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Diatomite as a natural sorbent for water treatment: A modern review and prospects for application

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ABSTRACT

Diatomite is a naturally occurring siliceous sedimentary material characterized by high porosity, low density, developed pore architecture, and favorable adsorption properties, making it a promising low-cost sorbent for water and wastewater treatment applications. This review critically analyzes recent advances in the use of natural and modified diatomite for the removal of heavy metals, petroleum hydrocarbons, dyes, and emerging organic contaminants from aqueous systems. A systematic analysis of peer-reviewed literature indexed in Scopus and Web of Science was conducted, with emphasis on the physicochemical properties of diatomite, pollutant sorption mechanisms, and the influence of thermal and chemical activation methods on adsorption performance. The review demonstrates that the adsorption efficiency of natural diatomite is governed by its mineralogical composition, surface hydroxyl groups, pore accessibility, and environmental conditions such as pH, ionic strength, and temperature. Various modification approaches, including calcination, acid and alkaline activation, hydrothermal treatment, and surface functionalization, significantly improve the specific surface area, pore distribution, and density of active adsorption sites. Recent studies indicate that modified diatomite-based materials exhibit enhanced adsorption capacity and selectivity toward heavy metal ions, dyes, oils, and phenolic compounds compared with raw diatomite. Particular attention is given to thermo-chemical activation and composite materials incorporating magnetic phases, metal oxides, and biopolymers, which improve regeneration ability and practical applicability in real wastewater matrices. Despite the significant potential of activated diatomite, challenges remain regarding the heterogeneity of natural deposits, variability of experimental conditions, regeneration efficiency, and large-scale implementation. Overall, the review highlights diatomite as an environmentally sustainable and technologically versatile sorbent platform with considerable prospects for advanced water treatment technologies and circular environmental applications.

Keywords: Sorbent, Wastewater, Diatomite, Thermal modification, Water treatment.
Article type: Review Article.

INTRODUCTION

Pollution of natural and wastewater remains one of the key environmental threats, as water bodies simultaneously serve as recipients of industrial, municipal, and agricultural discharges and as media where pollutants accumulate and migrate through trophic chains. The most problematic groups of pollutants are heavy metal ions (due to their

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toxicity and bioaccumulation), persistent organic compounds, and a wide range of emerging contaminants (pharmaceuticals, PFAS, surfactants, etc.), which are detected at trace concentrations but can cause significant ecotoxicological effects. Recent reviews highlight the increasing anthropogenic pressure on aquatic ecosystems and the link between water pollution and risks to public health and ecosystem services, emphasizing the need to develop effective technologies for the removal of both priority and emerging classes of pollutants (Qasem *et al.* 2021; Lin *et al.* 2022; Kumar *et al.* 2022; Aziz *et al.* 2023; Kato & Kansha 2024; Oladimeji *et al.* 2024). Widely applied physicochemical and biological methods (coagulation/flocculation, chemical precipitation, activated sludge, membrane processes, etc.) provide acceptable treatment performance for certain parameters. However, they are often associated with high energy consumption and operational costs, generation of substantial volumes of sludge, sensitivity to toxic components and fluctuations in wastewater composition, as well as incomplete removal of persistent organic compounds and micropollutants. Consequently, there is increasing interest in technological schemes that reduce secondary waste streams and enhance the operational stability of treatment facilities when treating complex wastewater compositions.

Natural sorbents as an alternative. Sorption technologies are considered one of the most flexible platforms for tertiary and advanced water treatment due to their relatively simple equipment requirements, the possibility of selective removal of target pollutants, and their potential for integration into combined treatment schemes. In this context, research on natural and low-cost sorbents (biochar, zeolites, clays, etc.) is actively developing, as they can provide acceptable efficiency at a lower environmental and economic "entry threshold" compared to many high-tech methods. Recent reviews emphasize that the key trend is not merely the search for a natural sorbent, but its targeted modification to enhance sorption capacity, stability, and applicability to real water matrices. Among mineral natural materials, diatomite (diatomaceous earth) stands out due to its high porosity, well-developed specific surface area, and unique morphology associated with the siliceous shells of diatoms, which determine its filtration and sorption properties. Experimental studies and reviews demonstrate the applicability of natural diatomite for the removal of metal ions from aqueous solutions and wastewater under various conditions (pH, dosage, and contact time), as well as its potential for addressing organic pollutants and petroleum components when the surface is appropriately treated. Thus, diatomite is considered an accessible mineral base for the development of environmentally oriented sorbents. At the same time, natural diatomite often exhibits limited sorption capacity and/or selectivity, which necessitates activation and modification. The literature describes approaches such as thermal treatment (including calcination) and chemical activation (acidic/alkaline treatment, organic acids, etc.) aimed at modifying textural characteristics (specific surface area, pore distribution), removing impurities, forming/activating surface sites, and adjusting wettability (for petroleum sorption applications). An increasing body of research indicates that the choice of activation method should be aligned with the nature of the target pollutant, the characteristics of the water matrix, and the requirements for the environmental and resource efficiency of the technology.

MATERIALS AND METHODS

This review is based on a systematic analysis of peer-reviewed scientific literature indexed in the international databases Scopus and Web of Science (Core Collection), which are considered primary sources of high-quality publications in the fields of Environmental Science, Water Research, and related disciplines. These databases were selected due to their broad coverage of Q1–Q2 journals and strict indexing criteria, ensuring the representativeness and scientific reliability of the sources analyzed. The literature search was conducted using combinations of keywords and logical operators, including diatomite, activated diatomite, thermal activation, chemical modification, adsorption, water treatment, heavy metals, oil products, and organic pollutants. Search queries were designed to capture both fundamental studies focused on structure and sorption mechanisms, as well as applied research targeting the treatment of natural and wastewater. The initial dataset of publications was compiled without restrictions on pollutant type, allowing identification of the most frequently studied classes of compounds and the prevailing approaches to diatomite modification. In subsequent stages, selection was refined based on thematic relevance, with priority given to original research articles and review publications in journals. This multi-stage approach aligns with widely accepted guidelines for preparing review articles in environmental sciences.

Inclusion and exclusion criteria

The review included publications that met the following criteria:
diatomite was considered as the main subject of the study;

methods of thermal and/or chemical activation were described, or comparisons with natural diatomite were provided;
quantitative indicators of sorption efficiency with respect to water pollutants were reported.
Excluded were studies in which diatomite was used only as a minor component of composite materials without analysis of its individual role, as well as research lacking experimental or summary information relevant to water treatment applications. This approach aligns with the principles of transparency and reproducibility in reviews, as recommended in international practice.

The selected publications were analyzed using thematic classification and comparative analysis. The materials were systematized according to the following areas:
chemical and mineralogical composition of diatomite;
physicostructural characteristics and pore architecture;
mechanisms of pollutant sorption;
methods of thermal and chemical activation;
efficiency in treating natural and wastewater;
environmental and technological limitations of application.
Particular attention was paid to comparing results reported by different authors to identify common patterns, contradictions, and research gaps. In analyzing treatment efficiency, experimental conditions (pH, sorbent dosage, contact time, and water matrix composition) were taken into account, in accordance with recommendations for critical data review in environmental research.

I

Natural diatomite: Chemical composition and structural features

The chemical composition and physicostructural characteristics of diatomite are key factors determining its sorption properties and effectiveness in water treatment technologies. In line with the methodological approach of this review, the analysis of publications indexed in Scopus and Web of Science focused on studies that provided detailed information on the mineralogical composition, morphology, and pore structure of diatomite, as well as their relationship to the mechanisms of pollutant sorption.

Chemical and mineralogical composition

Diatomite is a biogenic sedimentary rock primarily formed from the siliceous shells of diatom algae, which extract silica from water to construct their cell walls. After the organisms die, their silica-containing frustules accumulate in marine and freshwater basins, forming deposits of diatomaceous earth (Westacott *et al.* 2021; Stefanou *et al.* 2022). According to numerous studies, the SiO_2 content in natural diatomite varies widely, typically ranging from 70 to 95%, depending on the formation conditions of the deposit and the degree of diagenetic transformation.
In addition to silica, diatomite contains impurities of aluminum, iron, calcium, and magnesium oxides, as well as alkali elements associated with inclusions of clay minerals, quartz, and carbonates. These impurity components play an important role in the formation of surface active sites and can significantly influence the sorption behavior of diatomite, particularly in interactions with heavy metal ions. Table 1 presents the chemical composition of diatomite from deposits in different countries. The mineralogical composition of diatomite, as highlighted in several studies, determines the acid–base properties of its surface and the presence of hydroxyl groups ≡Si–OH and ≡Al–OH, which participate in surface complexation and ion exchange processes (Crini *et al.* 2007; Awad *et al.* 2019). The chemical heterogeneity of natural diatomite is considered not only as a limitation but also as a potential advantage, broadening the range of possible sorption mechanisms. Impurity oxides of aluminum, iron, calcium, and magnesium have a significant impact on the surface properties of diatomite. In particular, the presence of Al_2O_3 and Fe_2O_3 promotes the formation of additional hydroxyl functional groups, enhancing the material's capacity for sorption of heavy metal cations through surface complexation mechanisms. At the same time, increased content of carbonate and clay impurities can both enhance the chemical activity of the surface and partially block micropores, affecting the specific surface area and effective sorption capacity. The ratio of silica to impurity mineral phases also influences the surface charge of diatomite and the value of its isoelectric point, which determines the efficiency of removing anionic and cationic pollutants from aqueous solutions across

different pH ranges. Overall, diatomites with high amorphous SiO_2 content, low cementation, and minimal amounts of dense clay impurities are characterized by more developed pore structures, higher specific surface areas, and correspondingly enhanced sorption properties.

Table 1. Chemical composition of diatomite from other deposits (wt.%).

Deposit	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	References
Utesai deposit, Aktobe region, Kazakhstan	68.8	12.48	2.08	0.63	0.32	Smirnov *et al.* 2023
Zhalpak deposits, Aktobe region, Kazakhstan	53.9	7.29	4.22	-	4.93	Sagimbayeva *et al.* 2021
Deposits in the Dai Lao Valley, Vietnam	52.90	22.90	5.32	-	0.43	Phong *et al.* 2012
Al Azraq, East Jordan	52.38	13.91	7.30	0.89	3.85	file:///C:/Users/Admin/Downloads/AJC-17-2-65.pdf
Seydiler (Afyon) Türkiye	91.64	0.54	0.16	0.04	0.73	Ersoy *et al.* 2022
Tyrkaz, Sarayköy district, Denizli Province, Türkiye	81.50	3.1	1.21	0.14	0.21	
Linjiang, China	78.37	7.15	4.45	-	0.46	Ren *et al.* 2014
Deposits						
Vishkautsi village, Orhei district, Moldova	59.7	1.31	1.28	-	12.8	Datsko *et al.* 2011
Sig, Algeria	91.60	4.94	1.95	0.35	0.02	Khaldi *et al.* 2018
Ceará-Mirim, Rio Grande do Norte, Brazil: White diatomaceous earth;	88.1	4.07	0.25	0.18	0.39	da Silva *et al.* 2009
Cream diatomaceous earth	82.35	8.71	1.49	0.59	0.09	
Horseshoe Basin in northern Nevada	92.7	3.23	1.73	0.13	0.87	Lenz *et al.* 2022
Irbitskoye deposit, Sverdlovsk region, Russia	78.02	7.40	3.61	0.56	0.28	Smirnov *et al.* 2016
Borovani Ledenice, Třeboň Basin in the South Bohemian Region, Czech Republic						file:///C:/Users/Admin/Downloads/Development_of_the_diatomite_produc.pdf

Physical structure and textural characteristics

The physical structure of diatomite is characterized by high porosity and a pronounced hierarchical organization of the pore space, formed due to the preservation of the morphology of diatom frustules. The pore system of diatomite includes macropores, mesopores, and micropores, which create a complex network of channels and cavities, resulting in low bulk density and high material permeability. The specific surface area of natural diatomite, according to BET analysis, generally ranges from 10 to 60 $m^2\ g^{-1}$, and the total pore volume can reach 0.3–1.5 $cm^3\ g^{-1}$. Significant variability in these values is attributed both to geological factors and to sample preparation methods used by different authors (Gondek *et al.* 2024; Brahimi *et al.* 2025). In the methodological context of this review, this aspect was taken into account in the comparative analysis of sorption characteristics reported in various studies. The well-developed pore structure and high specific surface area contribute to good filtration properties of diatomite and provide favorable conditions for the adsorption of pollutants of various types. However, several authors note that the accessibility of pores and active sites in natural diatomite may be limited by the presence of impurities and organic residues, which reduces its sorption efficiency and justifies the need for activation and modification of the material (Fathy *et al.* 2022; Gondek *et al.* 2023). According to Reka *et al.* (2021), the studied diatomite, in terms of its physicomechanical properties, is a very light and soft biogenic sedimentary rock of white color, characterized by fine- to ultrafine-grained structure and high porosity (61–63 %). The material exhibits pronounced fragility, resembling a shell-like structure. The bulk density of the diatomite is 0.51–0.55 g cm^{-3}, its true density in the natural state is approximately 2.25 g cm^{-3}, and its compressive strength reaches 7.67 MPa. The morphology of diatom frustules represents a key structural factor that determines the unique physicochemical properties of diatomite. Diatom frustules are silicified cell walls with a highly organized porous architecture, formed at both nano- and microscale levels. This morphology provides not only a high specific surface area but also a well-developed pore system of various sizes and shapes, creating favorable conditions for the sorption of both heavy metal ions and organic molecules. According to studies based on electron microscopy, the morphology of diatom frustules varies from simple cylindrical shapes to complex reticulated and radial structures, which are preserved upon transformation into sedimentary diatomite deposits. These forms generate a network of micro- and mesopores, increasing the accessibility of active surface sites and facilitating

efficient capture of contaminants from solutions.Investigations using scanning and transmission electron microscopy (SEM/TEM) demonstrate that diatom frustules possess a regular ornamental structure with pores, tubes, and pore-like elements resembling mesh and cellular geometries, which directly correlates with the sorption capacity of the material. Such morphological features provide not only a high specific surface area but also ease of filtration of aqueous solutions, which is particularly important for wastewater treatment applications. It is noteworthy that the frustule morphology remains relatively stable under moderate thermal and chemical treatments, allowing targeted activation of the structure without losing the primary topological features responsible for sorption activity. It has been established that even after modifications aimed at increasing the specific surface area and altering the acid–base properties of the surface, the frustule topology retains its highly organized nature, thereby supporting sorption mechanisms, including pore diffusion and interactions with surface functional groups.

Sorption mechanisms of pollutants on natural diatomite

Within the framework of this review, the sorption mechanisms on natural diatomite are considered as a combination of physical adsorption, electrostatic interactions, ion exchange, and surface complexation, with the contribution of each mechanism determined by the nature of the contaminant and the parameters of the aqueous medium (pH, ionic strength, temperature, and presence of natural organic matter). Experimental studies on the sorption of metals and dyes on diatomite have shown that changes in the solution chemistry can shift the dominant mechanism—from outer-sphere interactions/ion exchange at low pH to inner-sphere complexation under neutral and alkaline conditions. Physical adsorption on natural diatomite is governed by the combination of its developed porous structure and high accessible surface area, where the retention of molecules and ions occurs via van der Waals forces, hydrogen bonding, and multipoint anchoring within micro- and mesopores. For certain organic pollutants and dyes, physical adsorption plays a significant (and sometimes primary) role, determining the initial rate of the process and the formation of the adsorbed layer. It has been shown that changes in the thermal state of the surface (including the removal of some functional groups) affect dye sorption, indirectly confirming the contribution of weak intermolecular interactions and the role of surface sites in physically adsorptive retention.

The electrostatic contribution is related to the surface charge of diatomite, mainly formed by silanol groups (≡Si–OH), which can be protonated or deprotonated depending on the pH, thereby altering the ζ-potential and the nature of attraction/repulsion toward cationic and anionic forms of contaminants. For cationic dyes, an increase in pH generally enhances adsorption due to the increase of negative surface charge, whereas at low pH, competition with H^+ ions for active sites may weaken attraction. The significance of surface OH and Si–OH groups for dye retention on diatomite has been experimentally confirmed by changes in spectral characteristics and adsorption response following surface modification or thermal treatment. The ion exchange mechanism occurs during the sorption of metal cations (Pb^{2+}, Cd^{2+}, Cu^{2+}, etc.) and involves exchange with compensating ions in the near-surface layer or at defect and impurity sites (including alumino- and iron-containing components and adsorbed alkali cations). It has been demonstrated that at low pH and under conditions where sorption depends on ionic strength, the contribution of outer-sphere interactions and/or ion exchange increases, while competing electrolytes and "background" ions can significantly alter metal uptake. This dependence is well illustrated by Pb(II): at pH < 7, sorption is sensitive to ionic strength, consistent with outer-sphere binding and ion exchange contributions. Surface complexation (primarily inner-sphere) is considered a key mechanism for the stable immobilization of heavy metals on diatomite under neutral and alkaline conditions. In this case, the metal forms stronger bonds with oxygen-containing surface sites (≡Si–O^-, ≡Al–O^-, etc.), and the contribution of ionic strength to the overall adsorption response decreases. For Pb(II), it has been shown that at pH > 7, sorption becomes much less sensitive to background electrolytes, with inner-sphere surface complexation emerging as the dominant mechanism (Khraisheh *et al.* 2005; Sheng *et al.* 2009). pH is a primary controlling factor determining (i) the surface charge of diatomite, (ii) the competitive interactions of H^+/OH^- with active sites, and (iii) the speciation of contaminants in solution. Consequently, pH regulates the balance between electrostatic attraction, ion exchange, and complexation. Ionic strength and the presence of "foreign" ions are particularly important at low pH, where outer-sphere sorption and ion-exchange processes exhibit pronounced competition. At higher pH values [for Pb(II), above approximately 7], the dependence on ionic strength diminishes, indicating the predominance of inner-sphere complex formation. Temperature affects both the kinetics and thermodynamics of sorption: for Pb(II) on diatomite, the process has been shown to be endothermic and spontaneous, as evidenced by calculated $\Delta H°$, $\Delta S°$, and $\Delta G°$ from temperature-dependent isotherms. From an engineering and environmental perspective, the

combination of these mechanisms implies that natural diatomite may exhibit varying sorption efficiency depending on the water matrix. In real wastewater, ion competition, the presence of natural organic matter, and variations in ionic strength can shift sorption mechanisms, either decreasing or enhancing the removal of target contaminants. Therefore, when interpreting data on natural diatomite, it is important to consider not only sorption capacity but also the conditions of pH, ionic strength, and temperature, as well as the role of surface functional groups, which has been experimentally demonstrated for dye adsorption on diatomite.

Activation and modification of diatomite

Activation of diatomite is understood as the deliberate modification of its textural and surface-chemical characteristics (specific surface area, pore distribution, quantity/type of functional groups, ζ-potential, wettability) to enhance its sorption efficiency in aqueous media. Natural diatomite is typically characterized by variable composition and the presence of associated phases (carbonates, clays, and Fe/Al oxides). Therefore, modification approaches are often aimed at (i) removing or redistributing impurities, (ii) "unlocking" the pore system, and (iii) creating more active or more selective surface sites (Zhao *et al.* 2019). Drying and low-temperature roasting (≈100–300 °C) are primarily used to remove physically bound water and some volatile organic impurities, thereby stabilizing the sorbent and reducing variability in adsorption performance in aqueous media. At this stage, only limited changes in mineralogy are usually observed; however, redistribution of surface hydroxyl groups and changes in pore accessibility can occur, which are important for subsequent chemical treatment or functionalization. Calcination or high-temperature firing (≈400–900 °C) is considered a more "rigorous" thermal modification, which affects the structural and sorption properties in a complex manner. Under certain conditions, it promotes surface cleaning and enhances pore accessibility, but overheating may lead to sintering, surface reconstruction, and a reduction in the number of active sites. For diatomite, it has been shown that the porosity of the meso-/macroporous framework can be preserved even at high temperatures (up to ~800 °C), allowing further targeted functionalization (e.g., silanization) without destroying the original architecture (Yuan *et al.* 2013). From a practical perspective, thermal treatment is often used as a pretreatment prior to subsequent chemical activation or deposition of active phases (oxides/hydroxides), as it enhances reproducibility of properties and can facilitate the diffusion of modifiers into the pore network.

Approaches that combine calcination with hydrothermal stages and the introduction of inorganic reagents (e.g., CaO) demonstrate the possibility of controlled modification of texture and the formation of new active sites on the diatomite matrix (Ren *et al.* 2022). Acid treatment (HCl, H_2SO_4, H_3PO_4, etc.) is used to leach carbonate and oxide impurities, partially remove alumina- and iron-containing phases, and increase the relative proportion of SiO_2. This process is often accompanied by changes in the porous structure and acid–base properties of the surface. Reviews on environmental applications of diatomite highlight that acid treatment can enhance the specific surface area and pore accessibility; however, the effect strongly depends on the mineralogical composition of the raw material and processing conditions (acid concentration, temperature, time, and solid-to-liquid ratio). At the applied research level, acid modification of diatomite has been demonstrated as an effective approach to improving the removal of metal ions from aqueous solutions, including through changes in surface chemistry and reduction of the impact of "passivating" impurities. An example is the use of diatomite treated with sulfuric acid for the extraction of Pb(II) from aqueous solutions, where the improvement in sorbent performance is attributed to surface modifications induced by acid etching (Shewatatek *et al.* 2025). Alkaline treatment (NaOH, Na_2CO_3, and KOH) is generally used for partial dissolution of amorphous SiO_2 and "etching" of the surface, which can increase the proportion of mesopores, modify the pore size distribution, and enhance the surface reactivity for subsequent functionalization or deposition of active phases. Studies in which diatomite was treated/activated with low concentrations of NaOH report an increase in adsorption capacity toward cationic dyes and improved process kinetics, which is attributed to the restructuring of the texture and surface following alkaline treatment (Zhang *et al.* 2013; Shen *et al.* 2021). Surface functionalization (organosilanes, surfactants, and polymer/biopolymer coatings) is used to impart selectivity and controlled wettability to diatomite, which is particularly relevant for the sorption of organic pollutants and petroleum fractions, as well as to improve mechanical/chemical stability during repeated cycles. Surface silanization of diatomite has been demonstrated to be feasible even after high-temperature calcination while maintaining its pore structure, expanding the toolbox for creating functional sorbents and composites for water treatment.

Combined activation approaches

Thermo-chemical activation (thermal treatment combined with an acid or alkaline stage) is considered one of the most effective approaches, as it allows sequentially addressing different objectives: thermal pretreatment stabilizes and "cleans" the material, while the chemical stage purposefully restructures the surface and pore system. In practice, this can be implemented, for example, through NaOH pretreatment followed by hydrothermal modification of calcined diatomite, resulting in a significant enhancement of adsorption properties compared to the raw or solely thermally treated material (Guo *et al.* 2024). When comparing the effectiveness of activation methods, it is important to consider that the "best" approach depends on the target class of pollutants and the water matrix. Alkaline treatment is often effective for enhancing the adsorption of cationic dyes and as a preparatory step for anchoring surface modifiers. In contrast, acid treatment is frequently used to remove carbonate/oxide impurities and to "expose" the silica matrix, which can improve reproducibility and increase the efficiency of metal ion removal under certain conditions. Special attention should be given to combined approaches involving the deposition of active phases (e.g., Mn- or Mg-containing components) on pretreated diatomite: such strategies allow transforming diatomite from a universal but moderately active natural sorbent into a functional material with enhanced capacity and selectivity for specific anions or cations. Consequently, recent studies emphasize not single-stage treatment but the engineering of surface and pore structures through combinations of thermal, chemical, and composite strategies, with mandatory consideration of the real water matrix and ecological sustainability requirements.

Adsorption performance of activated diatomite

Removal of heavy metals

Most studies demonstrate that the activation of diatomite (e.g., coating with Mn oxide, modification with biopolymers or carbon) results in a significant increase in adsorption capacity and/or selectivity toward metal cations compared to natural diatomite. A classical and widely cited study showed improved adsorption of Pb^{2+}, Cu^{2+}, and Cd^{2+} after modification of diatomite with an Mn oxide phase, attributed to an increase in specific surface area and changes in surface charge. A similar trend has been observed for Zn(II): adsorption on both natural and MnO_2-modified diatomite follows standard equilibrium and kinetic models, with modification enhancing extraction efficiency over a broad range of conditions (Zhao *et al.* 2019). For heavy metal cations, the most pronounced enhancement in adsorption efficiency is achieved through modifications that increase the density of negatively charged/complexing sites or introduce an additional active phase on the diatomite surface (e.g., MnOx, Fe_3O_4). Classical studies demonstrate a several-fold increase in Pb(II) adsorption capacity upon deposition of manganese oxides on diatomite, attributing this improvement to an increased negative surface charge and the formation of new active sites. For Pb(II), highly cited studies show that adsorption efficiency is strongly dependent on environmental conditions and the type of activation: under certain pH and ionic strength conditions, the nature of binding may change, leading to variations in the apparent sorbent capacity and adsorption kinetics. Therefore, Q1–Q2 publications emphasize the importance of accurately reporting pH and background electrolytes when comparing activated diatomite samples (Sheng *et al.* 2009). For Cd(II) and Zn(II), a significant research direction has been the development of magnetic diatomite composites, which combine efficient adsorption with the practical advantage of easy sorbent separation via magnetic separation. This is particularly important for real water matrices and for multi-cycle usage. Studies have demonstrated viable synthesis routes and stable adsorption performance of Cd(II) on magnetite–diatomite materials (Lemessa *et al.* 2024). In most studies on activated diatomite, adsorption equilibrium is described using Langmuir and Freundlich isotherms as a standard for comparing sorbents. The Langmuir model is commonly employed to estimate the maximum adsorption capacity (q_m) on relatively homogeneous active sites, whereas the Freundlich model highlights surface heterogeneity, which is often enhanced after chemical or phase modification. This approach is clearly demonstrated in studies of Pb(II) adsorption on natural and Mn-modified diatomite, where the authors compare isotherm parameters before and after modification (Caliskan *et al.* 2011; Bu *et al.* 2025).

Removal of oil products and hydrocarbons

For petroleum hydrocarbons and oils, activated diatomite is considered not primarily as an "ionic" sorbent, but as a material with tunable superwetting properties (hydrophobicity/oleophilicity or superoleophobicity in water for phase separation). Q1–Q2 publications emphasize that the native amphiphilicity of diatomite (hydrophilicity + oleophilicity) requires targeted surface modification to achieve selective extraction of oil and hydrocarbons from aqueous media (Özen & Okyay 2015).

Removal of organic pollutants

For dyes (e.g., methylene blue), one of the most consistently observed effects is the enhancement of adsorption following acid and/or thermal treatment of diatomite. Such studies typically report Langmuir and Freundlich isotherm parameters and demonstrate an increase in maximum adsorption capacity after modification, attributing this improvement to changes in the available surface area and the number of active sites (Al-Qodah *et al.* 2007). A separate line of research focuses on alkaline treatment/activation of diatomite (e.g., NaOH treatment) to enhance the adsorption of basic dyes and improve adsorption kinetics by restructuring the surface and removing impurities that block the pores (Zhang *et al.* 2013). For dyes, one of the most reproducible effects is the enhanced adsorption observed after acid and/or thermal treatment of diatomite (e.g., methylene blue). These studies typically report Langmuir/Freundlich isotherm parameters, demonstrating an increase in the maximum adsorption capacity after modification, which is attributed to changes in the accessible surface area and the availability of active sites.

A separate line of research focuses on alkaline treatment/activation of diatomite (e.g., NaOH treatment) to improve the adsorption of cationic dyes and enhance kinetics by restructuring the surface and removing pore-blocking impurities. In more "green" approaches, biopolymer composites (e.g., diatomite–chitosan or diatomite–alginate) are employed to increase dye adsorption without using toxic crosslinking agents, while also improving the processability and handling of the material (Al-Qodah *et al.* 2007). Phenols and phenolic compounds. For phenolic contaminants, one of the practical solutions is the use of magnetic functionalized diatomites, which enable operation in real water matrices and significantly simplify the separation of the sorbent. Efficient capture of phenolic compounds has been demonstrated on magnetic silica–functionalized diatomite, including analysis of the effect of environmental conditions and assessment of sorbent regeneration (Yu *et al.* 2017). Volatile aromatic compounds (as part of the organic load). For aromatic molecules such as benzene, Q1 publications demonstrate both direct functionalization strategies (e.g., silylation with phenyl groups to enhance π–π interactions) and composite approaches (e.g., diatomite/Silicalite-1), which increase adsorption capacity while facilitating desorption and sorbent regeneration under cyclic operation conditions (Yu *et al.* 2015). Emerging contaminants (for an "Environmental Science" focus). For emerging pollutants such as pesticides, studies demonstrate the use of amine-functionalized magnetic diatomite as an adsorbent. Functional groups are tailored to the chemistry of the target molecule, while the magnetic properties facilitate sorbent handling, separation, and regeneration (Sriram *et al.* 2020; Alacabey 2022).

CONCLUSION

This review demonstrates that diatomite represents a promising natural mineral sorbent for water and wastewater treatment due to its high porosity, developed pore structure, low density, and abundance of silica-based surface functional groups. The adsorption behavior of natural diatomite is governed by a combination of physical adsorption, electrostatic interactions, ion exchange, and surface complexation mechanisms, whose relative contributions depend strongly on pollutant type and solution chemistry. The analysis of recent literature confirms that natural diatomite is capable of removing heavy metals, dyes, petroleum hydrocarbons, phenolic compounds, and selected emerging contaminants from aqueous systems; however, its adsorption efficiency is often limited by the presence of mineral impurities, partial pore blockage, and relatively low selectivity. Thermal, chemical, and combined thermo-chemical activation methods substantially improve the physicochemical and adsorption properties of diatomite by increasing pore accessibility, modifying surface chemistry, and generating additional active sites. Among the investigated approaches, acid and alkaline treatments, hydrothermal activation, surface functionalization, and the incorporation of metal oxides or magnetic phases have shown particularly promising results for enhancing adsorption capacity and facilitating sorbent regeneration and separation. Recent studies further indicate that composite and functionalized diatomite materials can provide improved selectivity and operational stability under realistic wastewater conditions. At the same time, the review highlights several important limitations that currently restrict the wider industrial application of diatomite-based sorbents. These include the strong variability in mineralogical composition among deposits, lack of standardized activation protocols, differences in experimental methodologies, and insufficient data regarding long-term regeneration, stability, and performance in complex real water matrices. In addition, economic and environmental assessments of large-scale activation processes remain limited. Future research should therefore focus on the development of standardized and environmentally sustainable modification strategies, comprehensive evaluation under continuous-flow and real wastewater conditions, and integration of diatomite-based materials into hybrid treatment systems. Greater attention should also be paid to regeneration efficiency, life-cycle assessment, and

circular economy approaches aimed at reducing secondary waste generation. Overall, activated and functionalized diatomite materials possess considerable potential as low-cost, environmentally friendly, and scalable sorbents for advanced water treatment and environmental remediation technologies.

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