of hybrid adsorption/membrane pretreatment for low pressure membrane", *Water Res.*, **99**, 263-71. https://doi.org/10.1016/j.watres.2016.04.065.

Malczewska, B. (2021), "Adsorption of natural organic matter and phosphorus from surface water using heated aluminum oxide (predeposited) dynamic membrane adsorber", *Appl. Sci*., **11**(16), 7384. https://doi.org/10.3390/app11167384.

Malczewska, B., R.R. Farnood and S. Tabe (2022), "Natural organic matter removal by electrospun nanofiber membranes coated with heated aluminum oxide particles", *J. Water Proc. Eng*., **45**, 102498. https://doi.org/10.1016/j.jwpe.2021.102498.

Manamperuma, L.D., E.A. Vik, M. Benjamin, Z. Cai and J. Skjefstad (2019), "Effects of a novel adsorbent on membrane fouling by natural organic matter in drinking water treatment", *Membranes*, **9**(11), 151. https://doi.org/10.3390/membranes9110151.

Meramo-Hurtado, S.I. and González-Delgado, A.D. (2020), "Application of techno-economic and sensitivity analyses as decision-making tools for assessing emerging large-scale technologies for production of chitosan-based adsorbents", *ACS Omega*, **5**(28), 17601-10. https://doi.org/10.1021/acsomega.0c02064.

Modarresi, S. and M.M. Benjamin (2019), "Using adsorbent mixtures to mitigate membrane fouling and remove NOM with microgranular adsorptive filtration", *J. Membr. Sci*., **573**, 528-33. https://doi.org/10.1016/j.memsci.2018.12.009.

Mohammadi, M., M. Khodamorady, B. Tahmasbi, K. Bahrami and A. Ghorbani-Choghamarani (2021), "Boehmite nanoparticles as versatile support for organic-inorganic hybrid materials: synthesis, functionalization and applications in eco-friendly catalysis", *J. Ind. Eng. Chem.*, **97**, 1-78. https://doi.org/10.1016/j.jiec.2021.02.001.

Momin, Z.H., G.K.R. Angaru, L.P. Lingamdinne, J.R. Koduru and Y.Y. Chang (2023), "Highly efficient Cd(II) removal from groundwater utilizing layered mixed metal oxides-graphitic carbon nitride composite with improved cycling stability", *J. Water Proc. Eng*., **56**, 104276. https://doi.org/10.1016/j.jwpe.2023.104276.

Muedi, K.L., H.G. Brink, V. Masindi and J.P. Maree (2021), "Effective removal of arsenate from wastewater using aluminium enriched ferric oxide-hydroxide recovered from authentic acid mine drainage", *J. Hazard. Mater*., **414**, 125491. https://doi.org/10.1016/j.jhazmat.2021.125491.

Murambatsvina, G. and C. Mahamadi (2019), "Effective fluoride adsorption using water hyacinth beads doped with hydrous oxides of aluminium and iron", *Groundwater Sust. Develop*., **10**, 100302. https://doi.org/10.1016/j.gsd.2019.100302.

Murphy, O.P., M. Vashishtha, P. Palanisamy and K.V. Kumar (2023), "A review on the adsorption isotherms and design calculations for the optimization of adsorbent mass and contact time", *ACS Omega*, **8**(20), 17407-30. https://doi.org/10.1021/acsomega.2c08155.

Muslim, W.A., S.K. Al-Nasri, T.M. Albayati and I.K. Salih (2024), "Investigation of bentonite clay minerals as a natural adsorbents for Cs-137 real radioactive wastewater treatment", *Desalin. Water Treat*., **317**, 100121. https://doi.org/10.1016/j.dwt.2024.100121.

Nakarmi, A., R. Moreira, S.E. Bourdo, F. Watanabe, A. Toland and T. Viswanathan (2020), "Removal and recovery of phosphorus from contaminated water using novel, reusable, renewable resource-based aluminum/cerium oxide nanocomposite", *Water Air Soil Pollut*., **231**(12), 559. https://doi.org/10.1007/s11270-020-04927-x.

Odey, G., B. Adelodun, S.H. Kim and K.S. Choi (2021), "Status of environmental life cycle assessment (LCA): A case study of South Korea", *Sustainability*, **13**(11), 6234. https://doi.org/10.3390/su13116234.

Peinemann, N and A K Helmy. (1977), "Sorption of phosphate by hydrous oxides of aluminium and iron", *Journal of Electroanalytical Chemistry and Interfacial Electrochemistry*, **78** (2), 325-30. https://doi.org/10.1016/S0022-0728(77)80127-7.

Pellenz, L., C.R.S. de Oliveira, A.H. da Silva Júnior, L.J.S. da Silva, L. da Silva, A.A.U. de Souza, S.M.A.G.U. de Souza, F.H. Borba and A. da Silva (2023), "A Comprehensive guide for characterization of adsorbent materials", *Sep. Purif. Technol*., **305**, 122435. https://doi.org/10.1016/j.seppur.2022.122435.

Ravindhranath, K. and M. Ramamoorty (2017), "Nano aluminum oxides as adsorbents in water remediation methods: A review - a review", *Orient. J. Chem*., **33**(4), 1603-16013. https://doi.org/10.13005/ojc/330403.

Ren, F. and W. Liu (2023), "Review of CO_2 adsorption materials and utilization technology", *Catalysts*, **13**(8), 1176. https://doi.org/10.3390/catal13081176.

Safwat, S.M., N.Y. Mohamed, M.N.A. Meshref, A. Elawwad and S.K. Ponnusamy (2022), "Adsorption of phenol onto aluminum oxide nanoparticles: Performance evaluation, mechanism exploration and principal component analysis (PCA) of thermodynamics", *Adsorpt. Sci. Technol*., 1924117. https://doi.org/10.1155/2022/1924117.

Sahu, D., S. Pervez, I. Karbhal, A. Tamrakar, A. Mishra, S.R. Verma, M.K. Deb, … M.L. Satnami (2024), "Applications of different adsorbent materials for the removal of organic and inorganic contaminants from water and wastewater - a review", *Desalin. Water Treat*., **317**, 100253. https://doi.org/10.1016/j.dwt.2024.100253.

Satyam, S. and S. Patra (2024), "Innovations and challenges in adsorption-based wastewater remediation: a comprehensive review", *Heliyon*, **10** (9), e29573. https://doi.org/10.1016/j.heliyon.2024.e29573.

Shea, L.E., M.V. Collins and D.A. Hirschfel (2000), "Combustion synthesis and effects of processing parameters on physical properties of a-alumina", *Am. Ceram. Soc*., 750186.

Shen, Z., J. Jin, J. Fu, M. Yang and F. Li (2021), "Anchoring Al- and/or Mg-oxides to magnetic biochars for Co-uptake of arsenate and fluoride from water", *J. Environ. Manage*., **293**, 112898. https://doi.org/10.1016/j.jenvman.2021.112898.

Shi, W. and M.M. Benjamin (2008), "Membrane interactions with NOM and an adsorbent in a vibratory shear enhanced filtration process (VSEP) system", *J. Membr. Sci*., **312**(1), 23-33. https://doi.org/10.1016/j.memsci.2007.12.031.

Sivasenthil, E., R. Nandhini, D. Tamilselvi and R. Raja (2023), "Synthesis and characterization of Al_2O_3 nanoparticles by using Co-precipitation method", *AIP Conference Proceedings*, **2861**(1), 20008. https://doi.org/10.1063/5.0160270.

Sun, B., J. Zhang, C. Ding, F. Xu, Y. Cheng, Z. Tang, F. Pan, J. Liu and S. Zhu (2021), Synthesis and characterization of Fe-Al-Ni ternary composite metal oxides as highly efficient adsorbent for fluoride removal from water", *Desalin. Water Treat*., **229**, 243-51. https://doi.org/10.5004/dwt.2021.27399.

Tangjitjaroenkit, S., A. Pranudta, N. Chanlek, T.T. Nguyen, A.T. Kuster, A.C. Kuster, M.M. El-Moselhy and S. Padungthon (2021), "Fluoride removal by hybrid cation exchanger impregnated with hydrated Al(III) oxide nanoparticles (HCIX-Al) with novel closed-loop recyclable regeneration system", *React. Funct. Polym.*, **169**, 105067. https://doi.org/10.1016/j.reactfunctpolym.2021.105067.

Taniguchi, M., J.E. Kilduff and G. Belfort (2003) "Modes of natural organic matter fouling during ultrafiltration", *Environ. Sci. Tech*., **37**(8), 1676-83. https://doi.org/10.1021/es020555p.

Tran, A.T.K., N.T.T. Hoang and M.L. Nguyen (2025), "Eco-friendly membrane fabrication from polystyrene waste: A circular economy perspective", *Membr. Water Treat*., **16**(4), 177-86. https://doi.org/10.12989/mwt.2025.16.4.177.

Varma, A., A.S. Mukasyan, A.S. Rogachev and K.V. Manukyan (2016), "Solution combustion synthesis of nanoscale materials", *Chem. Rev*., **116**(23), 14493-586. https://doi.org/10.1021/acs.chemrev.6b00279.

Wang, G., Z. Zou, G. Liang, T. Ye, S. Ma, Y. Chen and G. Lv (2025), "Interplay of clay mineral structures and PDDA functionalization in enhancing perchlorate adsorption for water treatment", *J. Alloys Compd*., **1036**, 181707. https://doi.org/10.1016/j.jallcom.2025.181707.

W. Li, C. Shi, L. Wang, L. Pan, X. Zhang and J.J. Zou (2020), "Rational design, synthesis, adsorption principles and applications of metal oxide adsorbents: a review", *Nanoscale*, **12**(8), 4790-4815. https://doi.org/10.1039/C9NR09274A.

Wang, L.F. and M.M. Benjamin (2016a), "A multi-spectral approach to differentiate the effects of adsorbent pretreatments on the characteristics of NOM and membrane fouling", *Water Res*., **98**, 56-63. https://doi.org/10.1016/j.watres.2016.03.066.

Wang, L.F. and M.M. Benjamin (2016b), "HAOPs pretreatment to reduce membrane fouling: Foulant identification, removal and interactions", *J. Membr. Sci*., **515**, 219-29. https://doi.org/10.1016/j.memsci.2016.05.063.

Wang, R., W. Peng, D. Wang and J. Liu (2024), "Three dimensional porous magnesium aluminum hydrotalcite material doped with TiO_2 and Al_2O_3 for fluoride removal", *J. Phys. Chem. Solids*, **190**, 111982. https://doi.org/10.1016/j.jpcs.2024.111982.

Wang, T., J. Liu, T. Li, J. Mao, Z. Shao, X. Li and S. Ren (2025), "Construction of PAC@Zeolite@GO composite with high adsorption capacity and environmentally friendly for defluoridation by synergistic effects", *Micropor. Mesopor. Mater*., **387**, 113521. https://doi.org/10.1016/j.micromeso.2025.113521.

Wang, X., H. Song, W. Xia, Y. Yan, X. Ren, X. Sun, Y. Yang and Y. Li (2025), "Low-temperature rapid synthesis of high-purity Li_4SiO_4 adsorbent for cyclic CO_2 capture", *Sep. Purif. Tech*., **378**, 134456. https://doi.org/10.1016/j.seppur.2025.134456.

Wang, X., X. Sun, Q. Liu, Y. Liu, Y. Li, W. Wang, Z. Feng, W. Song and B. Jiang (2024), "Coupled electrochemical crystallization-electrocoagulation-flocculation process for efficient removal of hardness and silica from reverse osmosis concentrate", *Desalination*, **580**, 117549. https://doi.org/10.1016/j.desal.2024.117549.

Wang, Y., X. Cui, P. Zhang, Y. Wang and W. Lu (2023), "Synthesis of porphyrin porous organic polymers and their application of water pollution treatment: a review", *Environ. Tech. Innov*., **29**, 102972. https://doi.org/10.1016/j.eti.2022.102972.

Xiang, H., Z. Yang, X. Liu, F. Lu, F. Zhao and L. Chai (2025), "Advancements in functional adsorbents for sustainable recovery of rare earth elements from wastewater: A comprehensive review of performance, mechanisms and applications", *Adv. Colloid Interf. Sci*., **338**, 103403. https://doi.org/10.1016/j.cis.2025.103403.

Xie, L., Y. Zhong, R. Xiang, G. Fu, Y. Xu, Y. Cheng, Z. Liu, T. Wen, Y. Zhao and X. Liu (2017), "Sono-assisted preparation of Fe(II)-Al(III) layered double hydroxides and their application for removing uranium (VI)", *Chem. Eng. J*., **328**, 574-84. https://doi.org/10.1016/j.cej.2017.07.051.

Xie, N., L. Yi, J. Li, W. Wang, T. Gu, M.G. Ma, S. Wang and S. Liu (2024), "A green synthesis strategy toward calcined calcium-aluminum layered double hydroxide with sludge as aluminum source for efficient removal of phosphate from water", *Surf. Interf*., **46**, 104075. https://doi.org/10.1016/j.surfin.2024.104075.

Yang, J., Z. Lei, Y. Dai, Y. Luo, S. Xie, J. Wang, S. Zhou, B. Wei, C. Li and S. Hu (2020), "Preparation of aluminum sludge composite gel spheres and adsorption of U(IV) from aqueous solution", *Environ. Sci. Pollut. Res*., **27**(21), 26835-44. https://doi.org/10.1007/s11356-020-09032-4.

Yasasve, M., M. Manjusha, D. Manojj, N.M. Hariharan, P.S. Preethi, P. Asaithambi, N. Karmegam and M. Saravanan (2022), "Unravelling the emerging carcinogenic contaminants from industrial waste water for prospective remediation by electrocoagulation - A review", *Chemosphere*, **307**, 136017. https://doi.org/10.1016/j.chemosphere.2022.136017.

Yepuri, V. and P. Ramachandramurthy (2025), "Impact of Sol-Gel synthesized α-aluminium oxide nanoparticles for the enhancement of transformer oil insulation properties", *Kuwait J. Sci*., **52**(1), 100331. https://doi.org/10.1016/j.kjs.2024.100331.

Yu, W., L. Xiong, J. Teng, C. Chen, B. Li, L. Zhao, H. Lin and L. Shen (2024), "Advances in synthesis and application of amphoteric polymer-based water treatment agents", *Desalination*, **574**, 117280. https://doi.org/10.1016/j.desal.2023.117280.

Zakir, O., A. Ait-Karra, S. Khardazi, R. Idouhli, M.E. Khadiri, B. Dikici, A. Aboulaich, A. Outzourhit and A. Abouelfida (2025), "Recent progress in nanomaterials for water treatment: A comprehensive review of adsorption, photocatalytic and antibacterial applications", *J. Water Proc. Eng*., **72**, 107566. https://doi.org/10.1016/j.jwpe.2025.107566.

Zhang, X., B. Dai, S. Ren, Z. Hu, X. Zheng, Y. Wang, H. Sun, D. Niu and L. Wang (2020), "Iron diffusion-doped magnesium-aluminum layered double oxides as a multifunctional adsorbent for removal of F−, Sb(III) and methyl orange contaminants from water", *Korean J. Chem. Eng*., **37**(5), 792-803. https://doi.org/10.1007/s11814-020-0487-4.

Zhao, D., H. Chen, Q. Zhao, W. Qi, Y. Liu and Y. Tian (2025), "Recycling corn stalks as an effective biosorbent for heavy metal removal from wastewater: Investigation on the adsorption performance and mechanism", *Environ. Technol. Innov.*, **38**, 104140. https://doi.org/10.1016/j.eti.2025.104140.

Zhuravlev, V.D., V.G. Bamburov, A.R. Beketov, L.A. Perelyaeva, I.V. Baklanova, O.V. Sivtsova, V.G. Vasil'ev, E.V. Vladimirova, V.G. Shevchenko and I.G. Grigorov (2013), "Solution combustion synthesis of α-Al2O3 using urea", *Ceram. Int.*, **39**(2), 1379-84. https://doi.org/10.1016/j.ceramint.2012.07.078.

Ziva, A.Z., Y.K. Suryana, Y.S. Kurniadianti, R. Ragadhita, A.B.D. Nandiyanto and T. Kurniawan (2021), "Recent progress on the production of aluminum oxide (Al_2O_3) nanoparticles: A review", *Mech. Eng. Soc. Ind.*, **1**(2), 54-77. https://doi.org/10.31603/mesi.5493.

Zuo, H., Y. Xia, H. Liu, Z. Liu and Y. Huang (2023), "Preparation of activated carbon with high nitrogen content from agro-industrial waste for efficient treatment of chromium (VI) in water", *Ind. Crops Prod.*, **194**, 116403. https://doi.org/10.1016/j.indcrop.2023.116403.