



## ADVANCED ADSORPTION MATERIALS FOR PATHOGEN CONTROL A CRITICAL REVIEW ON VIRUS AND BACTERIA ELIMINATION IN WATER TREATMENT

*IHSAN T.<sup>1\*</sup>, ANANDA A.P.<sup>2</sup>, NASWA D.<sup>2</sup>*

<sup>1</sup> Associate Professor, Department of Environmental Engineering, Faculty of Engineering, Universitas Andalas, Indonesia

<sup>2</sup> Research Scholar, Department of Environmental Engineering, Faculty of Engineering, Universitas Andalas, Indonesia

(\* *taufiqihsan@eng.unand.ac.id*)

---

Research Article – Available at <http://larhyss.net/ojs/index.php/larhyss/index>  
Received May 18, 2025, Received in revised form January 27, 2026, Accepted January 29, 2026

---

### ABSTRACT

The escalating global water crisis and the persistent threat of waterborne pathogens, including viruses and bacteria, necessitate innovative and sustainable water treatment technologies. While conventional methods like chlorination and membrane filtration have served as cornerstones, they present significant limitations, such as the formation of harmful disinfection byproducts and severe fouling issues. This critical review bridges a key knowledge gap by providing a comprehensive analysis of advanced adsorption strategies for the effective and cost-efficient elimination of viruses and bacteria from water. We systematically examine a wide range of adsorbent materials, including carbon-based materials, oxide-based nanoparticles, layered double hydroxides (LDHs), and natural compounds. The review delves into the fundamental principles governing pathogen-adsorbent interactions, emphasizing the crucial roles of surface charge, hydrophobicity, and steric hindrance. We differentiate between mere physical removal and active inactivation mechanisms, highlighting how some adsorbents can render pathogens non-infectious through structural damage, oxidative stress, or local pH alteration. A comparative analysis identifies the strengths and limitations of each material class, noting that while traditional materials like activated carbon are cost-effective, advanced materials such as MOFs and functionalized nanoparticles offer superior efficiency and customizability. The review concludes by outlining key challenges—including regeneration, scalability, and secondary toxicity—and proposing future perspectives, such as the development of smart, multifunctional, and macro-structured hybrid materials to address the continuous necessity of combating new and unknown waterborne pathogens.

**Keywords:** Adsorption, Water treatment, Virus, Bacteria, Nanomaterials, Adsorbents

### **Abbreviation**

ACFC	Activated Carbon Fiber Composites
AI/ML	Artificial Intelligence/Machine Learning
CDs	Cyclodextrins
DBPs	Disinfection Byproducts
DFT	Density Functional Theory
DLVO	Derjaguin-Landau-Verwey-Overbeek (Theory)
GAC	Granular Activated Carbon
IEP	Isoelectric Point
LDHs	Layered Double Hydroxides
MD	Molecular Dynamics
MOFs	Metal-Organic Frameworks
MWCNT	Multi-Walled Carbon Nanotubes
PAC	Powdered Activated Carbon
POU	Point-of-Use
ROS	Reactive Oxygen Species
RSV	Respiratory Syncytial Virus
SPs	Sulfated Polysaccharides

### **INTRODUCTION**

Adsorption processes have seen spectacular progress in recent decades, showing an enthusiasm among water treatment practitioners. For instance, the objective of Achour and Seghairi study (2002) was to evaluate the retention capacity of bentonite toward humic substances in order to assess its suitability as a low-cost adsorbent for natural organic matter removal in water treatment; in the study by Achour et al. (2002), the substances considered are compounds responsible for long-term toxic effects, initially present in the water or generated during a treatment step. With a view to reducing, or even eliminating, these substances, the study sought to optimize various physicochemical processes such as chlorination, flocculation, and especially adsorption; Achour and Youcef investigations (2003) aimed to investigate the efficiency of sodium and calcium bentonites for cadmium removal, focusing on adsorption mechanisms and metal-clay interactions; Guesbaya and Achour (2003) sought to optimize a combined coagulation/flocculation-adsorption process using bentonitic clay to enhance organic matter elimination; The objective of Seghairi and Achour study (2003) was to determine the optimal activation conditions for the Algerian Mostaghanem city's bentonite during the removal of an organic test compound, aniline. We treated the bentonite with sulfuric acid for different activation times and rates. To observe the effects of this treatment on the bentonite's adsorption capacity, we determined the equilibrium parameters and studied the reaction kinetics. The results of these tests were systematically compared to those obtained with untreated, raw bentonite. The best results for aniline removal were

obtained with an acid/bentonite ratio of 0.20 and an activation time of 30 minutes; Benzizoune et al. (2004) investigations aimed to determine the adsorption kinetics and capacity of lake sediments for phosphorus retention in order to understand eutrophication control mechanisms; the relevant study by Bouchemal and Achour (2007), focused on evaluating granular and powdered activated carbon performance for tyrosine adsorption as a model organic compound; Khelili et al. (2010) aimed to compare aluminum sulfate coagulation and activated carbon adsorption efficiencies against aromatic organic pollutants; Ouakouak et al. (2010) investigated the removal of atrazine by powdered activated carbon to assess adsorption effectiveness for pesticide-contaminated waters; Yeddou et al. (2012) aimed to evaluate adsorption behavior for mixtures of bio-recalcitrant compounds, emphasizing competitive adsorption effects; Ghomri et al. (2013) aimed to quantify heavy metal ion removal (Cu, Zn, Ni, Co) by natural bentonite and assess its suitability for wastewater treatment; Guergazi et al. (2013) focused on comparing activated carbon and bentonite for humic substance removal from surface waters; Youcef et al. (2014) aimed to determine the adsorption capacity of powdered activated carbon for phosphate elimination from natural waters; Larakeb et al. (2014) conducted a comparative study to evaluate zinc removal efficiency using goethite and bentonite as adsorbents; Khelil et al. (2015) aimed to assess nitrate removal from groundwater through adsorption on activated carbon combined with coagulation-flocculation; Ouakouak and Youcef (2016) focused on quantifying  $\text{Cu}^{2+}$  adsorption capacity on powdered activated carbon and sodium bentonite; Khelifi et al. (2016) aimed to evaluate Algerian date pit biosorbent efficiency for methylene blue removal and characterize adsorption equilibrium behavior; Masmoudi et al. (2018) investigated mercury removal efficiency using activated carbon and examined adsorption isotherms and kinetic models; Khelifi et al. (2018) aimed to study methyl orange adsorption using mango pit-based biosorbent and determine optimal operating conditions; Chauhan and Dikshit (2023) focused on assessing spent tea grains as a sustainable low-cost biosorbent for cadmium removal from aqueous solutions; Khelili et al. (2024) aimed to conduct kinetic and isotherm analysis of methylene blue adsorption onto orange peel-derived activated carbon; and Berafta et al. (2025) aimed to develop a sustainable adsorption system using rosemary-derived activated carbon combined with green nanoparticles to enhance methylene blue removal efficiency and improve environmental compatibility in water purification applications.

The global water crisis, intensified by the tripartite pressures of aggressive industrialization, demographic surges, and shifting climatic patterns, has forced a critical re-evaluation of our current water treatment paradigms (He et al., 2021; Salehi, 2022). At the heart of this struggle lies the persistent vulnerability of public health to waterborne pathogens, a diverse and evolving array of viruses and bacteria that continue to bypass traditional safeguards (Faye, 2017; Tortajada and Biswas, 2018; Baba Hamed, 2021; Bose et al., 2024; Chadee et al., 2024). Data from the World Health Organization (WHO) consistently paint a grim picture, attributing millions of preventable fatalities annually to inadequate water infrastructure, primarily in developing nations (WHO, 2023). This systemic fragility was laid bare by the COVID-19 pandemic, which served as a stark catalyst for advancing our understanding of how water networks can inadvertently facilitate the spread of resilient viral agents (Girón-Navarro et al., 2021; Manoiu et al., 2022; Vizanko et al., 2024).

Standard disinfection protocols, most notably chlorination and ozonation, remain the industry's first line of defense; yet, their limitations are becoming increasingly problematic (Ihsan and Derosya, 2024; Ihsan, 2025). The inadvertent generation of carcinogenic disinfection byproducts (DBPs) presents a significant long-term health trade-off, leading to tightening regulatory frameworks worldwide. Similarly, while membrane filtration offers high-fidelity removal, it is frequently hampered by prohibitive energy demands and the persistent issue of membrane fouling, which complicates its use in low-resource settings (Amin et al., 2025). Furthermore, the emergence of viral strains with enhanced resistance to ultraviolet (UV) radiation suggests that our reliance on existing technologies may no longer be sufficient (Lanrewaju et al., 2022). Consequently, there is an undeniable impetus to develop alternative, environmentally benign strategies that can neutralize microbial threats without introducing secondary chemical risks.

Adsorption has emerged as a frontrunner among sustainable purification technologies, primarily due to its operational versatility and high affinity for microbial contaminants. At its core, the process relies on the sophisticated physicochemical adhesion of pathogens onto solid interfaces (Saleh, 2022). Unlike chemical oxidation, adsorption provides a passive yet highly efficient capture mechanism that typically avoids the formation of toxic residuals (Badran et al., 2023; Putra et al., 2023; Satyam and Patra, 2024). Moreover, the potential to regenerate and reuse these materials aligns with modern circular economy principles, making it a viable candidate for decentralized drinking water systems (Tran, 2023).

However, the rapid expansion of literature in this field has resulted in a fragmented body of knowledge that lacks a cohesive analysis of pathogen-adsorbent interactions. Existing reviews often focus on either the material's properties or the pathogen's biology in isolation, failing to address the complex "lock-and-key" dynamics that occur at the interface (surface charge crossing, pore selectivity, and hydrophobic partitioning). This review seeks to consolidate these disparate findings into a rigorous, state-of-the-art synthesis. We systematically dissect the performance of diverse material classes, from traditional carbon and metal oxides to advanced Layered Double Hydroxides (LDHs), Metal-Organic Frameworks (MOFs), and biomimetic carbohydrates. By evaluating the structural nuances and economic feasibility of these materials, this work aims to provide a definitive roadmap for the development of next-generation adsorption technologies capable of securing the global water supply against both known and emerging microbial agents.

## **METHODOLOGY**

The systematic framework of this review was designed to ensure a comprehensive and critical synthesis of the current state-of-the-art in pathogen adsorption for water treatment. The literature search was primarily conducted through major electronic databases, including Scopus, Web of Science, and Google Scholar, covering a publication window from 1995 to 2025 to capture both foundational theories and the most recent technological advancements. The search strategy utilized a combination of Boolean operators and

specific keywords such as "virus adsorption," "bacterial elimination," "nanomaterials in water treatment," "isoelectric point of pathogens," and "mechanistic water purification." This targeted approach allowed for the identification of studies that provide not only performance data but also fundamental insights into the physicochemical interactions at the adsorbent-pathogen interface.

Initial screening was based on the relevance of the titles and abstracts, followed by a rigorous full-text evaluation to ensure technical quality. After the initial screening of titles and abstracts, we conducted a comprehensive review of the full-text articles to verify their technical rigor and alignment with our study objectives. To maintain a systematic and objective comparison, we established three fundamental pillars as the basis for our literature synthesis. First, we prioritized studies that provided quantifiable metrics for pathogen removal, such as Log Removal Values (LRV) or percentage efficiency, to facilitate standardized benchmarking. Second, we selected research offering substantial mechanistic insights into the adsorbent-pathogen interface, particularly regarding surface charge dynamics, pore architecture, and hydrophobicity. Lastly, we focused on papers that included experimental data across varying environmental parameters, including pH fluctuations, ionic strength, and the presence of natural organic matter.

Data extraction focused on quantitative metrics, specifically LRV and adsorption capacities, alongside qualitative assessments of material stability, secondary toxicity, and scalability. We systematically categorized the selected literature based on the chemical nature of the adsorbents, ranging from traditional carbon-based materials to advanced metal-organic frameworks (MOFs) and bio-composites. Comparative analysis was performed by normalizing data from diverse experimental setups to evaluate the influence of material synthesis and fabrication on the final inactivation efficacy. By synthesizing these diverse findings, this review bridges the gap between laboratory-scale material development and practical water treatment applications, providing a coherent narrative on the effectiveness of adsorption strategies in neutralizing waterborne pathogens.

## **UNDERSTANDING PATHOGEN CHARACTERISTICS - THE BASIS FOR ADSORBENT DESIGN**

Effective adsorption relies heavily on the physicochemical properties of both the target microorganisms and the adsorbent materials. Viruses are non-cellular infectious agents, significantly smaller than bacteria, with sizes typically ranging from 20 to 300 nm (Edwards et al., 2021). They consist of genetic material (DNA or RNA) encased within a protein shell called a capsid. Some viruses also possess an outer lipid envelope (Motsa and Stahelin, 2021). The specific shape of the capsid and its surface proteins dictate how viruses interact with host cells (Mateu, 2013) and, crucially, with external materials like adsorbents.

Bacteriophages, viruses that infect bacteria, are frequently used as model organisms in virus adsorption studies due to their ease of cultivation and testing, especially for water sanitation research. Common bacteriophages used as models include MS2, φr, φGA, and φQβ (Bisen et al., 2024; Gerba et al., 2017; Haq et al., 2012; Pisharody et al., 2021). A key

factor influencing adsorption is the surface charge of both the microbial particle and the adsorbent (Natarajan et al., 2022). Viral capsids and bacterial cell surfaces often carry a net negative charge under neutral pH conditions (Wilhelm et al., 2021). Therefore, adsorbents with positively charged surfaces can leverage electrostatic interactions to effectively capture and inactivate these pathogens (Akbari and Palsson, 2022; Boubeta et al., 2018; Hartvig et al., 2011). Furthermore, the hydrophobicity of the microbial surface and the pore size and surface area of the adsorbent are critical parameters that dictate adsorption efficiency (Krasowska and Sigler, 2014; Saliba et al., 2016).

## **MECHANISMS GOVERNING PATHOGEN ADSORPTION AND INACTIVATION**

The efficiency of pathogen sequestration is dictated by a sophisticated interplay of molecular and atomic dialogues at the adsorbent-microbe interface. Moving beyond rudimentary physical trapping, this process is steered by interfacial forces that determine whether the attachment remains a transient contact or becomes an irreversible binding event. From an engineering perspective, deciphering these pathways is vital for embedding adsorption within existing treatment trains—either as a robust pre-treatment to shield membranes from biofouling or as a specialized polishing stage targeting chlorine-resistant viral lineages.

### **Reversible physical capture mechanisms**

#### ***Hydrogen Bonding***

This specific interaction is prevalent when adsorbents are engineered with hydroxyl (-OH) or amine (-NH<sub>2</sub>) moieties, characteristic of silica frameworks, Layered Double Hydroxides (LDHs), and carbohydrate-based polymers (Farhan et al., 2024; Luo et al., 2024). These surface groups engage in energetic hydrogen bonding with the polar residues—such as carbonyl (C=O) or hydroxyl groups—found on the proteinaceous capsids of viruses and bacterial cell envelopes, thereby tethering the pathogen to the surface.

#### ***Van der Waals forces***

These universal yet subtle intermolecular attractions, primarily London dispersion forces, arise from instantaneous electronic dipoles. While individually negligible, their cumulative impact over the expansive contact area of a microbe can dominate the adsorption profile, particularly in non-polar carbonaceous materials where more specific chemical cues are absent (Chen et al., 2025; Hermann et al., 2017).

### ***Covalent Bonding***

Though atypical for standard physical adsorption, targeted surface functionalization can bridge this gap by introducing reactive ligands that form stable covalent linkages with specific biological motifs (Isaeva et al., 2021; Nordholm and Bacskey, 2020; Sajid et al., 2022). This "chemical anchoring" ensures a high degree of specificity and binding strength, often serving as a precursor to total pathogen inactivation.

### **Electrostatic interactions: The dominant force**

The dominant force Pathogen capture is intrinsically sensitive to the aqueous environment, where solution pH and ionic strength act as the primary modulators of surface charge and attraction (Zhang et al., 2019).

### ***Effect of pH and IEP crossing***

The net charge of microorganisms fluctuates with pH as functional groups (amino, carboxyl, and phosphate) undergo protonation or deprotonation (Wilhelm et al., 2021). Most viruses and bacteria exhibit an isoelectric point (IEP), a pH at which their net surface charge is zero (Michen and Graule, 2010). For example, MS2 bacteriophage has an IEP of approximately 3.5 (C. et al., 2011), meaning it is negatively charged above this pH. Similarly, the surface charge of adsorbents is pH-dependent due to amphoteric surface groups. For instance, oxide-based materials (e.g., TiO<sub>2</sub>, Fe<sub>2</sub>O<sub>3</sub>, MgO) often have IEPs in the acidic to neutral range (Perera et al., 2024; Shivani et al., 2025; Yang et al., 2025). By engineering adsorbents to maintain a positive charge at typical water treatment pH (e.g., 5-9), we can ensure "IEP crossing" where the oppositely charged surfaces facilitate spontaneous electrostatic attraction.

### ***Effect of ionic strength and DLVO theory***

The concentration of dissolved ions dictates the architecture of the electrical double layer (EDL) surrounding both surfaces (Zhang et al., 2019). According to the Derjaguin-Landau-Verwey-Overbeek (DLVO) theory, high ionic strength can "compress" this layer, effectively shielding repulsive forces (Ohshima, 2024). This reduction in electrostatic barriers allows van der Waals attractions or hydrophobic partitioning to take over, permitting the pathogen to approach and eventually adhere to the adsorbent surface.

### **Steric hindrance and pore selectivity**

Sequestration is also a matter of spatial compatibility. Steric hindrance occurs when the intricate morphology of a microbe exceeds the accessible dimensions of the adsorbent's pore network (Xu et al., 2023). Even nanosized viruses can find themselves physically excluded from microporous materials (Goharshadi et al., 2022).

### ***Pore size optimization***

Pore size optimization: The literature suggests a "Goldilocks" zone for pore diameter—typically within the mesoporous range (2-50 nm) (Carlsson et al., 2014). Pores that are too narrow lead to physical exclusion, while excessively wide pores may fail to provide sufficient surface-to-volume ratios for effective contact (Kianfar and Sayadi, 2022).

### ***Morphological features***

Pathogens are rarely simple spheres; many viruses possess complex protrusions like spikes, fibers, or knobs (Laxmi et al., 2025). These biological "appendages" can create steric clashes that prevent the main viral body from seating properly within a pore, necessitating a rational design that accounts for surface topography to maximize effective contact area (Xu et al., 2023).

### **Irreversible Inactivation Mechanisms**

A critical threshold in water safety is the transition from mere sequestration to definitive inactivation—the permanent loss of infectivity. While traditional chlorination is the standard for bacterial control, its viral efficacy is inconsistent and hampered by the formation of carcinogenic byproducts. Modern adsorbents solve this by integrating active inactivation pathways:

#### ***Structural damage***

Adsorption can exert sufficient mechanical stress or localized adhesion force to physically rupture the pathogen's protective envelope. Evidence shows that contact with hematite ( $\text{Fe}_2\text{O}_3$ ) nanoparticles can induce irreversible capsid damage in rotaviruses, while Fe/Ni systems can mechanically disrupt bacteriophage f2 (Mohamed et al., 2024; Cheng et al., 2019).

#### ***Oxidative stress***

The catalytic generation of reactive oxygen species (ROS), such as hydroxyl ( $\text{OH}\cdot$ ) and superoxide ( $\text{O}_2\cdot^-$ ) radicals, triggers a lethal oxidative cascade (Bi et al., 2024). Whether through the bimetallic  $\text{Fe}^0/\text{Ni}^0$  reaction or the photocatalytic activation of nano- $\text{TiO}_2$  under UV, these radicals indiscriminately attack viral genomes (DNA/RNA) and structural proteins, rendering the pathogen incapable of replication (Pan et al., 2023; Nagaraj et al., 2025).

#### ***Local pH alteration***

Some adsorbents can significantly alter the local pH environment at their surface, creating conditions that are detrimental to microbial viability. For example, the presence of slightly soluble magnesium oxyhydroxide ( $\text{Mg}(\text{OH})_2$ ) in ceramic filters can cause the

increase of water pH above 9 (Salehi et al., 2019), an alkaline environment known to inactivate viruses such as bacteriophages MS2 and PhiX174 (Seguchi et al., 2024). This extreme alkaline condition denatures proteins and disrupts structural integrity, providing a chemical-free inactivation method that complements traditional disinfection.

### ***Practical Implications for Water Treatment***

Practical Implications for Water Treatment In the context of potable water, inactivation is non-negotiable to prevent secondary contamination if captured pathogens were to detach. In wastewater scenarios, adsorption acts as a high-capacity pre-treatment, stripping away the bulk of the microbial load to enhance the efficiency of downstream UV or chemical disinfection. Ultimately, the development of adsorbents that effectively "kill on contact" transforms the spent media from a biohazardous waste into a stable, manageable material.

## **THE NEXT GENERATION OF ADSORBENTS - TAILORING MATERIALS FOR DUAL PATHOGEN CONTROL**

### **Carbon-Based Nanomaterials and Composites: Beyond Traditional AC**

Activated carbons are widely recognized for their excellent adsorption properties in water treatment (Heryanto et al., 2024). Both granular activated carbon (GAC) and activated carbon fiber composites (ACFC) have been investigated for virus removal (Jjagwe et al., 2021; Joo et al., 2025). Comparative experimental data have shown that ACFC can be more efficient for virus adsorption than GAC, even with a smaller total surface area, primarily due to differences in morphological shape and size fraction (Powell et al., 2000) which influence the external mass transfer of pathogens.

Research on powdered activated carbon (PAC) has identified several crucial physicochemical parameters for enhanced virus removal:

- Pore size optimization through controlled activation processes leads to large pore diameter (20-50 nm), which facilitate better accessibility and capture of viral particles within the mesoporous framework (Delafosse et al., 2022; Matsushita et al., 2013);
- Increased hydrophobicity of the virus surface enhances the affinity towards carbonaceous surfaces, as hydrophobic interactions contribute to stronger adsorption energy (Li et al., 2020; Nam et al., 2014).
- The adjustment of the surface chemistry to achieve a low negative surface charge is vital; a less negative or even positively charged carbon surface promotes stronger electrostatic attraction with negatively charged viruses under typical aquatic pH conditions (Shim et al., 2024; Souza et al., 2014).

Furthermore, the fabrication of advanced composites by modifying carbon materials with metal nanoparticles can significantly boost their antiviral activity (Fritea et al., 2021). For

instance, multi-walled carbon nanotubes (MWCNT) sensitized by copper oxides ( $\text{Cu}_2\text{O}$ ) through specific deposition techniques have demonstrated high efficiency in removing MS2 bacteriophages. Experimental results indicate that these  $\text{Cu}_2\text{O}$ -MWCNT composites achieve up to 99.99% virus retention across a broad pH range of 5.0 to 9.0 (Gutierrez et al., 2009), showcasing the synergy between the high surface area of the carbon nanotubes and the potent antiviral properties of the copper species. This dual-action mechanism involves both physical entrapment and active site-mediated inactivation, addressing the limitations of pristine activated carbons in handling highly resilient viral strains.

### **Oxide-Based Materials**

Oxide nanoparticles are particularly effective due to their tunable surface charges and high surface areas, which create numerous adsorption sites. The fabrication and integration of these oxides into various substrates determine their final performance in pathogen control.

#### ***Copper (Cu) and copper oxide ( $\text{Cu}_2\text{O}$ ) nanoparticles on alumina granules***

Through the deposition of copper and  $\text{Cu}_2\text{O}$  onto alumina, these adsorbents achieve 99.9% removal of MS2 bacteriophages. Experimental observations revealed that notably, copper oxide ( $\text{CuO}$ ) did not show the same efficacy, highlighting the importance of the copper oxidation state during the material synthesis phase (Németh et al., 2019).

#### ***Hematite ( $\text{Fe}_2\text{O}_3$ ) nanoparticles***

Glass fibers coated with hematite nanoparticles demonstrated high removal rates for both rotavirus and MS2 bacteriophage. Beyond mere adsorption, high-resolution imaging and biochemical assays showed that interactions with hematite were observed to cause structural damage to rotaviruses, leading to their irreversible inactivation (Mazurkow et al., 2020).

#### ***Iron oxide nanoparticles in biosand filters***

By incorporating iron-sensitized sand columns significantly outperformed sand-only columns in removing bacteriophage MS2 (5 log reduction versus 0.5 log reduction). This enhanced performance is primarily due to the electrostatic interaction of negatively charged MS2 particles with the positively charged surface patches created by iron oxides under neutral pH conditions (Bradley et al., 2011).

#### ***Magnesium oxyhydroxide ( $\text{MgO}$ )***

Ceramic filters embedded with magnesium oxyhydroxide showed enhanced removal of bacteriophages MS2 and PhiX174 (about 4-log removal). This is attributed to favorable electrostatic interactions between the negatively charged virion particles and the positively charged sites of magnesium oxyhydroxides. Crucially, the dissolution of

Mg(OH)<sub>2</sub> induces an alkaline environment (pH > 9), which actively inactivates viruses by denaturing capsid proteins (Michen et al., 2013).

### ***Zirconium (hydroxide) nanoparticles (ZrO<sub>2</sub>)***

Coating ceramic microfilters with colloidal zirconia considerably increased their specific surface area and improved virus removal to a remarkable 7-log (99.99%) for MS2 bacteriophages (Wegmann et al., 2008).

### ***Nano-TiO<sub>2</sub> membranes***

These membranes utilize electrostatic attraction between the oppositely charged nano-TiO<sub>2</sub> and phage f2 under acidic conditions. Under UV irradiation, nano-TiO<sub>2</sub> acts as a potent photocatalyst, generating reactive oxygen species (ROS), such as hydroxyl radicals and superoxide radicals, which are highly destructive to viral genetic material (DNA/RNA) (Zheng et al., 2013).

### ***Spherical Fe/Ni nanoparticles***

These nanoparticles can completely remove bacteriophage f2 from water after 30 minutes of treatment. The synergistic fabrication of Fe and Ni allows for an advanced inactivation mechanism driven by oxidative stress. The oxidation of Fe<sup>0</sup> is catalyzed by Ni<sup>0</sup>, triggering the sustained production of reactive oxygen species (OH· and O<sub>2</sub>·) formed due to the oxidation of Fe<sup>0</sup> and catalyzed by Ni<sup>0</sup> (Zheng et al., 2013).

### **Layered Double Hydroxides (LDHs): High Cationic Density Adsorbents**

Layered Double Hydroxides (LDHs), also known as hydrotalcite-like materials, are a class of anionic clays with a unique layered structure. Their general formula is  $[M(1-x)^{2+}Mx^{3+}(OH)_2]x+(Ax/nn^-) \cdot mH_2O$ , where M<sup>2+</sup> and M<sup>3+</sup> are divalent and trivalent metal cations, respectively, and An<sup>-</sup> is an interlayer anion (Xu et al., 2023). The positively charged brucite-like layers and the anion-exchange properties make LDHs highly promising adsorbents for negatively charged species, including viruses and bacteria, in water treatment (Forano et al., 2018; Ihsan et al., 2025; Johan et al., 2023). Their high surface area, customizable interlayer spacing, and the ability to incorporate various metal cations allow for tailored surface chemistry to enhance microbial removal. Research has explored the use of various LDH compositions (e.g., MgAl-LDH, ZnAl-LDH) and modifications to optimize their performance for virus and bacteria adsorption, often leveraging strong electrostatic interactions (Ihsan et al., 2023; Ihsan et al., 2025; Johan et al., 2024). LDHs can also be functionalized with other active components to enhance their antimicrobial properties (Luo et al., 2025). Recent advancements in "corporealization" have led to the development of macro-structured LDH forms, such as LDH-embedded sheets or foils, which facilitate the practical deployment of these materials in point-of-use (POU) systems (Johan et al., 2023; Ihsan et al., 2023). The transition from laboratory powder synthesis to the fabrication of stable, permeable LDH substrates addresses a major

bottleneck in the practical application of these materials, ensuring high contact efficiency while preventing the leaching of nanoparticles into the treated water.

### **Zeolites and Silica Nanoparticles: Frameworks for Metal Doping**

Zeolites are crystalline, porous materials with regular framework structures composed of cages and pores of various size and shape (Parmar et al., 2025). They possess exceptional chemical selectivity, high adsorption capacity, and are biocompatible and safe, attracting considerable interest for various applications, including biomedical ones. The high stability of nanozeolites with regular micropores makes them suitable for selectively adsorbing and desorbing different molecules based on their size, allowing them to act as molecular sieves (Lu et al., 2024).

#### ***Mechanism of action***

Zeolites can remove viruses and bacteria primarily through electrostatic interactions with their charged frameworks, particularly when modified with metal ions. Their ion-exchange properties allow them to exchange their inherent cations with other metal ions, which can then act as active sites for pathogen adsorption or inactivation. The porous structure also provides a large surface area for physical adsorption (Bahmanzadegan and Ghaemi, 2025).

#### ***Metal functionalization***

The tunability of zeolite chemical composition allows for the introduction of different metal cations, such as silver (Ag) and copper (Cu), known for their antibacterial and antiviral properties (Antúnez-García et al., 2021).

#### ***Antiviral efficacy***

Silver- and copper-doped zeolites have demonstrated a significant reduction of coronavirus 229E in water solution after just 1 hour of treatment. Such functionalization has also been shown to be an efficient way to inhibit SARS coronavirus, other coronaviruses, and human norovirus (calicivirus) (Dutta and Wang, 2019).

Silica is a versatile adsorbent characterized by its large surface area, chemical purity, hydrophilicity, and high adsorption capacity for bioactive molecules, proteins, microorganisms, and viruses. The surface of silica particles contains silanol and hydroxyl groups that act as primary adsorption sites (Zeb et al., 2020).

#### ***Amino-functionalized silica particles (NH<sub>2</sub>-containing moieties)***

Modifying silica surfaces with positively charged amine groups significantly enhances their efficiency for bacteriophage MS-2 removal (greater than 98%). The mechanism of

virus inactivation is explained by the high density of positively charged NH<sub>2</sub> groups, electrostatic interaction, and hydrogen bonds formation (Z. Chen et al., 2006).

### ***Amine-functionalized magnetic Fe<sub>3</sub>O<sub>4</sub>-SiO<sub>2</sub>-NH<sub>2</sub> nanoparticles***

These nanoparticles effectively remove bacteriophage f2 and Poliovirus-1 (over 97% removal efficiency). The adsorption mechanism was rationalized by the surface charge, hydrophobicity, and surface properties of pathogens and NP matrix (Zhan et al., 2014).

### **Metal-Organic Frameworks (MOFs) - Precision Porosity and Multifunctionality**

Metal-Organic Frameworks (MOFs) represent a frontier in porous material science, characterized by their crystalline architecture composed of inorganic nodes—typically metallic clusters—linked by organic ligands. These materials are distinguished by their exceptional stability across diverse operating conditions, including extreme temperatures and various solvent environments (Jiao et al., 2019). The structural versatility of MOFs allows for the fabrication of highly tailored materials, including advanced biocomposites, by fine-tuning their textural properties such as pore volume, crystal morphology, and chemical functionality (Felix-Sahayaraj et al., 2023; Han et al., 2025; Zeggai et al., 2025).

### ***Tailored properties for bio-interactions***

The ultra-high porosity and expansive internal surface area of MOFs, when combined with tunable chemical moieties, create an ideal platform for interacting with complex biological macromolecules, including viruses and bacteria. Through rational design, MOFs can be engineered to encapsulate proteins and other bioactive molecules while meticulously preserving their structural and functional integrity. This precision in design allows for the creation of "biomimetic interfaces" where the MOF framework is synthesized to match the specific size and charge requirements of a target pathogen (Felix-Sahayaraj et al., 2023; Jiao et al., 2019).

### ***Mechanisms of pathogen interaction***

Experimental evidence indicates that MOFs engage with pathogens through a sophisticated interplay of multiple mechanisms:

- The highly ordered porous framework provides a dense array of active sites that facilitate physical adsorption via Van der Waals forces, hydrogen bonding, and electrostatic interactions. These interactions are governed by the specific functional groups integrated into the MOF ligands and the corresponding surface proteins of the pathogen (Jiao et al., 2019; Li et al., 2024).
- MOF structures can host a wide variety of both inorganic and organic compounds, including biological macromolecules and even living cells, offering a protective "exoskeleton" against harsh environments. This encapsulation can lead to pathogen immobilization and inactivation (Cai et al., 2019).

- Both the metal nodes and organic linkers can be fabricated to possess inherent antiviral or antibacterial properties. For instance, certain frameworks are designed to slowly release antimicrobial metallic species or utilize organic linkers that directly disrupt viral components (Jiao et al., 2019).

### ***Applications beyond adsorption***

MOFs have been explored not only for direct pathogen removal but also in other critical areas:

- - MOF-based materials have shown promising results as sensors for detecting Zika, Dengue (Xie et al., 2018) , human immune deficiency virus-1/ HIV-1 (Jia et al., 2019), and Japanese encephalitis virus (Yang et al., 2020), demonstrating their high selectivity and sensitivity for viral nucleic acids or proteins.
- - MOFs are being investigated for their potential in vaccine design, where they can serve as carriers or adjuvants, encapsulating viral nanoparticles to improve pharmacokinetics and enhance immune response (Zeggai et al., 2025).

### **Natural and Biocompatible Materials (Clay and Carbohydrates)**

The utilization of naturally occurring minerals and biological polymers offers a sustainable and biocompatible pathway for pathogen control, leveraging complex surface chemistry and biological mimicking strategies. Clays and their composites have demonstrated promising results in removing larger viruses like rotaviruses and coronaviruses from water (Das et al., 2022). Experimental data indicates that due to their relatively large size (60-220 nm for coronaviruses, 60-80 nm for rotaviruses), these viruses are primarily adsorbed onto the outer surface of the adsorbents. Studies have shown good (70-90%) to excellent (> 90%) removal capabilities for bovine rotavirus and bovine coronavirus (Clark et al., 1998). These high removal rates are theoretically attributed to non-specific protein binding and electrostatic attraction between the viral capsid and the charged clay layers.

The fabrication of carbohydrate-based adsorbents introduces a unique mechanism of action: competitive inhibition through the mimicry of host cell surface sugars, which effectively prevents the initial attachment of viruses to biological receptors.

### ***Sulfated polysaccharides (SPs)***

Derived from sources like marine algae and plants, SPs exhibit broad-spectrum antiviral properties. Mechanistic investigations suggest that their efficacy stems from direct interaction with viral particles, which alters the virus's ability to adsorb to cell receptors and inhibits penetration into host cells (Liu et al., 2015; Wijesinghe and Jeon, 2012). Experimental evidence underscores that the degree of sulfation is a critical determinant of efficacy, as higher sulfate densities generally correlate with enhanced biological activity and stronger electrostatic interference with viral attachment proteins.

### **Modified and sulfated cyclodextrins (CDs)**

These cyclic oligosaccharides, particularly those with sulfate groups, have shown significant antiviral activity against viruses like HIV, Herpes simplex virus (HSV), respiratory syncytial virus (RSV), Dengue virus, and Zika virus. The synthesis of modified CDs can interfere with the adsorption stage of the viral replicative cycle and have demonstrated broad-spectrum virucidal properties at micromolar concentrations (Jones et al., 2020). Remarkably, these materials have demonstrated broad-spectrum virucidal properties at micromolar concentrations, providing a high-efficiency, low-cytotoxicity alternative for targeted water disinfection.

## **CRITICAL COMPARISON, CHALLENGES, AND FUTURE IMPERATIVES**

While each class of adsorbent offers unique advantages for virus and bacteria elimination in water treatment, a critical comparative analysis is essential to understand their applicability, limitations, and synergistic potential.

### **Comparative Performance and Mechanisms**

The efficacy of different adsorbents varies significantly based on their intrinsic properties and the specific characteristics of the pathogens being targeted (Table 1).

**Table 1: Comparative Summary of Adsorbent Classes for Virus and Bacteria Elimination in Water Treatment**

<b>Adsorbent Class</b>	<b>Synthesis/Fabrication Method</b>	<b>Key Removal Mechanism(s)</b>	<b>Experimental Conditions (pH, Matrix)</b>	<b>LRV/Efficiency (Representative)</b>	<b>Advantages and Limitations</b>
Carbon-Based Materials (e.g., GAC, PAC, MWCNT)	Chemical/Physical Activation, Metal Sensitization	Hydrophobic interactions, Van der Waals forces, electrostatic (if modified)	Effective in pH 5.0–9.0 for Cu <sub>2</sub> O-MWCNT	MS2: Up to >99.99% (with Cu <sub>2</sub> O-MWCNT)	Adv: Cost-effective and widely available. Lim: May require modification for specific pathogens and prone to biofouling
Oxide-Based Materials (e.g., Fe <sub>2</sub> O <sub>3</sub> , TiO <sub>2</sub> , MgO, ZrO <sub>2</sub> )	Colloidal coating, Thermal deposition, Iron-sensitization	Electrostatic attraction, oxidative stress (ROS generation), direct structural damage	Neutral pH for Fe <sub>2</sub> O <sub>3</sub> -sand; UV activation for TiO <sub>2</sub>	MS2: 99.9% (Cu <sub>2</sub> O-alumina), 5 log (Fe <sub>2</sub> O <sub>3</sub> -sand), 7 log (ZrO <sub>2</sub> -coated)	Adv: High inactivation via oxidative stress. Lim: Potential metal leaching and pH-dependent performance
Layered Double	Co-precipitation, Isomorphous	Electrostatic attraction, anion exchange	Active in alkaline	High LRV for negatively charged	Adv: High specificity for anions and

Hydroxides (LDHs)	substitution, Foil-embedding		environments (pH > 9)	microbes (e.g., <i>E. coli</i> ).	thermal stability. Lim: More complex synthesis than natural clays
Zeolites & Silica Nanoparticles	Metal doping (Ag/Cu), Amine-functionalization	Ion exchange, molecular sieving, hydrogen bonding	1-hour treatment for metal-doped zeolites	Coronavirus 229E: Significant reduction (Ag/Cu-doped); MS-2:>98% (amine-functionalized)	Adv: Precision porosity and biocompatible. Lim: Potential steric hindrance for larger viruses
Metal-Organic Frameworks (MOFs)	Coordination of metal clusters with organic ligands	Host-guest interactions, electrostatic, coordination bonding	Controlled environment for bio-macromolecules	Emerging for adsorption; High sensor sensitivity	Adv: Exceptional customizability and high capacity. Lim: High production cost and water stability issues
Clay and Carbohydrates (e.g., Sulfated Polysaccharides, Cyclodextrins)	Natural extraction, Sulfation of polysaccharides	Non-specific protein binding, biomimicry, competitive inhibition	Micromolar concentrations for virucidal activity (CDs)	Rotavirus: 70-90%; Specific for HIV/Zika	Adv: Non-toxic and naturally abundant. Lim: Variable removal efficacy and limited scalability for modified forms.

### Comparative strengths and weaknesses

The choice of adsorbent is contingent upon the specific water matrix, target pathogen, desired removal efficiency, and economic considerations.

- Carbon-based materials and clays are generally the most cost-effective and readily available, making them suitable for large-scale applications, especially in developing regions (Egbedina et al., 2022; Worasith and Goodman, 2023). In contrast, MOFs and highly functionalized nanoparticles (e.g., Fe/Ni, some tailored silica) can be significantly more expensive to produce at scale (Kwon et al., 2017; Xu et al., 2024).
- Materials like sulfated polysaccharides and modified cyclodextrins offer high specificity through biomimicry, targeting viral entry mechanisms, which can be advantageous for specific outbreaks (Jones et al., 2020; Wang et al., 2014). However, oxide-based materials and amine-functionalized silica tend to provide broader spectrum removal due to more generalized electrostatic interactions with various negatively charged pathogens (Mazurkow et al., 2020; Zhan et al., 2014).

- Oxide-based nanoparticles (e.g., Fe/Ni, TiO<sub>2</sub>) are particularly notable for their ability to not only remove but also inactivate pathogens through oxidative stress or structural damage. Conversely, carbon materials primarily achieve physical removal, and additional disinfection steps might be necessary for complete inactivation.
- While highly effective, metal-containing adsorbents (e.g., Ag/Cu-doped zeolites, Cu<sub>2</sub>O-MWCNT, Fe/Ni NPs) pose a potential concern regarding the leaching of metal ions into the treated water, necessitating careful design and post-treatment evaluation to avoid secondary toxicity. Magnesium oxyhydroxide can increase water pH significantly, which might require further adjustment for potability (Ihsan et al., 2024; Ihsan et al., 2025).
- The regenerability of adsorbents is crucial for long-term sustainability. While some adsorbents like activated carbon are well-studied for regeneration (Vedenyapina et al., 2024), the processes for complex nanostructured materials or biological adsorbents are still under development and can influence their practical lifespan and economic viability (Harish et al., 2022).

### **Material synergies - The power of composites**

A growing trend in adsorbent development is the creation of hybrid or composite materials, which leverage the complementary properties of different components to achieve enhanced performance. This synergistic approach often leads to higher removal efficiencies, improved stability, or added functionalities not present in individual components.

- Combining materials can dramatically increase the overall surface area and the density of active sites. For example, MWCNT sensitized by Cu<sub>2</sub>O combines the high surface area and porous structure of carbon nanotubes with the antiviral activity and positive charge potential of copper oxide, leading to superior virus retention compared to either material alone (Domagała et al., 2020).
- Composite materials can offer multiple removal mechanisms simultaneously. Silica-decorated TiO<sub>2</sub> nanoparticles exemplify this, where the high adsorption capacity and favorable surface chemistry of silica are combined with the photocatalytic inactivation potential of TiO<sub>2</sub> under UV light (MiarAlipour et al., 2018). This allows for both effective adsorption and subsequent degradation/inactivation of captured pathogens. Similarly, Fe/Ni nanoparticles utilize both direct disruption and reactive oxygen species generation (Lin et al., 2025).
- Functionalizing materials with magnetic nanoparticles (e.g., amine-functionalized magnetic Fe<sub>3</sub>O<sub>4</sub>-SiO<sub>2</sub>-NH<sub>2</sub> NPs) is a prime example of synergy, where the core material handles adsorption, and the magnetic component facilitates easy separation

from treated water, overcoming a major challenge in nanoparticle application (Zhan et al., 2014).

- Composites can mitigate the weaknesses of individual components. For instance, while TiO<sub>2</sub> is a potent photocatalyst, its standalone use might be limited by aggregation or recovery challenges (Miar-Alipour et al., 2018). Coupling it with a robust membrane (e.g., nano-TiO<sub>2</sub> membranes) or a high-surface-area support (e.g., silica) improves its practical applicability.

The rational design of these composite materials, guided by an understanding of intermolecular forces and surface chemistry, represents a promising direction for developing highly effective and practical adsorbents for waterborne pathogen control.

### **Challenges and future perspectives for practical application**

The transition of promising laboratory-scale adsorption technologies to widespread practical application in water treatment faces several significant challenges that require dedicated future research.

#### ***Adsorbent regeneration***

A crucial aspect for the long-term sustainability and cost-efficiency of adsorption processes is the effective regeneration of saturated adsorbents. Pathogens captured on adsorbents can lead to filter clogging and a reduction in removal efficiency over time, necessitating regeneration or replacement. Challenges in regeneration include maintaining the structural integrity and adsorption capacity of the material after multiple cycles, and effectively desorbing/inactivating the trapped pathogens without secondary contamination. Various regeneration methods exist, such as thermal treatment (e.g., for activated carbon), chemical washing (acid, base, or oxidant solutions), and photocatalytic degradation (for TiO<sub>2</sub>-based materials). The impact on adsorbent lifespan and reusability varies significantly by material type and regeneration protocol, making it a critical area for optimization to ensure economic viability and reduce waste.

#### ***Economic feasibility and scalability***

The transition of promising laboratory-scale adsorption technologies to widespread practical application in water treatment faces several significant challenges, primarily dictated by synthesis costs and the availability of precursors. While traditional materials like granular activated carbon (GAC) and natural clays are economically viable for large-scale treatment due to their abundance and low production costs, they often lack the specificity required for emerging viral strains.

Conversely, high-performance materials such as Metal-Organic Frameworks (MOFs) and functionalized silica involve complex, multi-step synthesis using expensive precursors, making them currently prohibitive for large municipal plants. To address these economic

barriers, future research must focus on developing simpler, greener, and more cost-effective synthesis routes, such as utilizing abundant natural resources or waste materials. Furthermore, the industry must prioritize the "corporealization" or macro-structuring of these materials—immobilizing powdered adsorbents onto robust substrates such as membranes or ceramic filters. This approach is vital for creating practical, user-friendly, and scalable point-of-use (POU) devices that are affordable for resource-constrained regions, ensuring efficient contact with water and easy separation post-treatment.

### ***Secondary toxicity and environmental risks***

A critical safety concern, especially for drinking water applications, is the potential for secondary toxicity due to the leaching of adsorbent components or their byproducts into the treated water. This is particularly relevant for nanoparticles incorporating metals (e.g., Ag, Cu, TiO<sub>2</sub>, Fe/Ni) that possess inherent antimicrobial properties. While these materials are highly effective for pathogen inactivation, the release of metal ions or nanoparticles into the effluent must be rigorously ensured to remain below strict regulatory limits to prevent unintended human health risks.

Current research emphasizes that improper immobilization during the material synthesis phase can lead to the detachment of nanoparticles into the water matrix, which may pose long-term toxicological threats even if the treated water is pathogen-free. The risk of "secondary pollution" necessitates a shift from simple impregnated materials to robustly engineered substrates. Consequently, thorough toxicology studies and advanced material design—such as the implementation of strong covalent anchoring or grafting of active components onto stable, inert substrates—are indispensable to guarantee the environmental and human health safety of these adsorbent systems post-treatment. Ensuring the structural integrity of these composites under fluctuating hydraulic conditions is a vital prerequisite for their transition from laboratory settings to real-world municipal or household applications.

### ***Biological fouling (Biofouling)***

Despite their ability to remove pathogens, many adsorbents can paradoxically become substrates for the growth of biofilms, a process known as biofouling. This biological layer can significantly reduce the effective surface area available for adsorption, decrease flow rates (for filter media), and eventually lead to a decline in removal efficiency. More critically, if not managed, these biofilms can become a secondary source of microbial contamination, releasing pathogens back into the treated water, or harboring resistant strains. Future adsorbent designs must incorporate anti-biofouling strategies, such as embedding antimicrobial agents (e.g., silver, copper) directly into the matrix, designing surfaces with low adhesion properties, or integrating *in-situ* cleaning mechanisms (e.g., photocatalytic self-cleaning or electrochemical methods) to maintain long-term performance and hygiene.

### ***Long-term stability and performance degradation***

The long-term performance and structural stability of adsorbents under realistic environmental conditions (e.g., varying pH, ionic strength, presence of natural organic matter, flow dynamics) are paramount but often challenging to assess in short-term laboratory studies. Adsorbent degradation (e.g., loss of active sites, structural collapse, or breakdown of functional groups) can occur over time and usage cycles, affecting their consistent removal efficiency. Robust accelerated aging tests and pilot-scale, prolonged operational studies are necessary to accurately predict the useful lifespan of adsorbents and ensure their sustained effectiveness in practical water treatment systems.

The trajectory of future research must pivot immediately toward the rational design and precise synthesis of next-generation adsorbents, prioritizing optimized surface chemistry, porosity, and structural stability. It is an absolute imperative to develop purification processes that are not only highly efficient and low-cost but also readily scalable for large-scale water treatment, particularly across resource-constrained regions. This scalability is essential to effectively mitigate the uncontrolled propagation and potential mutation of dangerous viral and bacterial agents that contribute to global health threats. Consequently, the material science community must dedicate considerable effort to achieving the attractive goal of producing self-sanitizing objects, resulting in efficient, flexible, and miniaturized purifying agents. The emergence of novel pathogens, starkly highlighted by events such as the COVID-19 pandemic, provides a continuous, powerful reminder: developing new adsorbents equipped with exceptional antiviral capabilities is a permanent and continuous necessity to effectively counter the threat posed by both known and unknown viruses in our environment.

To push the boundaries of adsorption technology for waterborne pathogen control, future research should explore several innovative avenues:

#### ***Smart adsorbents (Stimuli-responsive materials)***

Developing adsorbents that are responsive to external stimuli (e.g., pH, light, temperature, magnetic fields) offers unprecedented control over adsorption and desorption processes. Such "smart" materials could enable on-demand release of adsorbed pathogens for analysis or targeted inactivation, or allow for efficient, non-destructive regeneration. For instance, pH-responsive polymers could reversibly change surface charge, enabling selective capture and release. Photothermal materials could heat up locally under light to inactivate adsorbed microbes.

#### ***Multifunctional hybrid materials***

The paradigm of developing adsorbents that not only remove but also perform additional functions (e.g., photocatalysis, oxidation, *in-situ* detection) is a highly promising direction. This involves creating hybrid materials that combine the adsorptive capacity with catalytic properties. For example, a material could adsorb pathogens and then, under light, photocatalytically degrade their genetic material or proteins. Another example is

adsorbents with integrated electrochemical properties that can generate disinfectants *in-situ* or apply an electric field for enhanced removal/inactivation.

### ***Integration with existing technologies***

Effective integration of adsorption processes into existing water treatment trains is crucial for maximizing overall efficiency and cost-effectiveness. Adsorption could serve as a pre-treatment step for membrane filtration to reduce fouling, or as a polishing step after conventional disinfection to capture any remaining or resistant pathogens. The concept of "integrated treatment" seeks to leverage the strengths of various technologies in a synergistic manner, optimizing resource use and enhancing final water quality.

### ***Computational modeling and rational design***

Leveraging advanced computational tools, such as Density Functional Theory (DFT) for molecular interactions, Molecular Dynamics (MD) simulations for dynamic behavior, and Artificial Intelligence/Machine Learning (AI/ML) for predictive material design, will accelerate the discovery and optimization of novel adsorbents. These *in silico* approaches can predict adsorbent-pathogen interactions, elucidate complex mechanisms at the atomic level, and screen vast material libraries to identify optimal candidates, significantly reducing the reliance on time-consuming and expensive trial-and-error experimental approaches.

### ***Circular economy principles in adsorption***

Adopting a circular economy mindset in adsorbent development means focusing not only on performance but also on the entire lifecycle of the material. This includes designing adsorbents from sustainable, renewable, or waste-derived precursors, developing efficient regeneration methods that minimize secondary waste, and exploring strategies to transform spent adsorbents into value-added products. For example, spent carbon-based adsorbents could potentially be repurposed as energy sources or components in construction materials, thereby closing the loop and reducing environmental impact.

### ***Corporealization of adsorbents for practical application***

A significant hurdle for widespread adoption, particularly for household-scale and point-of-use (POU) water treatment, is the physical form of adsorbents. Many high-performance adsorbent materials are developed as fine powders, which are difficult to handle, separate from treated water, and integrate into simple filtration systems for batch or household applications. Future research must focus on "corporealization" or "macrostructuring" of these advanced materials (Fukugaichi et al., 2024; Johan et al., 2023, 2024). This involves immobilizing powdered adsorbents onto robust, permeable substrates (e.g., membranes, ceramic filters, polymer beads, textile fibers) or fabricating them into granular, pelletized, or fibrous forms. This engineering aspect is vital for creating practical, user-friendly, and easily deployable filters and devices suitable for

various scales, from large municipal plants to small household purifiers, ensuring efficient contact with water and easy separation post-treatment.

The ongoing emergence of new pathogens, as exemplified by the COVID-19 pandemic, underscores that developing novel adsorbents with outstanding antiviral properties will be a permanent and continuous necessity to face the presence of known and unknown viruses in the environment.

## **CONCLUSIONS**

This review verifies the central importance of the adsorption process, being a very practical, flexible, and promising approach for the simultaneous removal and inactivation of viruses and bacteria. The course towards safe water, therefore, is grounded in a broad spectrum of adsorbing materials, ranging from traditional materials such as functionalized carbon-based filters, through nanosized materials and Layered Double Hydroxides, to particular biocompatible biological molecules.

One of the most essential and ever-present findings among all classes of materials is the prime consideration for adsorbent surface charge. Therefore, chemical functionalization is required for optimal surface properties to enhance electrostatic binding and neutralize negatively charged pathogens. Among these breakthroughs, nanoparticles are absorbing and hold immense potential for designing effective yet affordable sanitation technology, especially for water purification. Additionally, naturally sourced materials such as polysaccharides and cyclodextrins offer a fascinating, biocompatible approach for reducing viruses in liquids.

Despite the significant advances made in the area, there remain several challenges to their implementation. Though the drawbacks in conventional methods in terms of high operational expenses and the production of toxic DBPs pose essential grounds for the implementation of more environmentally friendly approaches, their commercial counterparts sometimes fail to meet expectations. They can be depleted of broad-spectrum properties against novel virus strains and incur high production costs, including the use of specific compounds for modification.

Now, the research roadmap should shift to a focus on rational design and application, rather than discovery alone. Future research should focus on the rational design and optimization of additional adsorbents with enhanced surface chemistry and improved structural and durability properties. More importantly, then, and indeed crucial, would be the focus on efficient and low-cost purification techniques and processes that can be scaled up and implemented on a large scale within developing countries around the globe, and which will play an unparalleled role within the prevention and containment of the uncontrolled evolution and mutations of harmful pathogens and disease agents with worldwide dangers and threats as exemplified within the catastrophic spread and ominous threat within the COVID-19 outbreak.

### **Declaration of competing interest**

The author declare that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### **Acknowledgments**

The author would like to express their gratitude to the Department of Environmental Engineering, Faculty of Engineering, Universitas Andalas, Indonesia, as well as all others involved in the realization of this study

### **REFERENCES**

- ACHOUR S., SEGHAIRI N. (2002). Possibilities for retaining humic substances by adsorption on bentonite, Larhyss Journal, No 1, pp. 129-138. (In French)
- ACHOUR S., GUERGAZI S., GUESBAYA N., SEGHAIRI N., YOUCEF L., (2002). Impact of chlorination, flocculation, and adsorption processes on the evolution of organic and mineral compounds in natural water, Larhyss Journal, No 1, pp. 107-128. (In French)
- ACHOUR S. YOUCEF L. (2003). Cadmium removal by adsorption on sodium and calcium bentonite, Larhyss Journal, No 2, pp. 68-81.
- AKBARI A., PALSSON B.O. (2022). Positively charged mineral surfaces promoted the accumulation of organic intermediates at the origin of metabolism, PLoS Computational Biology, Vol. 18, Issue 8, Paper ID e1010377.  
<https://doi.org/10.1371/journal.pcbi.1010377>
- AMIN M., SHAH H.H., KHALID S., SHARIF S., KHAN I.A. (2025). Issues and challenges of water purification membranes, International Journal of Energy and Water Resources, Vol. 9, Issue 3, pp. 1619-1643.  
<https://doi.org/10.1007/s42108-025-00337-z>
- ANTÚNEZ-GARCÍA J., GALVÁN D.H., PETRANOVSKII V., MURRIETA-RICO F.N., FUENTES-MOYADO S. (2021). The effect of chemical composition on the properties of LTA zeolite: A theoretical study, Computational Materials Science, Vol. 196, Paper ID 110557.  
<https://doi.org/https://doi.org/10.1016/j.commatsci.2021.110557>
- BABA HAMED S. (2021). Impact of water pollution on public health and the environment in Oran, Larhyss Journal, No 45, pp. 203-222.
- BADRAN A.M., UTRA U., YUSSOF N.S., BASHIR M.J.K. (2023). Advancements in Adsorption Techniques for Sustainable Water Purification: A Focus on Lead Removal, Separations, Vol. 10, Issue 11.  
<https://doi.org/10.3390/separations10110565>

- BAHMANZADEGAN F., GHAEMI A. (2025). A comprehensive review on novel zeolite-based adsorbents for environmental pollutant, *Journal of Hazardous Materials Advances*, Vol. 17, Paper ID 100617.  
<https://doi.org/https://doi.org/10.1016/j.hazadv.2025.100617>
- BENZIZOUNE S., NASSALI H., SRHIRI A. (2004). Study of the kinetics of adsorption of phosphorus in solution on the sediments of the Fouarat lake in Morocco, *Larhyss Journal*, No 3, pp. 171-184. (In French)
- BERAFTA M., KHELILI H., GUELLAL M., ACHOUR S., KONAN K.G. (2025). Sustainable methylene blue removal using rosemary-derived activated carbon and green nanoparticles, *Larhyss Journal*, No 62, pp. 215-241.
- BI Z., WANG W., ZHAO L., WANG X., CHEN C. (2024). The generation and transformation mechanisms of reactive oxygen species in the environment and their implications for pollution control processes: A review, *Environmental Research*, Vol. 260, Paper ID 119592.  
<https://doi.org/https://doi.org/10.1016/j.envres.2024.119592>
- BISEN M., KHARGA K., MEHTA S., JABI N., KUMAR L. (2024). Bacteriophages in nature: recent advances in research tools and diverse environmental and biotechnological applications, *Environmental Science and Pollution Research*, Vol. 3, Issue 15, pp. 22199-22242.  
<https://doi.org/10.1007/s11356-024-32535-3>
- BOSE D., BHATTACHARYA R., KAUR T., BANERJEE R., MONDAL S. (2024). Overcoming water, sanitation, and hygiene challenges in critical regions of the global community, *Water-Energy Nexus*, Vol. 7, pp. 277-296.  
<https://doi.org/https://doi.org/10.1016/j.wen.2024.11.003>
- BOUBETA F.M., SOLER-ILLIA G.J.A.A., TAGLIAZUCCHI M. (2018). Electrostatically Driven Protein Adsorption: Charge Patches versus Charge Regulation, *Langmuir: The American Chemical Society (ACS) Journal of Surfaces and Colloids*, Vol. 34, Issue 51, pp. 15727-15738.  
<https://doi.org/10.1021/acs.langmuir.8b03411>
- BOUCHEMAL F., ACHOUR S. (2007). Tyrosine adsorption tests on grained and powdered activated carbon, *Larhyss Journal*, No 6, pp. 81-89. (In French)
- BRADLEY I., STRAUB A., MARACCINI P., MARKAZI S., NGUYEN T H. (2011). Iron oxide amended biosand filters for virus removal, *Water Research*, Vol. 45, Issue 15, pp. 4501-4510.  
<https://doi.org/https://doi.org/10.1016/j.watres.2011.05.045>
- CHADEE A.A., RATHORE K., CHOUDHARY L.A., VERMA S., MEHTA D. (2024). The korba coal mining zone in India assessment of risk health and pollutant sources, *Larhyss Journal*, No 60, pp. 113-131.

- DIKA C., DUVAL-JFLLY-CHATAIN H.M., MERLIN C., GANTZER C. (2011). Impact of Internal RNA on Aggregation and Electrokinetics of Viruses: Comparison between MS2 Phage and Corresponding Virus-Like Particles, *Applied and Environmental Microbiology*, Vol. 77, Issue 14, pp. 4939-4948.  
<https://doi.org/10.1128/AEM.00407-11>
- CAI H., HUANG Y.L., LI D. (2019). Biological metal–organic frameworks: Structures, host–guest chemistry and bio-applications, *Coordination Chemistry Reviews*, Vol. 378, pp. 207-221.  
<https://doi.org/https://doi.org/10.1016/j.ccr.2017.12.003>
- CARLSSON N., GUSTAFSSON H., THÖRN C., OLSSON L., ÅKERMAN B. (2014). Enzymes immobilized in mesoporous silica: A physical–chemical perspective, *Advances in Colloid and Interface Science*, Vol. 205, pp. 339-360.  
<https://doi.org/https://doi.org/10.1016/j.cis.2013.08.010>
- CHAUHAN S.S., DIKSHIT P.K.S. (2023). Cadmium metal scavenging capability of spent tea grains - an agricultural biomass waste as a low-cost adsorbent, *Larhyss Journal*, No 55, pp. 161-189.
- CHEN R.Q., WANG Y., WU H., HU W. (2025). The collective power of weak van der Waals forces, *Chem*, Vol. 11, Issue 6, Paper ID 102620.  
<https://doi.org/https://doi.org/10.1016/j.chempr.2025.102620>
- CHEN Z., HSU F.C., BATTIGELLI D., CHANG H.C. (2006). Capture and release of viruses using amino-functionalized silica particles, *Analytica Chimica Acta*, Vol. 569, Issue 1, pp. 76-82.  
<https://doi.org/https://doi.org/10.1016/j.aca.2006.03.103>
- CHENG R., KANG M., ZHUANG S., WANG S., WANG J. (2019). Removal of bacteriophage f2 in water by Fe/Ni nanoparticles: Optimization of Fe/Ni ratio and influencing factors, *The Science of the Total Environment*, Vol. 649, pp. 995-1003.  
<https://doi.org/10.1016/j.scitotenv.2018.08.380>
- CLARK K.J., SARR A.B., GRANT P.G., PHILLIPS T.D., WOODE G.N. (1998). In vitro studies on the use of clay, clay minerals and charcoal to adsorb bovine rotavirus and bovine coronavirus, *Veterinary Microbiology*, Vol. 63, Issue 2, pp. 137-146.  
[https://doi.org/https://doi.org/10.1016/S0378-1135\(98\)00241-7](https://doi.org/https://doi.org/10.1016/S0378-1135(98)00241-7)
- DAS P., MANNA S., BEHERA A.K., SHEE M., SHARMA A.K. (2022). Current synthesis and characterization techniques for clay-based polymer nano-composites and its biomedical applications: A review, *Environmental Research*, Vol. 212, Paper ID 113534.  
<https://doi.org/https://doi.org/10.1016/j.envres.2022.113534>
- DELAFOSSÉ D., REINERT L., AZAÏS P., FONTVIEILLE D., DUCLAUX L. (2022). Potentialities of a mesoporous activated carbon as virus detection probe in aquatic systems, *Journal of Virological Methods*, Vol. 303, Paper ID 114496.  
<https://doi.org/https://doi.org/10.1016/j.jviromet.2022.114496>

- DOMAGAŁA K., JACQUIN C., BORLAF M., GRAULE T. (2020). Efficiency and stability evaluation of Cu<sub>2</sub>O/MWCNTs filters for virus removal from water, *Water Research*, Vol. 179, Paper ID 115879.  
<https://doi.org/https://doi.org/10.1016/j.watres.2020.115879>
- DUTTA P., WANG B. (2019). Zeolite-supported silver as antimicrobial agents, *Coordination Chemistry Reviews*, Vol. 383, pp. 1-29.  
<https://doi.org/https://doi.org/10.1016/j.ccr.2018.12.014>
- EDWARDS K.F., STEWARD G.F., SCHVARCZ C.R. (2021). Making sense of virus size and the tradeoffs shaping viral fitness, *Ecology Letters*, Vol. 24, Issue 2, pp. 363-373.  
<https://doi.org/https://doi.org/10.1111/ele.13630>
- EGBEDINA A.O., BOLADE O.P., EWUZIE U., LIMA E.C. (2022). Emerging trends in the application of carbon-based materials: A review, *Journal of Environmental Chemical Engineering*, Vol. 10, Issue 2, Paper ID 107260.  
<https://doi.org/https://doi.org/10.1016/j.jece.2022.107260>
- FARHAN A., KHALID A., MAQSOOD N., ASIF M.B. (2024). Progress in layered double hydroxides (LDHs): Synthesis and application in adsorption, catalysis and photoreduction, *Science of The Total Environment*, Vol. 912, Paper ID 169160.  
<https://doi.org/https://doi.org/10.1016/j.scitotenv.2023.169160>
- FAYE C. (2017). Water pollution challenges, a threat to public health: strengths and weaknesses of water laws and policies in Senegal, *Larhyss Journal*, No 32, pp. 107-126. (In French)
- FELIX-SAHAYARAJ A., JOY-PRABU H., MANIRAJ J., KANNAN M., SALAMON J. (2023). Metal–Organic Frameworks (MOFs): The Next Generation of Materials for Catalysis, Gas Storage, and Separation, *Journal of Inorganic and Organometallic Polymers and Materials*, Vol. 33, Issue 7, 1757-1781.  
<https://doi.org/10.1007/s10904-023-02657-1>
- FORANO C., BRUNA F., MOUSTY C., PREVOT V. (2018). Interactions between Biological Cells and Layered Double Hydroxides: Towards Functional Materials, *The Chemical Record*, Vol. 18, Issue 7-8, pp. 1150-1166.  
<https://doi.org/https://doi.org/10.1002/tcr.201700102>
- FRITEA L., BANICA F., COSTEA T.O., MOLDOVAN L., CAVALU S. (2021). Metal Nanoparticles and Carbon-Based Nanomaterials for Improved Performances of Electrochemical (Bio)Sensors with Biomedical Applications, *Materials*, Vol. 14, Issue 21. <https://doi.org/10.3390/ma14216319>
- FUKUGAICHI S., MARUYAMA S., JOHAN E., MATSUE N. (2024). Facile removal of *Escherichia coli* from water using amorphous membrane fabricated on aluminum plate, *Emergent Materials*, Vol/ 8, pp. 1523-1534.  
<https://doi.org/https://doi.org/10.1007/s42247-024-00816-9>

- GERBA C.P., BETANCOURT W.Q., KITAJIMA M. (2017). How much reduction of virus is needed for recycled water: A continuous changing need for assessment? *Water Research*, Vol. 108, pp. 25-31.  
<https://doi.org/https://doi.org/10.1016/j.watres.2016.11.020>
- GHOMRI F., LAHSINI A., LAAJEB A., ADDAOU A. (2013). The removal of heavy metal ions (copper, zinc, nickel and cobalt) by natural bentonite, *Larhyss Journal*, No 12, pp. 37-54.
- GIRÓN-NAVARRO R., LINARES-HERNÁNDEZ I., CASTILLO-SUÁREZ L.A. (2021). The impact of coronavirus SARS-CoV-2 (COVID-19) in water: potential risks, *Environmental Science and Pollution Research International*, Vol. 28, Issue 38, pp. 52651-52674.  
<https://doi.org/10.1007/s11356-021-16024-5>
- GOHARSHADI E.K., GOHARSHADI K., MOGHAYEDI M. (2022). The use of nanotechnology in the fight against viruses: A critical review, *Coordination Chemistry Reviews*, Vol. 464, Paper ID 214559.  
<https://doi.org/https://doi.org/10.1016/j.ccr.2022.214559>
- GUESBAYA N., ACHOUR S. (2023). Effect of flocculation – adsorption steps on the natural water’s quality, *Larhyss Journal*, No 2, pp. 83-89. (In French)
- GUERGAZI S., AMIMEUR D., ACHOUR S. (2013). Elimination of humic substances of two Algerian surface waters by adsorption on activated carbon and bentonite, *Larhyss Journal*, No 13, pp. 125-137. (In French)
- GUTIERREZ L., LI X., WANG J., NANGMENYI G., NGUYEN T.H. (2009). Adsorption of rotavirus and bacteriophage MS2 using glass fiber coated with hematite nanoparticles, *Water Research*, Vol. 43, Issue 20, pp. 5198-5208.  
<https://doi.org/https://doi.org/10.1016/j.watres.2009.08.031>
- HAN Z., YANG Y., RUSHLOW J., HUO J., ZHOU H.C. (2025). Development of the design and synthesis of metal–organic frameworks (MOFs) – from large scale attempts, functional oriented modifications, to artificial intelligence (AI) predictions, *Chemical Society Reviews*, Vol. 54, Issue 1, pp. 367-395.  
<https://doi.org/10.1039/D4CS00432A>
- HAQ I.U., CHAUDHRY W.N., AKHTAR M.N., ANDLEEB S., QADRI I. (2012). Bacteriophages and their implications on future biotechnology: a review, *Virology Journal*, Vol. 9, Issue 1, Paper ID 9.  
<https://doi.org/10.1186/1743-422X-9-9>
- HARISH V., TEWARI D., GAUR M., YADAV A. B., BARHOUM A. (2022). Review on Nanoparticles and Nanostructured Materials: Bioimaging, Biosensing, Drug Delivery, Tissue Engineering, Antimicrobial, and Agro-Food Applications, *Nanomaterials*, Vol. 12, Issue 3.  
<https://doi.org/10.3390/nano12030457>

- HARTVIG R.A., VAN DE WEERT M., ØSTERGAARD J., JORGENSEN L., JENSEN H. (2011). Protein Adsorption at Charged Surfaces: The Role of Electrostatic Interactions and Interfacial Charge Regulation, *Langmuir*, Vol. 27, Issue 6, pp. 2634-2643.  
<https://doi.org/10.1021/la104720n>
- HE C., LIU Z., WU J., PAN X., BRYAN B.A. (2021). Future global urban water scarcity and potential solutions, *Nature Communications*, Vol. 12, Issue 1, Paper ID 4667.  
<https://doi.org/10.1038/s41467-021-25026-3>
- HERMANN J., DISTASIO R.A.J., TKATCHENKO A. (2017). First-Principles Models for van der Waals Interactions in Molecules and Materials: Concepts, Theory, and Applications, *Chemical Reviews*, Vol. 117, Issue 6, Paper ID 4714-4758.  
<https://doi.org/10.1021/acs.chemrev.6b00446>
- HERYANTO H., TAHIR D., ABDULLAH B., KAVGACI M., SAYYED M.I. (2024). Carbon as a multifunctional material in supporting adsorption performance for water treatment: Science mapping and review, *Desalination and Water Treatment*, Vol. 320, Paper ID 100758.  
<https://doi.org/https://doi.org/10.1016/j.dwt.2024.100758>
- IHSAN T. (2025). Is chlorination the right solution for household water disinfection in Indonesia? A critical review, *Larhyss Journal*, No. 63, pp. 55-88.
- IHSAN T., AFRIANITA R., ILFAN F. (2025). Point-of-Use technology for clean water treatment in disaster areas: Effectiveness of LDH plate in eliminating pathogenic bacteria, *E3S Web Conference*, Vol. 604, Paper ID 05001.  
<https://doi.org/10.1051/e3sconf/202560405001>
- IHSAN T., DEROSYA, V. (2024). Drinking water problems in rural areas: Review of point-of-use methods to improve water quality and public health, *Larhyss Journal*, No. 58, pp. 55-71.
- IHSAN T., JOHAN E., FUKUGAICHI S., MITSUNOBU S., MATSUE N. (2024). Innovative DIY drinking water disinfection for underserved communities, *Science of The Total Environment*, Vol. 927, Paper ID 172257.  
<https://doi.org/https://doi.org/10.1016/j.scitotenv.2024.172257>
- IHSAN T., JOHAN E., FUKUGAICHI S., MATSUE N. (2023). Enhancing rural drinking water safety using an Mg–Al-type layered double hydroxide foil as a new point-of-use disinfection tool, *Journal of Water, Sanitation and Hygiene for Development*, Vol. 13, Issue 11, pp. 921-930.  
<https://doi.org/10.2166/washdev.2023.206>
- IHSAN T., NOVIA F., DEROSYA V., EDIHARSI T.A., AZZAHRA A. (2025). Sustainable layered double hydroxide foils: Calcium hydroxide and alternative magnesium sources for rapid point-of-use water disinfection in rural and disaster settings, *Journal of Ecological Engineering*, Vol. 26, Issue 11, pp. 342-350.  
<https://doi.org/10.12911/22998993/208261>

- IHSAN T., NOVIA F., TETRA O.N. (2025). Residue-free alkali-treated aluminum foil for water disinfection: A novel supernatant Mg(OH)<sub>2</sub> fabrication method. *Communications in Science and Technology*, Vol. 10, Issue 1, pp. 98-105.  
<https://doi.org/10.21924/cst.10.1.2025.1673>
- ISAEVA V.I., VEDENYAPINA M.D., KURMYSHEVA A.Y., NGUYEN N.P., KUSTOV L.M. (2021). Modern Carbon-Based Materials for Adsorptive Removal of Organic and Inorganic Pollutants from Water and Wastewater, *Molecules*, Vol. 26, Issue 21.  
<https://doi.org/10.3390/molecules26216628>
- JIA Z., MA Y., YANG L., GUO C., ZHANG Z. (2019). NiCo<sub>2</sub>O<sub>4</sub> spinel embedded with carbon nanotubes derived from bimetallic NiCo metal-organic framework for the ultrasensitive detection of human immune deficiency virus-1 gene, *Biosensors and Bioelectronics*, Vol. 133, pp. 55-63.  
<https://doi.org/https://doi.org/10.1016/j.bios.2019.03.030>
- JIAO L., SEOW J.Y.R., SKINNER W.S., WANG Z.U., JIANG H.L. (2019). Metal-organic frameworks: Structures and functional applications, *Materials Today*, Vol. 27, pp. 43-68.  
<https://doi.org/https://doi.org/10.1016/j.mattod.2018.10.038>
- JJAGWE J., OLUPOT P.W., MENYA E., KALIBBALA H.M. (2021). Synthesis and Application of Granular Activated Carbon from Biomass Waste Materials for Water Treatment: A Review, *Journal of Bioresources and Bioproducts*, Vol. 6, Issue 4, pp. 292-322.  
<https://doi.org/https://doi.org/10.1016/j.jobab.2021.03.003>
- JOHAN E., IHSAN T., FUKUGAICHI S., MATSUE N. (2023). Aluminum foil immersed in alkalinized seawater removes *Escherichia coli* from household drinking water, *Journal of Water, Sanitation and Hygiene for Development*, Vol. 13, Issue 9, pp. 681-686.  
<https://doi.org/10.2166/washdev.2023.057>
- JOHAN E., IHSAN T., MATSUE N. (2024). Simple sterilization of rural household water by LDH ( Layered Double Hydroxide )-embedded sheet, *IOP Conference Series: Earth and Environmental Science*, Vol. 1388, Paper ID 012059.  
<https://doi.org/10.1088/1755-1315/1388/1/012059>
- JONES S.T., CAGNO V., JANEČEK M., ORTIZ D., TAPPAREL C. (2020). Modified cyclodextrins as broad-spectrum antivirals, *Science Advances*, Vol. 6, Issue 5, Paper ID 9318.  
<https://doi.org/10.1126/sciadv.aax9318>
- JOO J.H., KIM S.H., KIM J.H., SEO M.K. (2025). Recent advances in activated carbon fibers for pollutant removal, *Carbon Letters*, Vol. 35, Issue 1, pp. 21-44.  
<https://doi.org/10.1007/s42823-024-00803-4>

- KHELIEL O., OUAKOOUAK A.E.K., YUCEF L., ACHOUR S. (2015). Groundwater denitrification by adsorption on activated carbon and by coagulation-flocculation with aluminum sulfate, *Larhyss Journal*, No 21, pp. 191-200. (In French)
- KHELIFI O., MEHREZ I., BEN SALAH W., BEN SALAH F., YOUNSI M. (2016). Study of methylene blue (MB) adsorption from aqueous solutions on biosorbent prepared from Algerian datte stones, *Larhyss Journal*, No 28, pp. 135-148. (In French)
- KHELIFI O., MEHREZ I., YOUNSI M., NACEF M., AFFOUNE A.M. (2018). Methyl orange adsorption on biosorbent derived from mango seed kernels, *Larhyss Journal*, No 36, pp. 145-156. (In French)
- KHELILI H., ACHOUR S., REZEG A. (2010). Effectiveness of aluminum sulfate and activated charcoal against organic aromatic pollutants, *Larhyss Journal*, No 9, pp. 99-110.
- KHELILI H., ACHOUR S., KONAN K.G., GUELLAL M. (2024). Kinetic and isotherm study of methylene blue adsorption on orange peel activated carbon, *Larhyss Journal*, No 58, pp. 89-103.
- KIANFAR E., SAYADI H. (2022). Recent advances in properties and applications of nanoporous materials and porous carbons, *Carbon Letters*, Vol. 32, Issue 7, pp. 1645-1669.  
<https://doi.org/10.1007/s42823-022-00395-x>
- KRASOWSKA A., SIGLER, K. (2014). How microorganisms use hydrophobicity and what does this mean for human needs? *Frontiers in Cellular and Infection Microbiology*, Vol. 4, Paper ID 102373.  
<https://doi.org/10.3389/fcimb.2014.00112>
- KWON J., MAO X., LEE J. (2017). Fe-based multifunctional nanoparticles with various physicochemical properties, *Current Applied Physics*, Vol. 17, Issue 8, pp. 1066-1078.  
<https://doi.org/https://doi.org/10.1016/j.cap.2017.04.018>
- LANREWAJU A.A., ENITAN-FOLAMI A.M., SABIU S., SWALAHA F.M. (2022). A review on disinfection methods for inactivation of waterborne viruses, *Frontiers in Microbiology*, Vol. 13, Paper ID 991856.  
<https://doi.org/10.3389/fmicb.2022.991856>
- LARAKEB M., YUCEF L., ACHOUR S. (2014). Comparative study of zinc removal by adsorption on goethite and Maghnia bentonite, *Larhyss Journal*, No 19, pp. 87-100. (In French)
- LAXMI B., DEVI P.U.M., NAVEEN T., BUDDOLLA V. (2025). Virus-like particles: Innovative strategies for combatting emerging and re-emerging viral threats, *The Microbe*, Vol. 7, Paper ID 100351.  
<https://doi.org/https://doi.org/10.1016/j.microb.2025.100351>

- LI D., YADAV A., ZHOU H., ROY K., LEE C. (2024). Advances and Applications of Metal-Organic Frameworks (MOFs) in Emerging Technologies: A Comprehensive Review, *Global Challenges*, Vol. 8, Issue 2, Paper ID 2300244.  
<https://doi.org/10.1002/gch2.202300244>
- LI X., ZHANG L., YANG Z., HE Z., RAN J. (2020). Hydrophobic modified activated carbon using PDMS for the adsorption of VOCs in humid condition, *Separation and Purification Technology*, Vol. 239, Paper ID 116517.  
<https://doi.org/https://doi.org/10.1016/j.seppur.2020.116517>
- LIN G., XUE N., QIU P., HE S., GUO Z. (2025). Ni-modified N-doped carbon nanosheets for Fe(VI) activation: Insights into charge transfer and reactive oxygen species pathways for ultrafast water treatment, *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, Vol. 721, Paper ID 137256.  
<https://doi.org/https://doi.org/10.1016/j.colsurfa.2025.137256>
- LIU J., WILLFÖR S., XU C. (2015). A review of bioactive plant polysaccharides: Biological activities, functionalization, and biomedical applications, *Bioactive Carbohydrates and Dietary Fibre*, Vol. 5, Issue 1, pp. 31-61.  
<https://doi.org/https://doi.org/10.1016/j.bcdf.2014.12.001>
- LUP., XU J., SUN Y., GUILLET-NICOLAS R., VALTCHEV V. (2024). A stable zeolite with atomically ordered and interconnected mesopore channel, *Nature*, Vol. 636, Issue 8042, pp. 368-373.  
<https://doi.org/10.1038/s41586-024-08206-1>
- LUO D., SUN G., WANG Y., SHU X., BIAN H. (2024). Metal ion and hydrogen bonding synergistically mediated carboxylated lignin/cellulose nanofibrils composite film, *Carbohydrate Polymers*, Vol. 323, Paper ID 121456.  
<https://doi.org/https://doi.org/10.1016/j.carbpol.2023.121456>
- LUO J., CUI Y., XU L., ZHANG J., SHAO L. (2025). Layered double hydroxides for regenerative nanomedicine and tissue engineering: recent advances and future perspectives, *Journal of Nanobiotechnology*, Vol. 23, Issue 1, Paper ID 370.  
<https://doi.org/10.1186/s12951-025-03448-1>
- MANOIU V.M., KUBIAK-WÓJCICKA K., CRACIUN A.I., AKMAN Ç., AKMAN E. (2022). Water Quality and Water Pollution in Time of COVID-19: Positive and Negative Repercussions, *Water*, Vol. 14, Issue 7, Paper ID 1124.  
<https://doi.org/10.3390/w14071124>
- MASMOUDI T., GUERGAZI S., ACHOUR S. (2018). Mercury removal by activated carbon, *Larhyss Journal*, No 34, pp. 21-38. (In French)
- MATEU M.G. (2013). Assembly, stability and dynamics of virus capsids, *Archives of Biochemistry and Biophysics*, Vol. 531, Issue 1, pp. 65-79.  
<https://doi.org/https://doi.org/10.1016/j.abb.2012.10.015>

- MATSUSHITA T., SUZUKI H., SHIRASAKI N., MATSUI Y., OHNO K. (2013). Adsorptive virus removal with super-powdered activated carbon, *Separation and Purification Technology*, Vol. 107, pp. 79-84.  
<https://doi.org/https://doi.org/10.1016/j.seppur.2013.01.017>
- MAZURKOW J.M., YÜZBASI N.S., DOMAGALA K.W., GRAULE T. (2020). Nano-Sized Copper (Oxide) on Alumina Granules for Water Filtration: Effect of Copper Oxidation State on Virus Removal Performance, *Environmental Science and Technology*, Vol. 54, Issue 2, pp. 1214-1222.  
<https://doi.org/10.1021/acs.est.9b05211>
- MIARALIPOUR S., FRIEDMANN D., SCOTT J., AMAL R. (2018). TiO<sub>2</sub>/porous adsorbents: Recent advances and novel applications, *Journal of Hazardous Materials*, Vol. 341, pp. 404-423.  
<https://doi.org/https://doi.org/10.1016/j.jhazmat.2017.07.070>
- MICHEN B., FRITSCH J., ANEZIRIS C., GRAULE T. (2013). Improved Virus Removal in Ceramic Depth Filters Modified with MgO, *Environmental Science & Technology*, Vol. 47, Issue 3, pp. 1526-1533.  
<https://doi.org/10.1021/es303685a>
- MICHEN B., GRAULE T. (2010). Isoelectric points of viruses, *Journal of Applied Microbiology*, Vol. 109, Issue 2, pp. 388-397.  
<https://doi.org/https://doi.org/10.1111/j.1365-2672.2010.04663.x>
- MOHAMED A.T., HAMEED R.A., EL-MOSLAMY S.H., FAREID M., ELNOUBY M. (2024). Facile synthesis of Fe<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>@CuO and WO<sub>3</sub> nanoparticles: characterization, structure determination and evaluation of their biological activity, *Scientific Reports*, Vol. 14, Issue 1, Paper ID 6081.  
<https://doi.org/10.1038/s41598-024-55319-8>
- MOTSA B.B., STAHELIN R.V. (2021). Lipid–protein interactions in virus assembly and budding from the host cell plasma membrane, *Biochemical Society Transactions*, Vol. 49, Issue 4, pp. 1633-1641.  
<https://doi.org/https://doi.org/10.1042/BST20200854>
- NAGARAJ K., RADHA S., DEEPA C.G., RAJA K., UTHRA C. (2025). Photocatalytic advancements and applications of titanium dioxide (TiO<sub>2</sub>): Progress in biomedical, environmental, and energy sustainability, *Next Research*, Vol. 2, Issue 1, Paper ID 100180.  
<https://doi.org/https://doi.org/10.1016/j.nexres.2025.100180>
- NAM S.W., CHOI D.J., KIM S.K., HER N., ZOH K.D. (2014). Adsorption characteristics of selected hydrophilic and hydrophobic micropollutants in water using activated carbon, *Journal of Hazardous Materials*, Vol. 270, Issue 144-152.  
<https://doi.org/https://doi.org/10.1016/j.jhazmat.2014.01.037>

- NATARAJAN R., SAIKIA K., PONNUSAMY S.K., RATHANKUMAR A.K., VAIDYANATHAN V.K. (2022). Understanding the factors affecting adsorption of pharmaceuticals on different adsorbents - A critical literature update, *Chemosphere*, Vol. 287, Paper ID 131958.  
<https://doi.org/https://doi.org/10.1016/j.chemosphere.2021.131958>
- NÉMETH Z., SZEKERES G.P., SCHABIKOWSKI M., GRAULE T. (2019). Enhanced virus filtration in hybrid membranes with MWCNT nanocomposite, *Royal Society Open Science*, Vol. 6, Issue 1, Paper ID 181294.  
<https://doi.org/10.1098/rsos.181294>
- NORDHOLM S., BACSKAY G. (2020). The Basics of Covalent Bonding in Terms of Energy and Dynamics, *Molecules*, Vol. 25, Issue 11, Paper ID 2667.  
<https://doi.org/10.3390/molecules25112667>
- OHSHIMA H. (2024). DLVO theory of colloid stability, *Fundamentals of Soft Interfaces in Colloid and Surface Chemistry*, Vol. 37, pp. 217-244.  
<https://doi.org/https://doi.org/10.1016/B978-0-443-16116-2.00009-6>
- OUAKOUAK A.E.K., YOUCEF L., ACHOUR S. (2010). Elimination of atrazine by adsorption onto powdered activated charcoal, *Larhyss Journal*, No 9, pp. 121-129. (In French)
- OUAKOUAK A.K., YOUCEF L. (2016). Adsorption of Cu<sup>2+</sup> ions on powder activated carbon and a sodique bentonite, *Larhyss Journal*, No 27, pp. 39-61. (In French)
- PAN Q., LIN F., LIU R., HE L. (2023). Fe/Ni layered double hydroxide biocatalysts inhibit tumor growth through ROS and ferroptosis signaling pathway, *Chemical Engineering Journal*, Vol. 466, Paper ID 142962.  
<https://doi.org/https://doi.org/10.1016/j.cej.2023.142962>
- PARMAR M., SHAHABUDDIN S., BANDYOPADHYAY M., GAUR R. (2025). Zeolites in the age of advanced materials: from structural refinement to scalable green synthesis and emerging applications, *Emergent Materials*, Vol. 8, Issue 5, Paper ID 1104.  
<https://doi.org/10.1007/s42247-025-01104-w>
- PERERA H.C.S., GURUNANTHANAN V., SINGH A., ARYA S. (2024). Magnesium oxide (MgO) nanoadsorbents in wastewater treatment: A comprehensive review, *Journal of Magnesium and Alloys*, Vol. 12, Issue 5, pp. 1709-1773.  
<https://doi.org/https://doi.org/10.1016/j.jma.2024.05.003>
- PISHARODY L., SURESH S., MUKHERJI S. (2021). Evaluation of adsorbents and eluents for application in virus concentration and adsorption-desorption isotherms for coliphages, *Chemical Engineering Journal*, Vol. 403, Paper ID 126267.  
<https://doi.org/https://doi.org/10.1016/j.cej.2020.126267>

- POWELL T., BRION G.M., JAGTOYEN M., DERBYSHIRE F. (2000). Investigating the Effect of Carbon Shape on Virus Adsorption, *Environmental Science & Technology*, Vol. 34, Issue 13, pp. 2779-2783.  
<https://doi.org/10.1021/es991097w>
- PUTRA N.R., YUSTISIA Y., HERYANTO R.B., ASMALİYAH A., ROHMAN G.A.N. (2023). Advancements and challenges in green extraction techniques for Indonesian natural products: A review, *South African Journal of Chemical Engineering*, Vol. 46, pp. 88-98.  
<https://doi.org/https://doi.org/10.1016/j.sajce.2023.08.002>
- SAJID M., ASIF M., BAIG N., KABEER M., MOHAMMAD A.W. (2022). Carbon nanotubes-based adsorbents: Properties, functionalization, interaction mechanisms, and applications in water purification, *Journal of Water Process Engineering*, Vol. 47, Paper ID 102815.  
<https://doi.org/https://doi.org/10.1016/j.jwpe.2022.102815>
- SALEH T.A. (2022). Adsorption technology and surface science, *Surface Science of Adsorbents and Nanoadsorbents*, Vol. 34, pp. 39-64.  
<https://doi.org/https://doi.org/10.1016/B978-0-12-849876-7.00006-3>
- SALEHI E., EIDI B., SOLEIMANI Z. (2019). An integrated process consisting of Mg(OH)<sub>2</sub> –impregnated ceramic foam filters as adsorbent and Mg(OH)<sub>2</sub> as scrubbing solution for intensified desulfurization of flue gas, *Separation and Purification Technology*, Vol. 216, pp. 34-42.  
<https://doi.org/https://doi.org/10.1016/j.seppur.2019.01.072>
- SALEHI M. (2022). Global water shortage and potable water safety; Today's concern and tomorrow's crisis, *Environment International*, Vol. 158, Paper ID 106936.  
<https://doi.org/https://doi.org/10.1016/j.envint.2021.106936>
- SALIBA S., RUCH P., VOLKSEN W., MAGBITANG T.P., MICHEL B. (2016). Combined influence of pore size distribution and surface hydrophilicity on the water adsorption characteristics of micro- and mesoporous silica, *Microporous and Mesoporous Materials*, Vol. 226, pp. 221-228.  
<https://doi.org/https://doi.org/10.1016/j.micromeso.2015.12.029>
- SATYAM S., PATRA, S. (2024). Innovations and challenges in adsorption-based wastewater remediation: A comprehensive review, *Heliyon*, Vol. 10, Issue 9, Paper ID e29573.  
<https://doi.org/https://doi.org/10.1016/j.heliyon.2024.e29573>
- SEGHAIRI N., ACHOUR S. (2003). Influence of time and bentonite activation rate on aniline adsorption, *Larhyss Journal*, No 2, pp. 115-125. (In French)
- SEGUCHI M., YAMAGUCHI S., TANAKA M., MORI Y., ITO M. (2024). Effects of Alkaline Solutions on the Structure and Function of Influenza A Virus, *Viruses*, Vol. 16, Issue 10, Paper 1636.  
<https://doi.org/10.3390/v16101636>

- SHIM K.B., IN J.J., LEE J.B., HAN H.G., AN B.K. (2024). Effects of the physical structure and surface charge of activated carbon on the reduction of biogenic amines in anchovy fish sauce, *Food Chemistry*, Vol. 443, Paper ID 138399.  
<https://doi.org/https://doi.org/10.1016/j.foodchem.2024.138399>
- SHIVANI-BHAT R.S., BINDU A.G., SAJANKILA S.P. (2025). Review on titanium oxide (TiO<sub>2</sub>) nanomaterials in multidomain investigations, *Nano-Structures & Nano-Objects*, Vol. 41, Paper ID 101455.  
<https://doi.org/https://doi.org/10.1016/j.nanoso.2025.101455>
- SOUZA C., MAJUSTE D., CIMINELLI V.S.T. (2014). Effects of surface properties of activated carbon on the adsorption mechanism of copper cyanocomplexes, *Hydrometallurgy*, Vol. 142, pp. 1-11.  
<https://doi.org/https://doi.org/10.1016/j.hydromet.2013.11.003>
- TORTAJADA C., BISWAS A.K. (2018). Achieving universal access to clean water and sanitation in an era of water scarcity: strengthening contributions from academia, *Current Opinion in Environmental Sustainability*, Vol. 34, pp. 21-25.  
<https://doi.org/https://doi.org/10.1016/j.cosust.2018.08.001>
- TRAN H.N. (2023). Adsorption Technology for Water and Wastewater Treatments, *Water*, Vol. 15, Issue 15, Paper ID 2857.  
<https://doi.org/10.3390/w15152857>
- VEDENYAPINA M.D., KURMYSHEVA A.Y., KULAISHIN S.A. (2024). Regeneration of Activated Carbons after Adsorption of Biologically Active Organic Compounds on Them (A Review), *Solid Fuel Chemistry*, Vol. 58, Issue 1, pp. 24-39.  
<https://doi.org/10.3103/S0361521924010099>
- VIZANKO B., KADINSKI L., OSTFELD A., BERGLUND E.Z. (2024). Social distancing, water demand changes, and quality of drinking water during the COVID-19 pandemic, *Sustainable Cities and Society*, Vol. 102, Paper ID 105210.  
<https://doi.org/https://doi.org/10.1016/j.scs.2024.105210>
- WANG L., WANG X., WU H., LIU R. (2014). Overview on Biological Activities and Molecular Characteristics of Sulfated Polysaccharides from Marine Green Algae in Recent Years, *Marine Drugs*, Vol. 12, Issue 9, pp. 4984-5020.  
<https://doi.org/10.3390/md12094984>
- WEGMANN M., MICHEN B., LUXBACHER T., FRITSCH J., GRAULE, T. (2008). Modification of ceramic microfilters with colloidal zirconia to promote the adsorption of viruses from water, *Water Research*, Vol. 42, Issue 6, pp. 1726-1734.  
<https://doi.org/https://doi.org/10.1016/j.watres.2007.10.030>
- WHO. (2023). *Drinking water*, Geneva, Switzerland, 58 p.
- WIJESINGHE W.A.J.P., JEON Y.J. (2012). Biological activities and potential industrial applications of fucose rich sulfated polysaccharides and fucoidans isolated from brown seaweeds: A review, *Carbohydrate Polymers*, Vol. 88, Issue 1, pp. 13-20.  
<https://doi.org/https://doi.org/10.1016/j.carbpol.2011.12.029>

- WILHELM M.J., SHARIFIAN G.H., WU T., LI, Y., DAI H L. (2021). Determination of bacterial surface charge density via saturation of adsorbed ions, *Biophysical Journal*, Vol. 120, Issue 12, pp. 2461-2470.  
<https://doi.org/https://doi.org/10.1016/j.bpj.2021.04.018>
- WORASITH N., GOODMAN B.A. (2023). Clay mineral products for improving environmental quality, *Applied Clay Science*, Vol. 242, Paper ID 106980.  
<https://doi.org/https://doi.org/10.1016/j.clay.2023.106980>
- XIE B.P., QIU G.H., HU P.P., CHEN J X. (2018). Simultaneous detection of Dengue and Zika virus RNA sequences with a three-dimensional Cu-based zwitterionic metal-organic framework, comparison of single and synchronous fluorescence analysis, *Sensors and Actuators B: Chemical*, Vol. 254, pp. 1133-1140.  
<https://doi.org/https://doi.org/10.1016/j.snb.2017.06.085>
- XU H., TIAN H., DENG J., ZHUO Q., YU P. (2023). Review of influence of steric effect on aggregation behavior of fine particles, *Minerals Engineering*, Vol. 203, Paper ID 108304.  
<https://doi.org/https://doi.org/10.1016/j.mineng.2023.108304>
- XU K., ZHANG S., ZHUANG X., ZHANG G., PANG H. (2024). Recent progress of MOF-functionalized nanocomposites: From structure to properties, *Advances in Colloid and Interface Science*, Vol. 323, Paper ID 103050.  
<https://doi.org/https://doi.org/10.1016/j.cis.2023.103050>
- YANG H., LIU L., SHU Z., ZHANG W., JIANG G. (2025). Magnetic iron oxide nanoparticles: An emerging threat for the environment and human health, *Journal of Environmental Sciences*, Vol. 152, pp. 188-202.  
<https://doi.org/https://doi.org/10.1016/j.jes.2024.04.045>
- YANG J., FENG W., LIANG K., CHEN C., CAI C. (2020). A novel fluorescence molecularly imprinted sensor for Japanese encephalitis virus detection based on metal organic frameworks and passivation-enhanced selectivity, *Talanta*, Vol. 212, Paper ID 120744.  
<https://doi.org/https://doi.org/10.1016/j.talanta.2020.120744>
- YEDDOU MEZENNER N., BENZAADI Z., LAGHA H. BENMAILI A. (2012). Study of the adsorption of a mixture of Bio-Calcitrating compounds in an aqueous medium, *Larhyss Journal*, No 11, pp. 7-16. (In French)
- YOUCEF L., OUAOUAK A., BOULANOUAR D., ACHOUR S. (2014). Study of the adsorbent power of powdered activated carbon for the elimination of phosphates from natural waters, *Larhyss Journal*, No 17, pp. 35-46. (In French)
- ZEB S., ALI N., ALI Z., BILAL M., IQBAL H.M.N. (2020). Silica-based nanomaterials as designer adsorbents to mitigate emerging organic contaminants from water matrices, *Journal of Water Process Engineering*, Vol. 38, Paper ID 101675.  
<https://doi.org/https://doi.org/10.1016/j.jwpe.2020.101675>

- ZEGGAI F., AIT-TOUCHENTE Z., BACHARI K., ELAISSARI A. (2025). Investigation of Metal-Organic Frameworks (MOFs): Synthesis, Properties, and Applications - An In-Depth Review, *Chemical Physics Impact*, Vol. 10, Paper ID 100864.  
<https://doi.org/https://doi.org/10.1016/j.chphi.2025.100864>
- ZHAN S., YANG Y., SHEN Z., SHAN J., ZHU D. (2014). Efficient removal of pathogenic bacteria and viruses by multifunctional amine-modified magnetic nanoparticles, *Journal of Hazardous Materials*, Vol. 274, pp. 115-123.  
<https://doi.org/https://doi.org/10.1016/j.jhazmat.2014.03.067>
- ZHANG Y., ZHU C., LIU F., YUAN Y., LI A. (2019). Effects of ionic strength on removal of toxic pollutants from aqueous media with multifarious adsorbents: A review, *Science of The Total Environment*, Vol. 646, pp. 265-279.  
<https://doi.org/https://doi.org/10.1016/j.scitotenv.2018.07.279>
- ZHENG X., CHEN D., WANG Z., LEI Y., CHENG R. (2013). Nano-TiO<sub>2</sub> membrane adsorption reactor (MAR) for virus removal in drinking water, *Chemical Engineering Journal*, Vol. 230, pp. 180-187.  
<https://doi.org/https://doi.org/10.1016/j.cej.2013.06.069>