Advances in Low-Cost Adsorption Technologies for Energy Sector Water Management

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Abstract

Water scarcity, escalating regulatory pressure, and rising operational costs have intensified the need for efficient and affordable water treatment solutions in the energy sector, particularly in oil and gas, thermal power, and emerging renewable energy systems. Among available treatment options, adsorption technologies have gained renewed attention due to their operational simplicity, adaptability to diverse water matrices, and potential for cost reduction through material innovation. This abstract examines recent advances in low-cost adsorption technologies for energy sector water management, with emphasis on materials, system integration, and sustainability performance. Significant progress has been achieved in the development of adsorbents derived from agricultural residues, industrial by-products, and naturally abundant minerals, including biochar, modified clays, fly ash, and metal-oxide composites. These materials demonstrate competitive adsorption capacities for hydrocarbons, heavy metals, salts, and emerging contaminants commonly present in produced water, cooling tower blowdown, and wastewater streams. Advances in surface functionalization, nano-structuring, and hybrid adsorption–filtration systems have further enhanced selectivity, regeneration efficiency, and lifecycle performance while maintaining low production costs. Additionally, modular adsorption units and decentralized treatment configurations enable deployment in remote and resource-constrained energy operations. From a systems perspective, adsorption technologies are increasingly integrated within circular water management frameworks, supporting water reuse, reduced freshwater intake, and lower effluent discharge volumes. Despite these advances, challenges remain related to long-term stability, multi-contaminant competition, adsorbent regeneration, and field-scale validation under variable operational conditions. Addressing these limitations through pilot-scale studies, techno-economic assessments, and policy-aligned design will be critical for widespread adoption. Overall, low-cost adsorption technologies represent a strategically important pathway for enhancing water security, regulatory compliance, and environmental sustainability across the energy sector.

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1. Introduction

Water is a critical input across the energy sector, underpinning extraction, processing, conversion, and cooling operations in oil and gas production, power generation, mining, and bioenergy systems (Idowu *et al*., 2020; Giwah *et al*., 2020). As global energy demand continues to rise alongside increasing water scarcity, the water intensity of energy operations has emerged as a major sustainability and operational challenge (Adeyoyin *et al*., 2020; Nwafor *et al*., 2020). Oil and gas activities generate large volumes of produced water and flowback fluids containing hydrocarbons, dissolved salts, heavy metals, radionuclides, and chemical additives. Thermal power plants require substantial quantities of water for cooling and steam generation, often discharging wastewater with elevated temperatures, biocides, corrosion inhibitors, and trace metals (Erinjogunola *et al.*, 2020; Egemba *et al.*, 2020). Similarly, mining operations produce acidic and metal-laden effluents, while bioenergy processes generate nutrient-rich and organic wastewater streams. These complex and highly variable water matrices pose significant risks to ecosystems, public health, and regulatory compliance if inadequately managed (Nwafor *et al.*, 2020; Oziri *et al.*, 2020).

Conventional water treatment technologies have been widely deployed to address these challenges, including chemical precipitation, coagulation–flocculation, membrane filtration, advanced oxidation processes, and thermal desalination (Seyi-Lande *et al.*, 2020; Giwah *et al.*, 2020). While effective in specific contexts, these approaches often exhibit limitations when applied to energy-sector wastewaters. High capital and operational costs, intensive energy requirements, membrane fouling, chemical consumption, and the generation of secondary waste streams frequently constrain their feasibility, particularly in remote or resource-limited energy operations (Idowu *et al.*, 2020; Omisola *et al.*, 2002). Moreover, many conventional systems are optimized for municipal or relatively uniform industrial effluents and perform poorly under the high salinity, multi-contaminant, and fluctuating conditions characteristic of energy-related water streams (Osho *et al.*, 2020; Sanusi *et al.*, 2020). These constraints have driven growing interest in alternative treatment strategies that balance technical performance with affordability, robustness, and environmental sustainability.

Adsorption-based water treatment has gained renewed attention as a promising low-cost and scalable solution for energy sector water management. Adsorption offers several intrinsic advantages, including operational simplicity, adaptability to diverse contaminants, and compatibility with decentralized and modular treatment systems (Umoren *et al.*, 2020; Omisola *et al.*, 2020). A wide range of low-cost adsorbent materials such as agricultural by-products, biochars, natural minerals, and industrial waste-derived materials can be locally sourced and engineered to target specific pollutants, including hydrocarbons, heavy metals, nutrients, and emerging contaminants. Compared to energy-intensive separation technologies, adsorption processes typically require lower energy inputs and can be integrated into multi-barrier treatment trains to enhance overall system resilience (Oshoba *et al.*, 2020; Akinrinoye *et al.*, 2020). Importantly, advances in material modification, regeneration techniques, and hybrid adsorption systems have significantly improved adsorption capacity, selectivity, and reusability, strengthening their viability for large-scale and field-based applications (Filani *et al.*, 2020; Adekunle *et al.*, 2020).

The scope of this review is to critically examine recent advances in low-cost adsorption technologies for water management in the energy sector. It aims to synthesize current knowledge on adsorbent materials, adsorption mechanisms, system integration strategies, and performance under energy-relevant water conditions. Particular emphasis is placed on cost considerations, scalability, and environmental implications, as well as on practical deployment challenges and regulatory alignment. By identifying key technological trends, application pathways, and research gaps, this review seeks to inform researchers, practitioners, and policymakers on the role of low-cost adsorption technologies in advancing sustainable, resilient, and circular water management across energy systems.

2. Methodology

This study adopts a Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)–guided methodology to systematically identify, evaluate, and synthesize existing research on advances in low-cost adsorption technologies for water management in the energy sector. The review focuses on adsorption materials, system configurations, performance metrics, and applicability to energy-related water streams, including produced water, cooling water, and industrial wastewater.

A comprehensive literature search was conducted across major scientific databases, including Scopus, Web of Science, ScienceDirect, and Google Scholar. Search strings combined keywords and Boolean operators related to adsorption technologies, low-cost or waste-derived adsorbents, energy sector applications, and water or wastewater treatment. Only peer-reviewed journal articles, review papers, and selected conference proceedings published in English were considered to ensure scientific rigor and accessibility. The search period emphasized studies published within the last 15 years to capture recent technological advances while retaining seminal earlier works for contextual relevance.

Records identified through database searching were compiled, and duplicate entries were removed prior to screening. Titles and abstracts were independently assessed against predefined inclusion and exclusion criteria. Studies were included if they reported on adsorption-based water treatment technologies applicable to energy sector operations, explicitly addressed low-cost or locally available adsorbent materials, and presented experimental, pilot-scale, or techno-economic performance data. Excluded studies included those unrelated to energy-sector water streams, focused solely on high-cost commercial adsorbents without cost analysis, or lacking sufficient methodological detail.

Full-text articles meeting the screening criteria were then assessed for eligibility. Data extraction captured information on adsorbent type and source, target contaminants, adsorption capacity, regeneration potential, operational conditions, cost considerations, and reported environmental or sustainability impacts. To reduce bias, data extraction and synthesis followed a standardized template, and inconsistencies were resolved through comparative analysis of reported methodologies and outcomes.

The final synthesis employed qualitative and comparative analysis rather than meta-analysis, due to heterogeneity in adsorbent materials, experimental designs, and performance indicators. The PRISMA-guided approach ensures transparency, reproducibility, and methodological robustness, enabling a structured assessment of current progress, limitations, and research gaps in low-cost adsorption technologies for sustainable energy sector water management.

2.1. Water Management Challenges in the Energy Sector

Water management has become one of the most critical cross-cutting challenges facing the global energy sector, as energy production and conversion processes are inherently water-intensive and generate complex wastewater streams (Akinola *et al.*, 2020; Adesanya *et al.*, 2020). Oil and gas extraction, power generation, mining, and renewable energy systems all rely on large volumes of water for drilling, processing, cooling, and cleaning operations. At the same time, these activities produce wastewater containing a wide range of contaminants that are difficult to treat using conventional approaches. Increasing water scarcity, stricter environmental regulations, and rising sustainability expectations have intensified pressure on energy operators to improve water efficiency, reduce pollution, and enable safe reuse.

One of the most significant water management challenges arises from produced water and flowback fluids generated during oil and gas operations. Produced water refers to the water that is brought to the surface during hydrocarbon extraction, while flowback fluids are the liquids recovered after hydraulic fracturing. These streams often exceed the volume of hydrocarbons produced and represent the largest waste stream in upstream oil and gas activities. Produced water is characterized by high salinity, complex chemical composition, and spatial and temporal variability. It commonly contains dispersed and dissolved hydrocarbons, heavy metals, naturally occurring radioactive materials, chemical additives, and suspended solids. Managing these large volumes of contaminated water poses logistical, technical, and economic challenges, particularly in onshore fields located in arid or remote regions where disposal and freshwater availability are limited.

The presence of diverse contaminants further complicates energy-sector water management. Heavy metals such as arsenic, lead, mercury, chromium, and cadmium are frequently detected in produced water, mining effluents, and power plant discharges. These metals are persistent, toxic, and bioaccumulative, requiring stringent control to prevent environmental and human health impacts. Hydrocarbons, including oils, grease, and polycyclic aromatic compounds, pose additional risks due to their toxicity and potential to disrupt aquatic ecosystems. High concentrations of dissolved salts, particularly sodium, calcium, chloride, and sulfate ions, contribute to elevated total dissolved solids, which can impair soil quality, damage infrastructure, and limit water reuse options (Giwah *et al*., 2020; Osho *et al*., 2020). In recent years, emerging contaminants such as treatment chemicals, surfactants, corrosion inhibitors, biocides, and trace organic compounds have gained attention due to their potential ecological effects and resistance to traditional treatment methods. The simultaneous presence of these contaminants creates complex water matrices that challenge single-technology treatment solutions.

Cooling water demand represents another major challenge, particularly in thermal power generation systems such as coal, gas, nuclear, and concentrated solar power plants. These facilities require large quantities of water for heat dissipation and steam cycle efficiency, making them highly vulnerable to water shortages and temperature constraints. Cooling water withdrawals can place significant stress on local water resources, while thermal discharges may raise receiving water temperatures and disrupt aquatic ecosystems. Additionally, cooling system blowdown wastewater often contains elevated concentrations of salts, scaling compounds, anti-fouling chemicals, and trace metals. As climate variability increases the frequency of droughts and heatwaves, the reliability of cooling water supplies has become a critical operational risk for energy infrastructure.

Water management challenges also extend to renewable energy systems. Bioenergy production generates wastewater rich in organic matter, nutrients, and fermentation by-products that require careful treatment to avoid eutrophication and odor issues (Olatunde-Thorpe *et al*., 2020; Aifuwa *et al*., 2020). Geothermal energy operations produce saline brines containing dissolved minerals, metals, and gases that can cause scaling and corrosion if not properly managed. Even solar and wind energy systems, though less water-intensive during operation, require water during manufacturing, panel cleaning, and equipment maintenance. These diverse water demands highlight the need for integrated water management strategies across the entire energy value chain.

Wastewater reuse has emerged as a strategic response to water scarcity and sustainability pressures in the energy sector. Reusing treated produced water for hydraulic fracturing, cooling, or enhanced oil recovery can reduce freshwater withdrawals and disposal volumes. Similarly, power plants increasingly seek to recycle cooling tower blowdown or use non-traditional water sources such as municipal wastewater. However, achieving reliable reuse requires consistent treatment performance, protection of equipment from fouling and corrosion, and compliance with regulatory standards. The high variability and contaminant load of energy-sector wastewater often make reuse technically challenging and economically uncertain.

Overlaying these technical challenges are growing regulatory pressures and sustainability targets. Environmental regulations governing water withdrawals, effluent discharge quality, and chemical usage have become more stringent in many jurisdictions. Energy companies are also subject to corporate sustainability commitments, investor expectations, and reporting frameworks that emphasize water stewardship, pollution reduction, and climate resilience. Failure to address water-related risks can result in operational disruptions, regulatory penalties, and reputational damage. Conversely, effective water management can enhance social license to operate, reduce costs, and support long-term energy security.

Water management challenges in the energy sector are driven by the large volumes of contaminated water generated, the complexity of pollutant mixtures, the high demand for cooling and process water, and increasing regulatory and sustainability expectations. Addressing these challenges requires treatment technologies and management strategies that are robust, adaptable, and cost-effective. These constraints provide a strong rationale for exploring alternative and complementary approaches such as low-cost adsorption technologies that can support sustainable water management and enable safer reuse across diverse energy systems (Osabuohien, 2019; Frempong *et al*., 2020).

2.2. Fundamentals of Adsorption for Water Treatment

Adsorption is a widely applied physicochemical process in water treatment, valued for its simplicity, versatility, and effectiveness in removing a broad range of contaminants. In energy-sector and industrial water management, adsorption plays a critical role in treating produced water, cooling tower effluents, and wastewater streams containing hydrocarbons, heavy metals, salts, and emerging pollutants. Understanding the fundamental mechanisms, performance metrics, system configurations, and cost drivers is essential for designing efficient and sustainable adsorption-based treatment systems.

Adsorption mechanisms are commonly classified into physical adsorption, chemical adsorption, and ion exchange. Physical adsorption (physisorption) is governed by weak intermolecular forces such as van der Waals interactions. It is typically reversible, occurs rapidly, and does not involve significant changes in the electronic structure of the adsorbate or adsorbent. This mechanism is dominant in porous materials such as activated carbon and biochar, where large surface areas facilitate contaminant uptake. Chemical adsorption (chemisorption), in contrast, involves the formation of stronger chemical bonds between adsorbate molecules and active sites on the adsorbent surface (Odejobi *et al*., 2020; Ahmed *et al*., 2020). Chemisorption is usually more selective and stable but may be less reversible, affecting regeneration efficiency. Ion exchange represents a specialized adsorption mechanism in which ions in solution are exchanged with counter-ions bound to the adsorbent surface, as observed in zeolites, modified clays, and ion-exchange resins. This mechanism is particularly effective for removing dissolved metals, ammonium, and certain inorganic contaminants.

Evaluating adsorption performance requires several key metrics, including adsorption capacity, selectivity, kinetics, and regeneration potential. Adsorption capacity refers to the maximum amount of contaminant that an adsorbent can retain per unit mass, typically expressed in milligrams per gram. High capacity is desirable for minimizing material requirements and reducing system size. Selectivity describes the preferential adsorption of specific contaminants in the presence of competing species, a critical factor in complex water matrices such as produced water. Adsorption kinetics indicate the rate at which contaminants are removed, influencing contact time, reactor design, and overall treatment efficiency. Rapid kinetics are advantageous for high-throughput applications. Regeneration potential assesses the ability of an adsorbent to be reused after contaminant removal, often through thermal, chemical, or solvent-based processes. Effective regeneration extends adsorbent lifespan, reduces waste generation, and significantly lowers operational costs.

Adsorption systems can be broadly categorized into batch and continuous configurations. Batch adsorption systems involve mixing a fixed quantity of adsorbent with contaminated water for a defined period, followed by separation of the spent material. These systems are simple, flexible, and well suited for laboratory studies, pilot testing, or low-volume applications. However, they are generally less efficient for large-scale or continuous operations. Continuous adsorption systems, such as fixed-bed or packed-column reactors, allow water to flow through a stationary adsorbent bed. These systems are more suitable for industrial-scale deployment, offering consistent effluent quality and better process control. Design considerations for continuous systems include breakthrough behavior, pressure drop, and bed regeneration or replacement strategies.

Cost considerations are central to the feasibility of adsorption-based water treatment. Major cost drivers include adsorbent material production or procurement, system infrastructure, energy requirements, regeneration processes, and waste handling. Low-cost adsorption technologies increasingly rely on waste-derived or naturally abundant materials, such as agricultural residues, industrial by-products, and local minerals, to reduce raw material expenses (Nwafor *et al*., 2020; Sanusi *et al*., 2020). Operational costs are influenced by adsorption efficiency, regeneration frequency, and system maintenance. Transportation and disposal of spent adsorbents can also contribute significantly to lifecycle costs, particularly in remote energy-sector operations.

Adsorption fundamentals underpin the effective design and deployment of water treatment systems across diverse applications. By understanding adsorption mechanisms, optimizing performance metrics, selecting appropriate system configurations, and addressing cost drivers, adsorption-based technologies can deliver reliable, scalable, and economically viable solutions for sustainable water management.

2.3. Low-Cost Adsorbent Materials

The development and deployment of low-cost adsorbent materials have become central to advancing adsorption-based water treatment in the energy sector. Given the large volumes and complex composition of energy-related wastewaters, commercially manufactured adsorbents are often prohibitively expensive for full-scale application. Consequently, increasing research attention has focused on alternative materials derived from agricultural residues, industrial by-products, and naturally occurring minerals. These materials offer economic and environmental advantages while supporting resource efficiency and waste valorization.

Agricultural and biomass-derived adsorbents represent one of the most widely studied classes of low-cost materials due to their abundance, renewability, and low acquisition cost. Biochar and activated carbon produced from agro-waste such as rice husks, coconut shells, palm kernel shells, corn cobs, and sawdust have demonstrated significant potential for removing hydrocarbons, heavy metals, dyes, and organic contaminants from water. Biochar is typically produced through pyrolysis under limited oxygen conditions, resulting in a porous carbon-rich structure with surface functional groups that facilitate adsorption. Although biochar generally exhibits lower adsorption capacity than commercially activated carbon, chemical or physical activation can substantially enhance its surface area and reactivity while maintaining cost advantages (Oguntegbe *et al*., 2019; Michael and Ogunsola, 2019).

Lignocellulosic residues and nutshell-based materials have also attracted attention as sorbents for energy-sector wastewater. Materials such as peanut shells, walnut shells, banana peels, and sugarcane bagasse contain cellulose, hemicellulose, and lignin, which provide functional groups capable of binding metal ions and organic compounds. These materials can be used directly or modified through treatments such as acid washing, impregnation with metal oxides, or carbonization to improve adsorption performance. Their low density and availability in agricultural regions make them particularly attractive for decentralized treatment systems near energy operations. However, challenges remain related to mechanical stability, biodegradability, and performance under high-temperature or high-salinity conditions typical of oil and gas wastewaters.

Performance and scalability considerations are critical when evaluating biomass-derived adsorbents. While laboratory studies frequently report high removal efficiencies, translating these results to field-scale applications requires consistent feedstock quality, standardized production methods, and effective regeneration strategies. Variability in raw biomass composition can lead to fluctuations in adsorption performance, and repeated regeneration cycles may degrade material structure. Addressing these challenges is essential to enable reliable, large-scale deployment in energy-sector water management.

Industrial and mining by-products offer another promising category of low-cost adsorbents, particularly in regions with significant industrial activity. Materials such as fly ash from coal-fired power plants, red mud from aluminum production, metallurgical slag, and waste-derived clays contain metal oxides and aluminosilicate phases that can effectively adsorb heavy metals, phosphates, and certain organic compounds (Filani *et al*., 2019; Ahmed *et al*., 2019). Utilizing these materials for water treatment provides a dual benefit by reducing waste disposal burdens while lowering the cost of adsorption systems.

Fly ash has been widely investigated due to its fine particle size, large surface area, and affinity for metal ions. Similarly, red mud is rich in iron and aluminum oxides, which contribute to strong adsorption of arsenic, chromium, and other toxic metals. Slag-based materials have shown potential for neutralizing acidic wastewaters and immobilizing contaminants through both adsorption and precipitation mechanisms. These properties make industrial by-products particularly relevant for treating mining effluents and produced water with elevated metal concentrations.

Despite their advantages, environmental safety and leaching risks remain key concerns. Some industrial by-products may contain hazardous constituents that could leach into treated water under certain conditions, undermining environmental protection goals. Comprehensive characterization, stabilization, and regulatory oversight are therefore necessary before large-scale application. Surface modification and encapsulation techniques have been explored to minimize leaching while enhancing adsorption performance.

The use of industrial by-products as adsorbents aligns strongly with circular economy principles. By converting waste materials into valuable treatment media, energy operators can reduce raw material consumption, lower treatment costs, and improve overall resource efficiency. Integrating these materials into energy-sector water management strategies supports sustainability objectives and contributes to waste-to-resource innovation.

Naturally occurring minerals such as zeolites, bentonite, laterite, and iron-rich soils have long been used in water treatment due to their availability, chemical stability, and ion-exchange properties. Zeolites, in particular, exhibit high cation-exchange capacity and porous structures that make them effective for removing ammonium, heavy metals, and certain radionuclides (Dako *et al*., 2019; Bayeroju *et al*., 2019). Bentonite clays offer high surface area and swelling properties that enhance adsorption of organic compounds and metals. Laterite and iron-rich soils are abundant in many developing regions and are effective in binding arsenic and other oxyanions.

Surface modification has been widely employed to enhance the adsorption capacity and selectivity of natural minerals. Techniques such as acid activation, impregnation with metal oxides, and organic functionalization can significantly improve contaminant uptake while maintaining low material costs. Modified minerals can be tailored to target specific contaminants prevalent in energy-sector wastewaters, improving treatment efficiency and adaptability.

The suitability of mineral-based adsorbents for high-salinity energy wastewaters is a critical consideration. Many natural minerals demonstrate good structural stability under saline conditions, making them particularly attractive for produced water treatment. However, high ionic strength can reduce adsorption efficiency due to competition between target contaminants and background ions. Ongoing research focuses on optimizing mineral modification strategies to maintain performance in such challenging environments.

Overall, low-cost adsorbent materials derived from biomass, industrial by-products, and natural minerals offer viable pathways for cost-effective and sustainable water treatment in the energy sector. Continued innovation in material processing, modification, and scale-up is essential to fully realize their potential in real-world applications.

2.4. Emerging Advances in Adsorption Technologies

Adsorption technologies continue to evolve as critical tools for addressing complex water and wastewater treatment challenges across industrial, energy, and environmental sectors. Traditional adsorbents such as activated carbon and natural clays have demonstrated effectiveness for decades; however, their limitations in selectivity, regeneration efficiency, and cost have driven the development of advanced adsorption materials (Umoren *et al*., 2019; Akinrinoye *et al*., 2019). Emerging advances increasingly focus on nanoscale engineering, hybrid material synthesis, and data-driven optimization to enhance performance while maintaining economic and environmental sustainability. Among these innovations, nanostructured and composite adsorbents, functionalized biochars, magnetic materials, and artificial intelligence (AI)–guided material design represent major frontiers in adsorption science.

Nanostructured and composite adsorbents have gained significant attention due to their high surface area, tunable pore structures, and enhanced surface reactivity. Nanomaterials such as carbon nanotubes, graphene derivatives, metal–organic frameworks (MOFs), and layered double hydroxides offer exceptional adsorption capacities for heavy metals, organic pollutants, and emerging contaminants. When integrated into composite structures, these materials overcome individual limitations such as agglomeration, mechanical fragility, or poor water stability. For example, polymer–nanoparticle composites and MOF–carbon hybrids combine structural robustness with high adsorption efficiency. The ability to tailor surface chemistry at the nanoscale allows for selective binding of target contaminants, improving treatment efficiency in complex, multi-contaminant water matrices.

Functionalized biochars and hybrid materials represent a parallel advancement aimed at improving sustainability and cost-effectiveness. Biochar, derived from agricultural residues, forestry waste, or other biomass, is inherently porous and carbon-rich, making it a promising low-cost adsorbent. Recent advances involve chemical and physical functionalization strategies, including acid or base activation, metal impregnation, and surface grafting with oxygen-, nitrogen-, or sulfur-containing functional groups. These modifications significantly enhance affinity for heavy metals, nutrients, and polar organic compounds. Hybrid biochar materials, such as biochar–metal oxide or biochar–polymer composites, further improve adsorption performance while retaining environmental benefits. By valorizing waste biomass, functionalized biochars contribute to circular economy principles and reduce the overall environmental footprint of water treatment technologies.

Magnetic adsorbents constitute another important innovation, addressing operational challenges related to solid–liquid separation. Conventional adsorption processes often require energy-intensive filtration or sedimentation steps, which increase operational costs. Magnetic adsorbents, typically synthesized by embedding iron oxide nanoparticles within carbon, polymeric, or inorganic matrices, enable rapid and efficient separation using external magnetic fields (Awe, 2017; Akpan *et al*., 2017). This property facilitates easy recovery, regeneration, and reuse of adsorbents without complex infrastructure. Magnetic biochars and magnetic nanocomposites have demonstrated high adsorption capacities for metals, dyes, and hydrocarbons, alongside excellent recyclability. Their application is particularly attractive in decentralized or resource-constrained settings, where simplicity and operational efficiency are critical.

Artificial intelligence–guided material design and optimization are emerging as transformative tools in adsorption research. Traditional material development relies heavily on trial-and-error experimentation, which is time-consuming and resource-intensive. AI and machine learning techniques enable the analysis of large datasets linking material properties, synthesis conditions, and adsorption performance. Predictive models can identify optimal pore structures, surface functional groups, and composite formulations for specific contaminants. Furthermore, AI-driven optimization supports the design of adsorption systems under real-world operating conditions, accounting for variables such as pH, temperature, and competing ions. By accelerating material discovery and improving performance predictability, AI enhances the scalability and industrial relevance of advanced adsorption technologies.

Emerging advances in adsorption technologies are reshaping water treatment strategies by integrating material science innovations with sustainability and digital intelligence. Nanostructured and composite adsorbents deliver high efficiency and selectivity, functionalized biochars offer low-cost and environmentally friendly alternatives, magnetic adsorbents improve operational practicality, and AI-guided design accelerates innovation and optimization. Together, these advances position adsorption as a versatile and future-ready solution for managing increasingly complex water quality challenges in energy, industrial, and environmental applications.

2.5. System Integration and Process Design

Effective deployment of adsorption technologies for water treatment depends not only on material performance but also on thoughtful system integration and process design. In complex energy-sector water streams, contaminants often occur as mixtures of suspended solids, dissolved organics, metals, salts, and microorganisms. As a result, adsorption is rarely used as a standalone solution; instead, it is most effective when integrated within multi-barrier treatment trains, coupled with complementary processes, and designed for modularity, regeneration, and waste minimization.

Adsorption plays a critical role within multi-barrier treatment trains by providing targeted removal of specific contaminants that are inadequately addressed by primary or secondary treatment steps. In typical energy-sector applications, adsorption is positioned downstream of physical pretreatment processes such as screening, sedimentation, or media filtration, which remove suspended solids and reduce fouling potential (Adebiyi *et al*., 2017; Efobi *et al*., 2017). Within the treatment train, adsorption acts as a polishing step, capturing dissolved hydrocarbons, trace metals, organic acids, and emerging contaminants. This layered approach enhances overall treatment reliability, improves effluent quality, and provides redundancy against process upsets. In circular water management systems, adsorption barriers are strategically placed to protect downstream reuse applications, such as reinjection, cooling, or process water recycling.

Coupling adsorption with membrane, oxidation, and biological processes further enhances system performance and flexibility. When integrated with membrane technologies such as ultrafiltration, nanofiltration, or reverse osmosis, adsorption can reduce organic loading and fouling propensity, thereby extending membrane lifespan and lowering cleaning frequency. In turn, membranes provide high-quality effluent that stabilizes adsorption performance by limiting particulate interference. Advanced oxidation processes, including ozonation and photocatalysis, are often paired with adsorption to transform refractory organic compounds into more adsorbable or biodegradable intermediates. In hybrid adsorption–biological systems, adsorption buffers shock loads and toxic spikes, enabling biological reactors to operate under more stable conditions. Biological processes can also partially regenerate adsorbent surfaces through biodegradation of adsorbed organics, improving overall system efficiency.

Modular and decentralized system designs are particularly important for remote energy sites, such as offshore platforms, shale gas fields, and isolated power plants, where infrastructure, space, and skilled labor may be limited. Modular adsorption units are typically skid-mounted, standardized, and scalable, allowing rapid deployment and incremental capacity expansion. These systems support decentralized treatment strategies that reduce reliance on centralized facilities and long-distance water transport. For energy operations in resource-constrained regions, decentralized adsorption systems enhance operational resilience, enable compliance with local discharge regulations, and support on-site water reuse.

Regeneration, reuse, and waste minimization strategies are central to sustainable adsorption system design. Regeneration methods, including thermal desorption, chemical washing, and solvent extraction, are selected based on adsorbent type, contaminant characteristics, and energy availability. Efficient regeneration restores adsorption capacity while minimizing material degradation. Reuse strategies may involve cascading adsorbents through multiple treatment stages, where partially spent materials are reassigned to less demanding applications (Farounbi *et al*., 2018; Akinola *et al*., 2018). Waste minimization is further achieved by converting spent adsorbents into secondary products, such as fuel additives, construction materials, or soil amendments, when environmentally safe. Lifecycle-based design approaches increasingly emphasize closed-loop material flows, aligning adsorption systems with circular economy principles.

Overall, system integration and process design determine the practical success of adsorption-based water treatment in the energy sector. By embedding adsorption within multi-barrier treatment trains, coupling it with complementary technologies, adopting modular and decentralized configurations, and prioritizing regeneration and waste minimization, adsorption systems can deliver robust, cost-effective, and sustainable water management solutions across diverse operational contexts.

2.6. Economic and Environmental Performance

The economic and environmental performance of water treatment technologies is a critical determinant of their adoption in the energy sector, where large wastewater volumes, remote operating conditions, and cost-sensitive operations prevail. Low-cost adsorption technologies have gained increasing attention because they offer the potential to balance treatment effectiveness with reduced capital and operational expenditures, while also supporting sustainability objectives. A systematic evaluation of their cost-benefit profile, life cycle impacts, energy requirements, and inherent trade-offs is therefore essential for informed decision-making (Blainey and Preston, 2019; Fauzi *et al*., 2019).

From a cost-benefit perspective, low-cost adsorption systems often compare favorably with conventional water treatment methods such as membrane filtration, advanced oxidation processes, and thermal desalination. Conventional technologies typically require high upfront capital investment, complex infrastructure, skilled operation, and significant energy input. Membrane-based systems, for example, are prone to fouling and require frequent replacement and chemical cleaning, increasing operational costs over time. In contrast, adsorption systems are relatively simple to design and operate, with lower capital requirements and flexible scalability. When low-cost adsorbents are sourced from agricultural residues, industrial by-products, or locally available minerals, material costs can be substantially reduced. Additionally, adsorption units can be deployed modularly, allowing incremental capacity expansion and minimizing financial risk. However, the economic viability of adsorption is strongly influenced by adsorbent lifetime, regeneration efficiency, and disposal costs, which must be carefully considered in comparative assessments.

Life cycle assessment (LCA) provides a comprehensive framework for evaluating the environmental performance of low-cost adsorbents across their entire life cycle, from raw material sourcing and processing to use, regeneration, and end-of-life disposal. Biomass-derived adsorbents often demonstrate favorable life cycle profiles due to their renewable nature and the avoidance of waste disposal impacts. Utilizing agricultural or industrial waste streams as adsorbent feedstocks can significantly reduce environmental burdens associated with raw material extraction and landfilling. Nevertheless, energy-intensive processing steps such as high-temperature pyrolysis or chemical activation can offset some of these benefits if not optimized. Similarly, mineral-based adsorbents typically exhibit low environmental impacts during use but may incur higher extraction and transportation footprints. LCA studies highlight the importance of localized sourcing, low-energy processing methods, and effective regeneration strategies in minimizing the overall environmental footprint of adsorption systems.

Energy consumption and associated carbon footprint are particularly important considerations in the energy sector, where treatment processes should not undermine broader decarbonization goals. Compared to pressure-driven membrane systems or thermal treatment processes, adsorption generally requires lower energy input, as it often relies on gravity-driven flow and ambient operating conditions. This characteristic makes adsorption especially attractive for off-grid or remote energy operations. However, energy consumption can increase during adsorbent production, regeneration, and handling. Thermal regeneration of spent adsorbents, for instance, can be energy-intensive and contribute to greenhouse gas emissions if powered by fossil fuels. Alternative regeneration approaches, such as chemical desorption or low-temperature treatment, can reduce energy demand but may introduce additional chemical usage (Chen *et al*., 2019; Wu *et al*., 2019). The overall carbon footprint of adsorption systems therefore depends on a balance between low-energy operation and upstream material processing impacts.

Despite their advantages, low-cost adsorption technologies involve trade-offs between performance and affordability that must be carefully managed. While many low-cost adsorbents demonstrate high removal efficiencies in laboratory settings, their performance may decline under real-world conditions characterized by high salinity, competing ions, and variable contaminant loads. Enhancing adsorption capacity through surface modification or activation often increases material cost and environmental impact, potentially eroding economic benefits. Conversely, using minimally processed materials may reduce costs but limit treatment effectiveness and consistency. These trade-offs underscore the need for context-specific optimization, where adsorbent selection and system design are tailored to the target contaminants, water quality requirements, and operational constraints of a given energy facility.

The economic and environmental performance of low-cost adsorption technologies positions them as a compelling alternative or complement to conventional water treatment methods in the energy sector. Their favorable cost structure, potential for low life cycle impacts, and relatively low energy requirements support sustainable water management goals. However, realizing these benefits at scale requires careful consideration of life cycle trade-offs, regeneration strategies, and performance limitations. Integrating techno-economic analysis with environmental assessment will be essential to guide the effective deployment of adsorption-based solutions that balance affordability, efficiency, and sustainability in energy-sector water management.

2.7. Field Applications and Case Studies

The transition of adsorption technologies from laboratory-scale research to field deployment has been critical in demonstrating their practical viability for industrial water management. Real-world applications across oil and gas operations, power generation facilities, and resource recovery systems illustrate the adaptability of adsorption-based processes under complex operating conditions. Field applications and case studies provide valuable insights into performance reliability, economic feasibility, and operational challenges, thereby informing the broader adoption of adsorption technologies in industrial water treatment and reuse.

In oil and gas fields, adsorption has been increasingly applied for the treatment of produced water, which represents the largest waste stream by volume in hydrocarbon extraction. Produced water contains high salinity, dispersed and dissolved hydrocarbons, heavy metals, and chemical additives from drilling and production processes. Field-scale adsorption systems, often integrated as polishing units following primary separation and membrane treatment, have demonstrated effectiveness in removing residual organics, trace metals, and dissolved aromatic compounds (Liu *et al*., 2020; Park e al., 2020). Modified activated carbons, organoclay adsorbents, and functionalized biochars have been deployed to meet discharge or reuse standards. Case studies from onshore and offshore fields show that adsorption units can stabilize effluent quality despite fluctuations in flow rate and contaminant composition, enabling reuse for enhanced oil recovery, drilling operations, or safe environmental discharge.

Adsorption technologies have also found practical application in power plant wastewater treatment, particularly for polishing and reuse. Thermal power plants generate wastewater streams from cooling systems, boiler blowdown, and flue gas desulfurization units, often containing heavy metals, nutrients, and trace organics. In several commercial deployments, adsorption columns using activated carbon, metal oxide-based adsorbents, or composite materials have been employed as tertiary treatment steps. These systems effectively reduce mercury, selenium, arsenic, and residual organic compounds to meet stringent regulatory limits. Field experience demonstrates that adsorption-based polishing improves the reliability of water reuse for cooling or process applications, reduces freshwater intake, and supports compliance with increasingly strict environmental regulations.

Beyond contaminant removal, adsorption has enabled resource recovery from industrial wastewater streams, transforming waste management into a value-generating process. In mining, energy, and agricultural sectors, adsorption-based systems have been used to recover metals such as lithium, cobalt, and rare earth elements from dilute aqueous streams. Similarly, nutrient recovery, particularly phosphate and ammonium, has been demonstrated using tailored adsorbents such as metal-doped biochars and ion-exchange materials. Pilot-scale studies show that recovered resources can be regenerated and reused, contributing to circular economy strategies and reducing dependency on virgin raw materials. These applications highlight the dual role of adsorption as both a treatment and resource recovery technology.

Lessons learned from pilot-scale and commercial deployments emphasize the importance of system integration, material selection, and long-term performance evaluation. One key insight is that adsorption performs best when positioned within a treatment train, complementing physical separation, biological treatment, or membrane processes. Field studies also reveal that adsorbent fouling, competitive adsorption, and regeneration efficiency significantly influence lifecycle costs. Pilot-scale testing under site-specific conditions has proven essential for optimizing operating parameters and predicting full-scale performance. Additionally, economic analyses from commercial deployments indicate that locally sourced or regenerable adsorbents substantially improve cost-effectiveness, particularly in resource-constrained or remote locations (Banerjee *et al*., 2018; Kua *et al*., 2019).

Field applications and case studies demonstrate that adsorption technologies are mature, flexible, and capable of addressing diverse industrial water challenges. Successful deployment in produced water treatment, power plant wastewater polishing, and resource recovery underscores their operational robustness and strategic value. Lessons from real-world implementations highlight the need for system-level design, long-term monitoring, and adaptive management to ensure sustainable and scalable adsorption-based solutions.

2.8. Policy, Regulation, and Adoption Barriers

The large-scale adoption of low-cost adsorption technologies for water management in the energy sector is strongly influenced by policy frameworks, regulatory acceptance, and institutional capacity. While technological advances have demonstrated promising performance, regulatory uncertainty and governance challenges often constrain deployment, particularly when novel or waste-derived adsorbents are involved. Understanding these barriers and opportunities is essential for translating laboratory and pilot-scale innovations into operational systems.

Regulatory acceptance of waste-derived adsorbents remains a central challenge. Adsorbents produced from agricultural residues, industrial by-products, or municipal wastes raise concerns regarding consistency, trace contaminant leaching, and long-term environmental impacts. Regulatory agencies often require extensive characterization of material composition, stability, and toxicity before approving such materials for water treatment applications. In many jurisdictions, existing regulations are designed around conventional adsorbents, such as activated carbon, and lack clear pathways for certifying alternative materials (McCubbin *et al*., 2019; Syafiuddin *et al*., 2020). This regulatory gap can delay approval processes and discourage operators from adopting low-cost adsorbents despite their potential economic and environmental benefits. Harmonized testing protocols and performance-based certification standards could significantly improve regulatory confidence and market acceptance.

Quality standards for treated water reuse also shape the feasibility of adsorption-based systems. Energy-sector water reuse applications—such as reinjection, cooling, steam generation, and process reuse—are governed by stringent limits on dissolved solids, hydrocarbons, metals, and microbial content. Adsorption technologies are often used as polishing steps to meet these standards; however, variability in influent water quality can make consistent compliance challenging. Regulatory frameworks that recognize risk-based and fit-for-purpose water quality criteria, rather than uniform discharge standards, can better accommodate adsorption systems within integrated treatment trains. Clear guidance on monitoring, reporting, and compliance verification is equally important for operator confidence and regulatory oversight.

Institutional and operational challenges further hinder adoption. Energy-sector operators may lack familiarity with adsorption technologies beyond conventional activated carbon systems, leading to conservative decision-making. Limited technical capacity for system design, operation, and regeneration, particularly in remote locations, increases perceived operational risk. Additionally, fragmented governance structures—where water, energy, and environmental regulations are managed by separate agencies—can complicate permitting and delay implementation. Financial constraints, especially for smaller operators, also limit investment in pilot testing and system optimization.

Despite these barriers, significant opportunities exist in developing and energy-intensive regions. Many such regions face acute water scarcity, weak centralized infrastructure, and high costs associated with freshwater procurement and wastewater disposal. Low-cost adsorption technologies, particularly those utilizing locally available waste materials, offer a pathway to context-appropriate and scalable solutions. Supportive policies that encourage local material utilization, technology transfer, and public–private partnerships can accelerate adoption. Capacity-building programs, demonstration projects, and inclusion of adsorption technologies in national water and energy strategies can further reduce institutional resistance (Ullah and Rasul, 2018; Ferrero *et al*., 2019).

Policy and regulatory environments play a decisive role in shaping the adoption of adsorption-based water treatment technologies. Addressing regulatory uncertainty, aligning water quality standards with reuse objectives, strengthening institutional capacity, and leveraging regional opportunities are critical steps toward realizing the full potential of low-cost adsorption solutions in sustainable energy-sector water management.

2.9. Research Gaps and Future Directions

Despite significant progress in the development of low-cost adsorption technologies for energy-sector water management, several critical research gaps remain that must be addressed to enable widespread adoption, reliable performance, and integration into sustainable water-energy systems. Current studies largely focus on laboratory-scale evaluations and short-term batch experiments, leaving unresolved questions about long-term stability, multi-contaminant efficacy, and operational resilience under real-world conditions. Addressing these gaps is essential for transitioning adsorption technologies from promising prototypes to practical, field-ready solutions.

One of the foremost research priorities is understanding the long-term performance and fouling resistance of adsorbents. Energy-sector wastewaters—particularly produced water, flowback fluids, and cooling water—contain high concentrations of salts, oils, suspended solids, and organic matter that can rapidly foul adsorbent surfaces, reduce adsorption capacity, and limit regeneration cycles. While some studies report promising initial removal efficiencies, the durability of adsorbents under repeated use, high ionic strength, and temperature fluctuations remains poorly quantified. Investigating mechanisms of fouling, adsorption site deactivation, and strategies for enhancing material resilience—such as surface modification, hybridization with other treatment technologies, or controlled regeneration protocols is critical for ensuring reliable long-term operation.

Another key gap lies in the treatment of multi-contaminant and variable water matrices. Most research has been conducted using simplified model solutions containing one or two target pollutants, which do not reflect the complex composition of energy-sector wastewaters. Produced water, for example, may simultaneously contain hydrocarbons, heavy metals, salts, radionuclides, and chemical additives, with concentrations varying over time and across extraction sites. The competitive adsorption of multiple contaminants, the influence of pH and ionic strength, and potential synergistic or antagonistic interactions remain insufficiently understood (Martínez-Costa *et al*., 2018; Pincus *et al*., 2020). Systematic studies that evaluate adsorbent performance across realistic, heterogeneous water matrices are necessary to design robust, adaptable treatment strategies.

Scale-up and field validation represent additional priorities. Laboratory findings often fail to translate directly to operational contexts due to differences in flow regimes, contact times, hydraulic loading, and site-specific constraints. Pilot-scale studies, demonstration projects, and long-term monitoring under operational conditions are urgently needed to assess process reliability, regeneration feasibility, and maintenance requirements. These efforts will also provide critical economic and environmental performance data that can inform decision-making and justify investment in larger-scale deployment.

Finally, aligning low-cost adsorption technologies with circular water and energy systems is a significant future direction. Integrating adsorbent use with water reuse, resource recovery, and waste valorization can create closed-loop systems that reduce freshwater consumption, minimize discharge volumes, and recover valuable constituents such as metals or nutrients. Similarly, sourcing adsorbents from locally available biomass or industrial by-products strengthens the circularity of both water and energy systems. Future research should explore strategies for material lifecycle optimization, energy-efficient regeneration, and hybrid systems that combine adsorption with other sustainable water treatment processes.

Addressing these research gaps long-term performance and fouling resistance, multi-contaminant treatment under variable water matrices, scale-up and field validation, and integration within circular water-energy systems is essential for advancing low-cost adsorption technologies from laboratory studies to practical, sustainable solutions. Targeted investigations in these areas will enhance treatment reliability, promote environmental and economic sustainability, and support the transition toward resilient, circular water management practices in the energy sector (Zabaniotou, 2018; Guerra-Rodríguez *et al*., 2020).

3. Conclusion

Advances in adsorption technologies have significantly expanded the toolkit available for sustainable water management in energy and industrial sectors. Recent innovations including nanostructured and composite adsorbents, functionalized biochars, magnetic materials, and AI-guided design have enhanced contaminant removal efficiency, selectivity, and operational flexibility. These developments address critical limitations of traditional adsorption methods, such as low capacity, poor regeneration, and limited adaptability to complex water matrices. Field applications in produced water treatment, power plant wastewater polishing, and resource recovery have demonstrated the practical relevance of these technologies, confirming their ability to meet stringent discharge standards, enable water reuse, and recover valuable metals and nutrients. Case studies underscore the operational robustness of adsorption systems when integrated into multi-stage treatment trains and highlight the importance of pilot-scale validation for optimizing material selection and process parameters.

The strategic importance of low-cost and high-performance adsorption is particularly pronounced in the energy sector, where water scarcity, regulatory pressures, and sustainability targets intersect. Low-cost adsorbents such as functionalized biochars and hybrid composites offer a practical route to circular water management, minimizing environmental impact while maximizing resource efficiency. By enabling effective water reuse and pollutant recovery, adsorption technologies contribute to operational resilience, reduce dependence on freshwater resources, and align with broader sustainability and climate mitigation objectives.

Looking forward, continued innovation in material science, coupled with AI-driven optimization, is expected to accelerate the development of next-generation adsorbents tailored to site-specific challenges. Wider deployment will benefit from integrated policy frameworks, incentives for circular water use, and standardization of performance metrics to support scale-up. Collaborative efforts between industry, researchers, and regulators will be essential for translating laboratory advances into reliable, cost-effective, and environmentally sustainable solutions. Overall, adsorption technologies are poised to play a pivotal role in sustainable energy water management, combining technological innovation with strategic, policy-aligned impact.

4. References

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