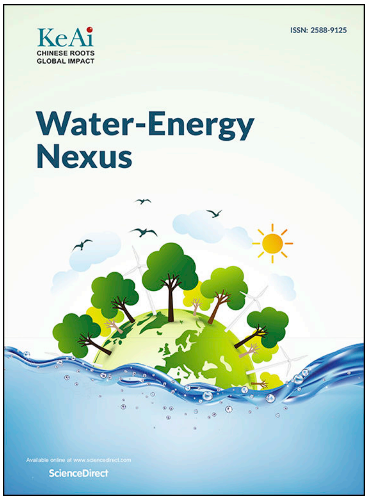

Review Article

Biochar-Layered Double Hydroxide vs Biochar-Layered Double Oxide: A Critical Review on Their Applications in Water Pollution Control

Yudha Gusti Wibowo, Dedy Anwar, Hana Safitri, Arif Rohman, Asnan Rinovian, Bimastyaji Surya Ramadan, Indra Surya, Sudibyo, Ahmad Tawfiequrahman Yuliansyah, Himawan Tri Bayu Murti Petrus

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Biochar-Layered Double Hydroxide vs Biochar-Layered Double Oxide: A Critical Review on Their Applications in Water Pollution Control

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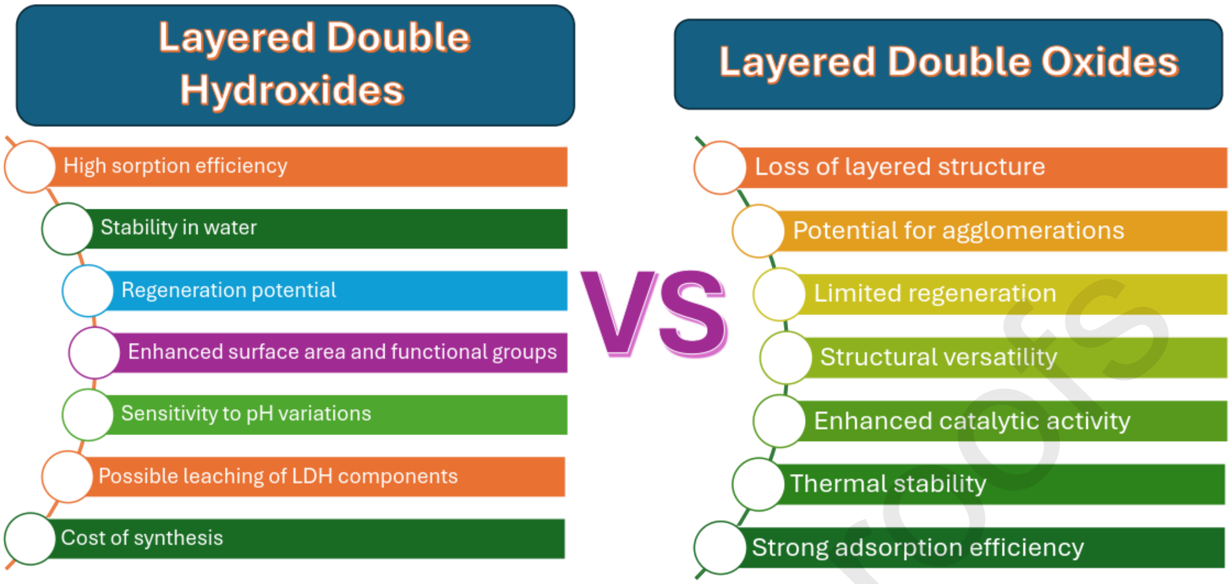
Graphical abstract



Highlights

1. First review of biochar-LDH vs biochar-LDO in wastewater treatment
2. Both biochar-LDH and biochar-LDO are promising for wastewater adsorption
3. Biochar-LDH has unique advantages and limitations for wastewater treatment
4. Biochar-LDO also has its own strengths and weaknesses in wastewater treatment

Abstract

Water pollution is a growing global challenge, necessitating innovative and sustainable solutions for effective pollutant removal. Among the various strategies, adsorption has emerged as a promising approach because of its simplicity, cost-effectiveness, and efficiency. Biochar, when modified with layered double hydroxides (LDHs) or layered double oxides (LDOs), exhibits enhanced adsorption properties, making it a versatile material for water pollution control. While numerous studies have explored the potential of biochar-LDH and biochar-LDO composites, a systematic comparison of their strengths, limitations, and real-world applications remains unexplored. This review provides a comprehensive analysis of biochar-LDH and biochar-LDO composites, focusing on their synthesis, adsorption mechanisms, and performance in removing contaminants such as heavy metals, phosphates, and organic pollutants. By comparing their adsorption efficiencies, regeneration capabilities, and environmental benefits, this study highlights the unique advantages of each material and identifies key areas for future research. The findings underscore the potential of these composites as next-generation adsorbents for sustainable water treatment, offering valuable insights for researchers, industries, and policymakers aiming to address global water pollution challenges.

Keywords: Adsorption; Biochar-based composites; Modified materials; Pollutant removal; Wastewater treatment

1. Introduction

Water pollution has been growing steadily year by year, driven by population growth, industrial expansion, and increased human activity (Jones et al., 2023; Whelan et al., 2022). A previous study predicted a significant rise in wastewater pollution, estimating an increase of 24% by 2030 and 51% by 2052, with 380 cubic meters reported in 2020 alone (Qadir et al., 2020). This escalating issue has garnered global attention, becoming a key focus of international bodies like the United Nations through Sustainable Development Goal 6, which aims to ensure the availability and sustainable management of water (Arora and Mishra, 2022; Mujtaba et al., 2024). An analysis of 51,347 research contributions on water pollution highlighted the leading countries in this field, with the U.S. contributing ~23%, China ~15%, and India ~5% (Vellaichamy and Jeyshankar, 2018). The impacts of water pollution are widespread. For instance, studies on agricultural insecticide pollution in surface waters revealed that over 50% of 11,300 measured insecticide concentrations exceeded regulatory thresholds, leading to a 30% reduction in aquatic biodiversity, specifically macroinvertebrate richness (Stehle and Schulz, 2015).

In South Korea, a source apportionment study identified agriculture as contributing ~22% to water pollution, with industrial and domestic waste adding ~20% in highly polluted regions (Cho et al., 2022). Meanwhile, an eco-economic model evaluating water pollution losses in Kaifeng City, China, estimated annual pollution-related energy losses at 145 million yuan, or 0.76% of the city's (Lv et al., 2022). Other previous study reported that 80% of diseases and 50% of child deaths are linked to poor water quality, with diarrhea emerging as the most prevalent waterborne disease (Lin et al., 2022). In China, the situation is particularly concerning. Another previous study found a direct correlation between water pollution and increased morbidity and mortality, with the most severe impacts observed among low-income communities (Wang and Yang, 2016). Several studies have investigated different strategies for treating pollution in wastewater, including chemical, biological, and physical techniques. Methods like coagulation/flocculation, phytoremediation, and filtration have been designed to minimize the harmful effects on ecosystems, water bodies, and human health (Gusti Wibowo et al., 2024). Although these approaches have proven effective in reducing heavy metal concentrations, they come with certain drawbacks. For example, biological methods such as phytoremediation and bacterial treatment require lengthy processing times to remove heavy metals from wastewater (Gusti Wibowo et al., 2023; Kurniawan et al., 2025). Similarly, advanced techniques like membrane filtration are hindered by high production and maintenance costs (Cevallos-Mendoza et al., 2022). Consequently, there is an urgent demand for innovative, cost-effective, and fast-acting solutions capable of addressing wastewater that contains both dyes and heavy metals simultaneously.

Adsorption is widely recognized as one of the most effective and efficient techniques for removing pollutants from wastewater (Wibowo, 2025; Wibowo et al., 2024). Among the various adsorbent materials explored, biochar has emerged as a promising candidate for water pollution control due to its carbon-rich composition, diverse functional groups, and unique properties (He et al., 2022; Liu et al., 2015). Biochar's effectiveness in removing heavy metals has been demonstrated in multiple studies (Ambaye et al., 2021). Previous study reported that straw-derived biochar achieved a lead (Pb) sorption capacity of 1343 mmol/kg, demonstrating high removal efficiency even under acidic conditions (Gao et al., 2020). Similarly, light biochar derived from *Medulla tetrapanacis* exhibited maximum adsorption capacities of ~1031 mg/g for Pb and ~458 mg/g for Cu, while maintaining over 80% efficiency for multiple ions (L. Zhang et al., 2019), this result is higher if comparing with adsorbent from magnetite bentonite-Cao that only reach 39 mg/g of sorption capacity (Wibowo et al., 2025b). Further enhancements in biochar performance can be achieved through chemical or physical modifications. One of the most effective modifications involves combining biochar with layered double hydroxide (LDH) (Huang et al., 2019; Wibowo et al., 2025a, 2025c) or layered double oxide (LDO) (Z. Zhang et al., 2019a). Integrating these materials significantly improves the surface area and adsorption capacity of the composite. LDHs consist of metal cation layers interspersed with exchangeable anions, enhancing their adsorption efficiency for heavy metal ions (Duan et al., 2022). Following calcination, LDHs convert into LDOs, which possess regenerative properties due to their ability to reabsorb ions and revert to the original LDH structure Chen et al., 2024), This transformation not only contributes to material recyclability but also supports sustained use in water treatment applications, highlighting the advantage of integrating LDH and LDO phases in biochar-based composites.

The biochar component further enriches the composite through its abundant functional groups, such as hydroxyl and carboxyl groups, which facilitate additional adsorption mechanisms via covalent bonding or electrostatic interactions (Qiu et al., 2022). This synergy between biochar and LDH/LDO broadens the range of pollutants that the composite can effectively capture. While LDH and LDO are particularly efficient at adsorbing anions such as phosphate and chromate, biochar is more suited for the adsorption of cations, including heavy metals. The chemical and thermal stability of the composite is also enhanced, making it a robust material for environmental applications. Furthermore, LDH's intercalation ability, where specific anions are inserted between its layers, enables the material's adsorption properties to be tailored to target pollutants effectively.

Despite the growing body of research on biochar-LDH and biochar-LDO composites, there is a notable lack of systematic comparisons between these materials. While individual studies have demonstrated their potential, no comprehensive review has critically evaluated their relative strengths, limitations, and suitability for specific applications. This gap in the literature hinders the development of optimized materials and limits their practical implementation in water treatment systems. To address this, the present review provides a holistic comparison of biochar-LDH and biochar-LDO composites, focusing on their synthesis methods, adsorption mechanisms, and performance in real-world applications. By systematically analyzing their adsorption efficiencies, regeneration potential, and environmental benefits, this study aims to guide the selection of appropriate materials for specific pollution control scenarios. Furthermore, it will assess the economic and operational implications of both composites, providing practical recommendations for industries and policymakers on adopting sustainable and cost-effective treatment technologies. This comparison will not only guide the selection of optimal materials for specific environmental applications but also identify research gaps for future studies, such as the environmental impact of scaling up production and opportunities for multifunctional use in areas beyond water treatment. The outcomes of this study will advance the understanding of modified biochar systems, contributing to the development of next-generation adsorbents and promoting innovative, sustainable pollution control strategies.

2. Methods and Data Acquisition

The data for this study were collected from the Scopus database, a globally recognized indexing platform for academic journals. The search was conducted using the keywords "biochar layered double hydroxide for wastewater" and "biochar layered double oxide for wastewater." Only articles written in English were included to maintain consistency and accessibility in the analysis. The search was comprehensive, with no restrictions on publication year, subject area, or article type, ensuring a broad and inclusive collection of relevant literature (**Figure 1**). Overall, the steps in data acquisition and analysis of this review following the previous studies (Ramadan et al., 2024; Wibowo et al., 2023b).

To support bibliometric mapping and data visualization, VOSviewer, an open-source software widely used for analyzing and visualizing research networks, was employed. The data exported from Scopus were converted into RIS format, enabling efficient management and seamless integration of references. Zotero version 6.0.37 was used to consolidate and organize the data, ensuring that the literature retrieved from both keyword searches was combined without redundancy and properly curated. This structured data handling enhanced the accuracy and reliability of the analysis. Additionally, all the information reviewed in this manuscript was sourced from highly reputable journals to ensure the accuracy, credibility, and relevance of the content. By focusing on peer-reviewed, high-impact publications, the study maintains a high standard of scientific rigor and reliability.

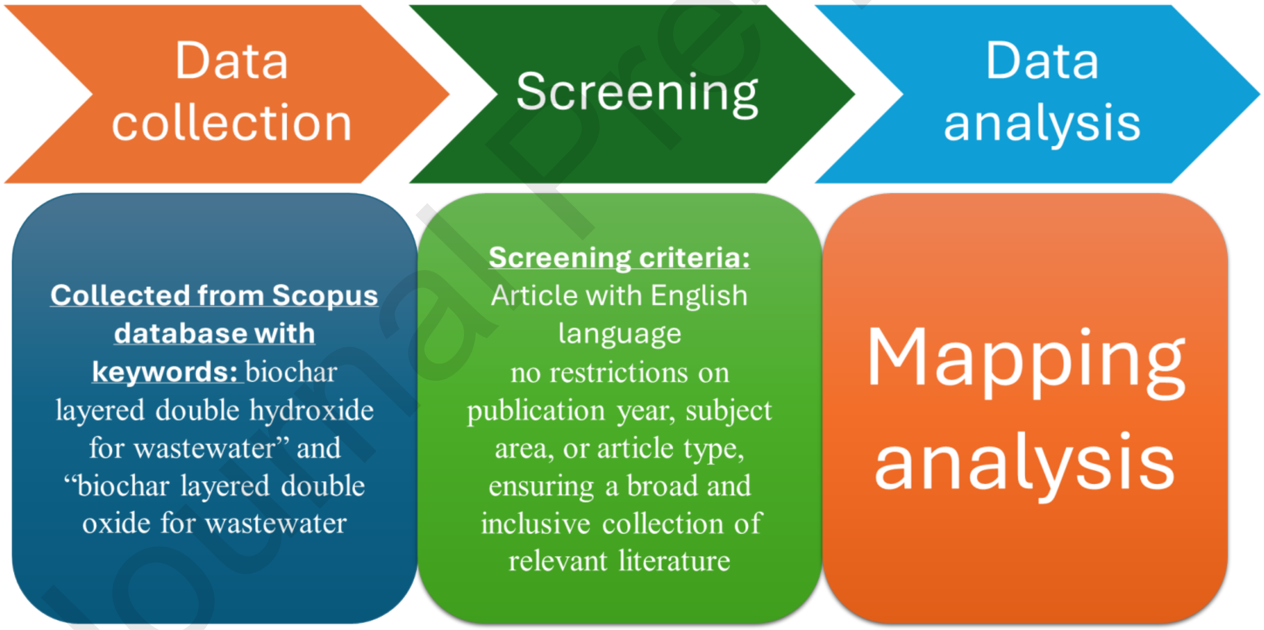


Figure 1. Method in data collection and analysis

3. Result and Discussion

3.1 Water Pollution Impact on Environmental and Human Health

Water pollution, a critical global issue, affects both the environment and human health, with implications that extend across ecosystems and society. Contaminants from industrial, agricultural, and urban sources often infiltrate water systems, leading to a decline in water quality that disrupts ecological balance and poses significant risks to human well-being. Addressing the impacts of water pollution involves understanding the sources and effects of various pollutants, as well as recognizing the intertwined environmental and public health repercussions. This overview provides a synthesis of current research on the impacts of water pollution, emphasizing the urgent need for mitigation measures to preserve both biodiversity and public health.

The degradation of water quality has far-reaching consequences for aquatic ecosystems. Pollutants, including heavy metals, nitrates, and pathogens, enter water systems from untreated or inadequately treated wastewater, agricultural runoff, and industrial discharges. These contaminants compromise the health of aquatic species and degrade biodiversity, leading to the loss of habitats and essential ecosystem functions. Heavy metals, such as mercury, cadmium, and lead, bioaccumulate in aquatic organisms, impairing reproductive processes and altering behaviors that are essential for species survival (Baba, 2024). In their study on ecosystem health, Baba emphasizes that heavy metals and other pollutants in water pose significant threats to biodiversity, highlighting the urgency for effective pollution control measures (Baba, 2024).

Moreover, chemical and microbiological contaminants present in water bodies lead to ecological imbalances that can have cascading effects on broader ecosystems. According to a study, industrial discharges and improper waste disposal introduce chemical pollutants and pathogenic microbes into water sources, disrupting not only individual species but entire aquatic communities (Cuc et al., 2020). For example, an excess of nutrients like nitrates from agricultural runoff causes eutrophication, where the overgrowth of algae depletes oxygen in water bodies, leading to “dead zones” where aquatic life cannot survive. Another study adds that such long-term contamination from industrial pollutants can devastate local ecosystems, leading to a loss of species diversity and diminishing the resilience of habitats (Denisov et al., 2020). Such degradation weakens the ecological services that these habitats provide, such as nutrient cycling, water purification, and supporting biodiversity, which are essential for environmental stability and human prosperity.

Water pollution also has profound implications for human health, primarily due to contaminated drinking water sources. Exposure to polluted water has been linked to a range of health issues, from acute gastrointestinal illnesses to chronic conditions such as cancer, cardiovascular diseases, and renal disorders (**Figure 2**). Heavy metals, in particular, pose a severe threat to health; they are non-biodegradable and can accumulate in human tissues over time, leading to toxic effects. Wasana et al. found that prolonged exposure to drinking water contaminated with heavy metals and nitrates increases the risk of kidney damage and other serious health complications (Wasana et al., 2017). These findings underscore the need for stringent monitoring of drinking water sources to minimize human exposure to such hazardous substances.

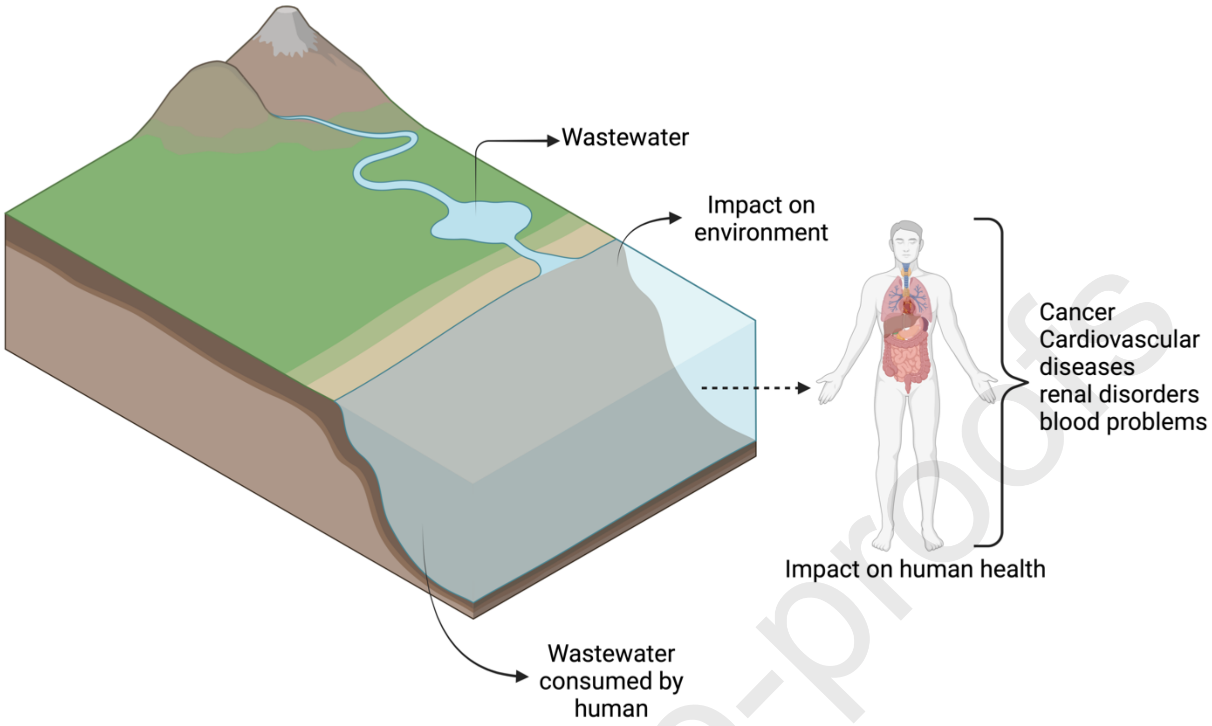


Figure 2. Wastewater impact on the environment and human health

In addition to chronic health conditions, waterborne pathogens pose immediate risks, particularly to vulnerable populations like infants and those with compromised immune systems. Contaminated water often carries pathogens that can cause illnesses such as cholera, dysentery, and typhoid fever, diseases that remain prevalent in areas with inadequate water treatment infrastructure. A study identifies fecal coliform as a crucial indicator of potential health risks from waterborne pathogens, highlighting the dangers posed by untreated sewage and other sources of microbiological contamination (Soticha et al., 2014). This type of pollution is particularly concerning in densely populated or low-income areas where access to clean water is limited, and sanitation infrastructure is insufficient. Another study also reports that high levels of nitrates in drinking water are associated with methemoglobinemia or “blue baby syndrome,” a condition that reduces the oxygen-carrying capacity of infants’ blood, underscoring the critical health risks linked to polluted water sources (Ward et al., 2018).

The socio-economic impact of water pollution is substantial, as it increases health care costs and places a strain on water treatment infrastructure. Waterborne diseases caused by pathogens, heavy metals, and chemical pollutants lead to a significant economic burden, particularly in low- and middle-income countries where resources are often limited. Petronella and Comparelli highlight how the economic burden of water pollution manifests through lost productivity, reduced biodiversity, and the high costs associated with treating pollution-related illnesses (Petronella and Comparelli, 2021). This economic strain is exacerbated in regions with limited access to clean water, where the public health system may lack the capacity to address widespread waterborne diseases, and residents often bear the financial burden of purchasing bottled water or seeking medical treatment for pollution-related health issues.

Access to safe and clean drinking water is not evenly distributed across the globe, and disparities in water quality and treatment contribute to the disproportionate impact of water pollution on marginalized communities. A study examines these inequalities, noting that people in low-income regions are more likely to rely on contaminated water sources due to a lack of reliable water quality monitoring and limited access to sanitation infrastructure (Lopes et al., 2022). These disparities highlight the need for equitable water management policies and infrastructure improvements to protect vulnerable communities from the adverse effects of water pollution. For instance, initiatives aimed at expanding access to clean water and building robust sanitation systems in underserved areas are crucial for reducing health risks and promoting social equity.

The cumulative impact of water pollution on ecosystems, human health, and socio-economic stability calls for comprehensive strategies that address both prevention and remediation. Effective water pollution control requires regulatory measures to limit pollutant discharge, investments in wastewater treatment technologies, and public awareness campaigns to encourage responsible waste disposal. Environmental regulations play a critical role in mitigating water pollution, especially in industrial sectors, by enforcing limits on pollutant emissions and promoting sustainable practices. Additionally, the development and implementation of advanced water treatment technologies, such as biochar-LDH and biochar-LDO composites, offer promising solutions for removing contaminants from water and reducing the risks associated with polluted water sources.

Public awareness and education are also essential in fostering community-level engagement in pollution prevention efforts. By raising awareness of the health risks associated with water pollution and encouraging individuals and organizations to adopt environmentally friendly practices, communities can play a proactive role in protecting water resources. Innovative technologies, combined with community involvement and regulatory oversight, can form a multi-pronged approach to address water pollution effectively.

Water pollution is a complex issue with profound implications for environmental health, public health, and economic stability. Contaminants from various sources disrupt aquatic ecosystems, threaten biodiversity, and pose significant risks to human health. The socio-economic costs of water pollution are particularly burdensome for low- and middle-income countries, where the lack of clean water access exacerbates health disparities and limits economic development. To safeguard water resources and public health, it is essential to implement a comprehensive strategy that includes regulatory enforcement, technological innovations, and public education initiatives. By addressing water pollution from multiple angles, society can better protect both natural ecosystems and human communities, fostering a more sustainable and equitable future.

3.2 Analysis of Published Articles

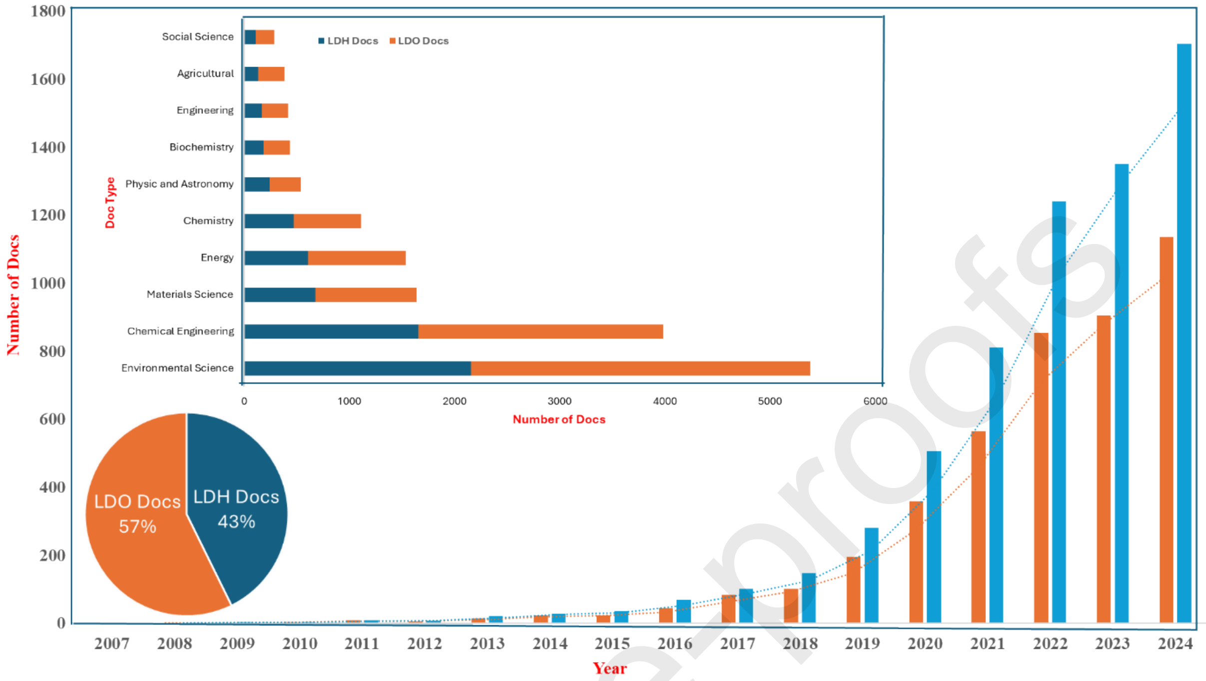


Figure 3. Trends in published articles according to the number of docs (a), open access docs (b), and doc types (c) from biochar-LDH and biochar-LDO docs

Note: Bibliometric data was collected on 29 October 2024. Due to the rapidly growing interest in this research area, the number of publications in 2024–2025 may now be higher than depicted in this figure.

The data presented in **Figure 3** indicates a notable upward trend, with two materials, potentially LDH-based composites and biochar, showing increased values over time or under different experimental conditions. The blue and orange bars reflect the performance or accumulation of these two treatments. While both demonstrate an increasing trend, the orange bars, particularly in the later stages, exhibit a steeper rise. This suggests that the material represented by the orange bars, likely biochar-based derivatives, may possess superior characteristics under the tested conditions. This improved performance could be attributed to biochar's inherently high surface area, enhanced porosity, or better chemical affinity for pollutants compared to LDH-based materials. The result suggests that biochar might respond more effectively to increasing concentrations or prolonged exposure, making it a preferable material in applications such as adsorption or heavy metal removal (Qiu et al., 2022; Wibowo et al., 2023a, 2022).

Figure 3, a pie chart, further elaborates on the comparative contribution of the two materials, with the orange section accounting for 57% and the blue section representing 43%. This slight but meaningful difference indicates that biochar-based materials play a more substantial role in achieving the desired performance outcomes. The higher share of biochar derivatives may reflect their operational advantages, such as higher adsorption efficiency, faster kinetics, or reduced costs in comparison to LDH composites. Biochar's ability to undergo functionalization could also amplify its efficiency, making it more adaptable to various environmental or industrial applications

(Oliveira et al., 2017; Wang and Wang, 2019). The economic and environmental sustainability associated with biochar might further position it as a favorable material, particularly in the development of eco-friendly technologies and circular economy frameworks (Kurniawan et al., 2023; Mukherjee et al., 2023).

Figure 3, a horizontal bar plot, provides a more granular comparison, breaking down specific performance metrics across different parameters or applications. The varying lengths of the bars, with the majority of longer bars in orange, highlight biochar's relative superiority across multiple performance indicators. This suggests that biochar, either in its pristine or modified form, may excel in specific scenarios, such as higher adsorption capacities, better regeneration potential, or enhanced selectivity for targeted pollutants. LDH-based materials, though effective, appear to be more limited in certain aspects, possibly due to lower surface area or structural constraints, which might affect their adsorption efficiency under certain conditions. However, LDH composites may still offer valuable synergies when combined with biochar, leveraging their unique properties such as anion exchange capacity.

The cumulative insights from these visual representations highlight the comparative advantages of biochar over LDH-based materials. While both materials exhibit significant potential, the superior performance and higher contribution of biochar suggest that it might be the material of choice for future research and industrial applications. This finding aligns with the broader trend in materials science, where bio-based adsorbents are increasingly being recognized for their cost-effectiveness, environmental sustainability, and adaptability. The synergistic effects of surface functionalization in biochar might further unlock new applications, offering innovative solutions for complex environmental challenges.

Thus, the data suggest that biochar-based materials outperform LDH composites in various performance metrics, making them a more viable option for practical applications. The growing trend in **Figure 3,** combined with the proportional advantage and the detailed breakdown, underscores the importance of prioritizing biochar research and development. Future studies should explore the optimization of biochar's properties through advanced functionalization strategies, while also investigating the potential benefits of hybrid composites with LDH materials. This approach would provide a comprehensive understanding of how these materials can be utilized effectively to meet both environmental and industrial needs, particularly in areas such as water treatment, waste remediation, and resource recovery

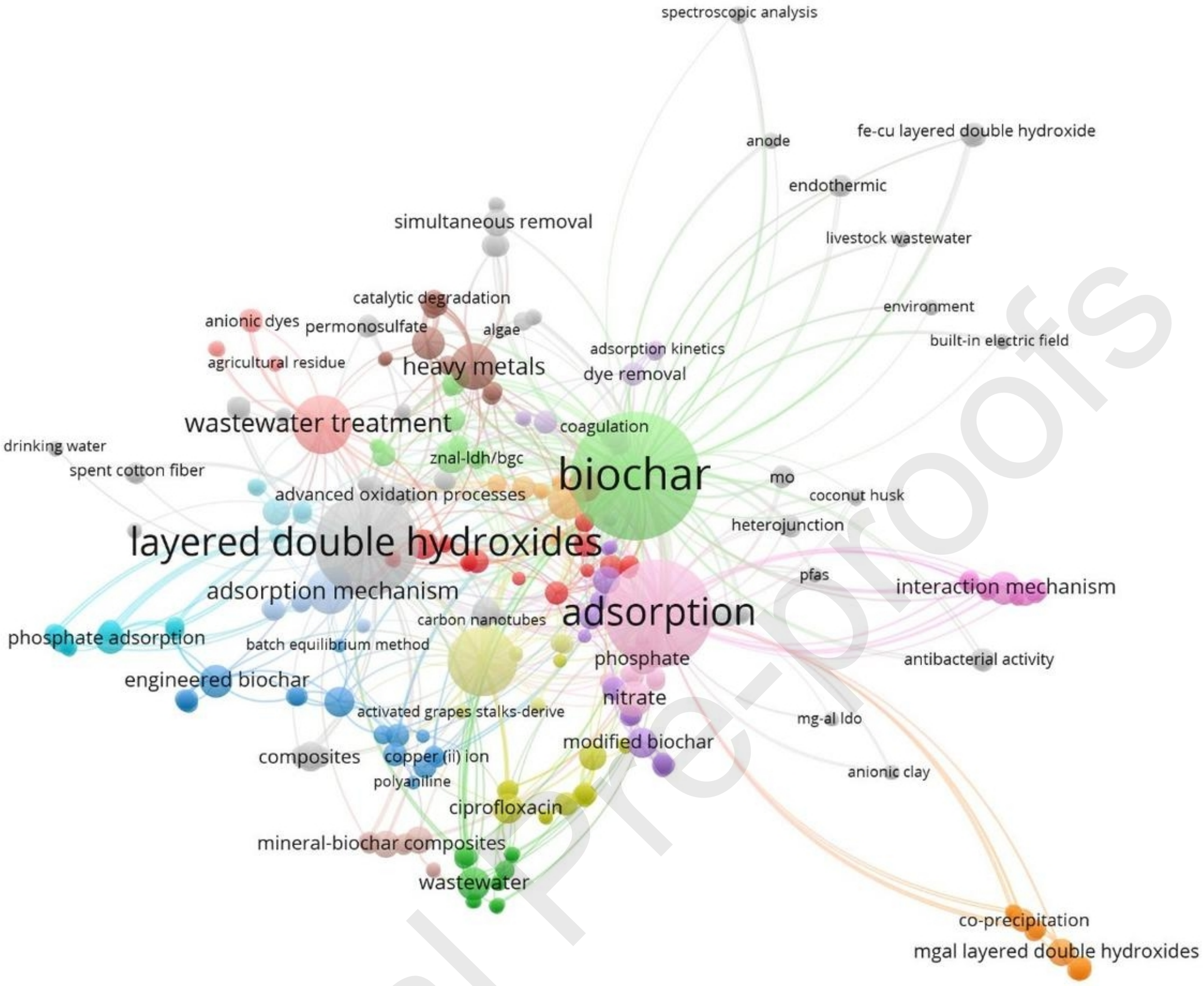


Figure 4. Mapping analysis of biochar LDH and LDO

The keyword network analysis generated by VOSviewer (**Figure 4**) identifies several recurring research themes, with "adsorption mechanism" emerging as one of the most prominent keywords. This reflects the scientific community's growing emphasis on elucidating how biochar-based composites interact with contaminants at the molecular level. The high frequency of this term highlights the centrality of understanding physicochemical interactions such as ion exchange, surface complexation, electrostatic attraction, hydrogen bonding, and π–π interactions, especially in distinguishing the performance of LDH and LDO structures.

In the case of biochar-LDH composites, studies have frequently explored the anion exchange mechanisms enabled by the interlayer regions of the LDH structure, which are particularly relevant for phosphate and chromate removal. Meanwhile, the memory effect and surface rehydration behavior of LDO-based composites are often studied to explain their capacity for adsorbing organic molecules and nanoplastics.

The recurrence of the keyword also aligns with other terms such as "surface modification," "isotherm," and "kinetics," which point to a collective research focus on optimizing adsorption efficiency through chemical tailoring and modeling. This hotspot confirms that the advancement of biochar-LDH and biochar-LDO composites depends not only on synthesis but also on deep mechanistic understanding, particularly for applications involving multi-component wastewater systems.

The combination of biochar and LDH is a prominent theme in the visualization, reflecting strong research interest in these materials for adsorption and water purification. LDH materials are known for their layered structure, which enables them to perform ion exchange and adsorb both cations and anions. Integrating LDH with biochar leverages the strengths of both materials: biochar's high surface area, porosity, and functional versatility, and LDH's ion-exchange capacity and chemical flexibility. This synergy makes biochar-LDH composites highly effective in wastewater treatment, where various pollutants, including heavy metals and organic contaminants, need to be removed simultaneously (Fang et al., 2021; Vithanage et al., 2020a; Zubair et al., 2021b).

The network also highlights keywords related to adsorption mechanisms and kinetic models, indicating that studies on biochar-LDH composites often focus on optimizing adsorption conditions such as pollutant concentration and contact time. Researchers are investigating the behavior of these composites in diverse environmental matrices to maximize their adsorption capacity. Additionally, the connectivity between functionalization and surface modification suggests that biochar-LDH systems are being tailored to enhance their pollutant selectivity and performance under specific environmental conditions.

While biochar-LDH composites excel in adsorption, biochar-LDO systems offer distinct advantages in terms of thermal stability and catalytic activity. LDO materials are obtained by the calcination of LDH, which removes interlayer water and hydroxyl groups, creating highly reactive oxide surfaces. These materials are more stable at elevated temperatures and exhibit enhanced catalytic potential, making them suitable for oxidative transformations and chemical degradation processes. This feature is particularly advantageous in applications such as the removal of heavy metals, dyes, pharmaceuticals and anions (Zubair et al., 2021b).

The visualization also suggests that phosphate removal is a key focus in biochar-LDO research. LDO composites demonstrate superior performance in redox-sensitive applications due to their enhanced surface reactivity, which is crucial in catalytic degradation and chemical transformation processes. The network points to surface modification as a strategy used in both biochar-LDH and biochar-LDO systems. Still, LDO composites may offer better reusability after multiple cycles of adsorption and desorption, owing to their structural stability and resistance to degradation under harsh environmental conditions.

The visualization highlights both biochar-LDH and biochar-LDO composites as promising materials, each with specific strengths suited to different environmental challenges. Biochar-LDH composites excel in adsorption-heavy environments, such as wastewater treatment, where they effectively remove a wide range of pollutants. Their ability to adsorb both anionic and cationic contaminants makes them versatile solutions for water purification applications (Vithanage et al., 2020a; Zubair et al., 2021b). In contrast, biochar-LDO composites stand out in environments where thermal stability and oxidative performance are crucial (Azalok et al., 2021a; Yu et al., 2025a). Their reactivity under high temperatures and enhanced catalytic properties make them ideal candidates for phosphate removal and advanced oxidation processes (Azalok et al., 2021b; Gong et al., 2024; A. Li et al., 2021).

Both systems benefit from surface modification and functionalization to improve their adsorption selectivity and efficiency. However, biochar-LDO composites may offer an advantage in long-term applications, as their thermal stability and reusability can reduce material degradation over multiple cycles. In contrast, biochar-LDH composites are better suited for conditions requiring rapid adsorption and efficient removal of diverse pollutants.

The network suggests exciting research opportunities for both biochar-LDH and biochar-LDO systems. Future studies could explore the development of hybrid composites that combine the adsorption capabilities of LDH with the catalytic and thermal stability of LDO. Such multi-functional materials could address complex environmental challenges that require simultaneous adsorption, chemical transformation, and stability under varying operational conditions. Additionally, comparative research focusing on the specific conditions under which each composite performs optimally would help guide material selection for different environmental applications.

Further research should also focus on scaling these systems for real-world applications, ensuring that laboratory results translate effectively to industrial processes. Investigations into life cycle assessments (LCA) would provide insights into the environmental impact of these materials and support their development as sustainable solutions. Mechanistic studies exploring pollutant interactions with biochar-LDH and biochar-LDO composites under complex environmental matrices would enhance the understanding of their behavior and optimize their use in practice.

3.3 Synthesis and Characteristic Materials

The synthesis of biochar-LDO and biochar-LDH composites has emerged as a promising field within environmental remediation, particularly in water pollution control. Biochar-LDO and biochar-LDH composites leverage biochar's porous and high surface area structure, enhancing pollutant adsorption properties when combined with layered materials like LDOs and LDHs. Synthesizing these composites involves advanced techniques that optimize biochar's adsorption capacity by modifying it with materials known for their structural versatility, high anion exchange capacities, and stability, thereby making the composites suitable for diverse environmental applications. The synergy between biochar and these layered materials has allowed biochar-LDO and biochar-LDH composites to advance in both performance and applicability significantly, reflecting broader trends in green material science and sustainable environmental technology.

The most prevalent synthesis technique for biochar-LDO composites is one-step calcination, a process that subjects biochar-LDH composites to high temperatures, transforming hydroxides into oxides (Taher et al., 2023). This calcination not only changes the composition but also enhances biochar's adsorption capabilities by exposing additional basic sites, significantly improving CO_2 and pollutant capture. For example, a cellulose-derived biochar-LDO composite achieved a threefold increase in CO_2 adsorption capacity due to the effective availability of basic sites after calcination (Taher et al., 2023). The LDOs integrated into the biochar matrix create sites with a high affinity for CO_2 molecules, addressing environmental concerns around atmospheric CO_2 concentrations, which have risen by approximately 50% over the past two centuries and are a key contributor to climate change (Taher et al., 2023). Thus, synthesizing biochar-LDO composites is aligned with the goals of carbon capture and sequestration (CCS), contributing to emissions reduction by optimizing biochar's adsorption capacities and structural stability.

In contrast, biochar-LDH composites are commonly synthesized using co-precipitation, hydrothermal, or co-pyrolysis methods, each contributing distinct advantages in pollutant adsorption **(Figure 5)**. For instance, previous research (Y. Wang et al., 2020) employed a rapid co-precipitation method to synthesize a corn stalk-derived biochar-LDH composite with Ni-Fe-Zn layered hydroxides, which demonstrated efficient atrazine removal from water. This synthesis approach ensured a uniform distribution of LDH particles on the biochar surface while maintaining the adsorptive qualities of both biochar and LDHs (Y. Wang et al., 2020). The coprecipitation method is valued for its energy efficiency, occurring at moderate temperatures (60–90°C), and for its ability to produce composites with high specific surface areas and abundant active sites (Y. Wang et al., 2020). Furthermore, another research (Cui et al., 2019) synthesized a magnetic biochar-LDH composite with Mg-Al LDHs, enhancing pollutant recovery efficiency by making it easier to separate the composite from the aqueous solution. This magnetic modification demonstrates the practicality of biochar-LDH composites for real-world applications, particularly in large-scale water treatment facilities where rapid, efficient recovery of the adsorbent is necessary (Cui et al., 2019).

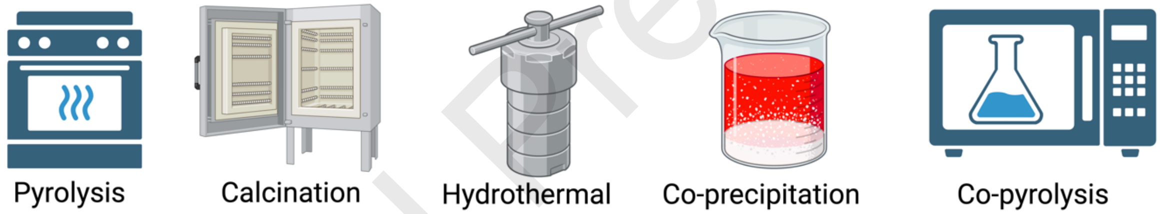


Figure 5. Several common methods in preparation material

Characterization techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), and Fourier transform infrared spectroscopy (FTIR) are integral to assessing the effectiveness of these synthesis methods. These techniques reveal details about crystallinity, morphology, and functional groups, which directly correlate to adsorption capabilities. For example, characterization studies showed that the synthesized biochar-LDH maintained a pure LDH phase with a large surface area, an essential feature for high adsorption capacity (Li et al., 2022). Such insights also clarify the roles that the composite's layered structures and surface functional groups play in pollutant adsorption, informing further optimization of synthesis processes. For biochar-LDO composites, similar techniques confirm the transformation of LDH into oxide phases, showing a more pronounced porosity and greater basicity than their LDH counterparts, which are critical for CO_2 and pollutant adsorption in water treatment scenarios (Taher et al., 2023).

Moreover, the application of biochar-LDH composites in removing specific pollutants like phosphates demonstrates the synergy between biochar's porosity and LDH's anion exchange capacity. The research documented how Mg/Al-LDH modified biochar achieved enhanced phosphate removal due to the material's hierarchical structure, which allows effective interaction with anionic pollutants (Ma et al., 2022). Similarly, another research highlighted the role of LDHs in increasing the surface area and enabling more efficient adsorption, thus showcasing the potential of biochar-LDH composites for wastewater treatment. In this way, biochar-LDH composites not only facilitate pollutant capture but also contribute to sustainable waste valorization and carbon sequestration efforts, aligning with the global emphasis on reducing carbon footprints in industrial practices (Zhang et al., 2022).

The environmental benefits of biochar-LDO composites in CO_2 capture are substantial, as rising atmospheric CO_2 levels directly impact climate change. Synthesizing biochar-LDO composites through calcination enables the creation of basic sites with high affinity for CO_2, thereby positioning these composites as effective materials for CCS initiatives (Taher et al., 2023). Additionally, the versatility of biochar-LDH composites allows for the inclusion of various metal ions in the LDH structure, tailoring the composite's chemical composition for targeted pollutant removal. This adaptability extends beyond environmental applications; for instance, ZnCr/C-LDH nanocatalysts demonstrated that they could be used in photocatalytic applications, underscoring the composites' cross-disciplinary potential (Zarewa and Muhammad, 2022). This adaptability indicates a broader scope of functionality for biochar-LDH composites, from pollutant adsorption in water treatment to photocatalysis and even biomedical applications.

Overall, the synthesis methods of biochar-LDO and biochar-LDH composites are at the forefront of sustainable material development, offering robust solutions for environmental remediation and beyond. As the synthesis and characterization processes continue to evolve, future research should focus on refining the stability and reusability of these composites. Previous study noted that the structural integrity of LDHs can be compromised under specific conditions, potentially impacting long-term effectiveness in adsorption applications (Mohammadi et al., 2022). Therefore, efforts to enhance the durability of biochar-LDH composites through novel synthesis techniques and stabilizing agents are essential to maintaining their performance and viability.

The synthesis of biochar-LDO and biochar-LDH composites embodies a convergence of biochar's adsorptive properties with the structural advantages of layered materials. Each synthesis technique from calcination for biochar-LDO to co-precipitation and hydrothermal methods for biochar-LDH contributes unique qualities that enhance pollutant adsorption and enable these materials to address pressing environmental challenges. By optimizing synthesis methods, characterizing structural properties, and exploring new applications, researchers are continuously advancing Biochar-LDO and biochar-LDH composites, ensuring their place as sustainable and effective materials in water pollution control, carbon capture, and beyond. Table 1 shows the synthesis methods and recent trends in biochar-LDH and biochar-LDO utilization

Table 1. Synthesis and recent trends in materials utilization

Material	Synthesis method	Performance	Reference
Pinecone Biochar-LDH	LDH modification on pinecone biochar	Pb^{2+}: ~135 mg/g, Phosphate: 160.8 mg/g	(Huang et al., 2024)

MgFe-LDH/Biochar	Co-precipitation with FeCl$_3$ and Mg(OH)$_2$ followed by pyrolysis	Phosphorus adsorption capacity: ~379 mg/L	(Bian et al., 2023)
MgAl-LDO/Biochar	In-situ fabrication from Al-rich sewage sludge	Nanoplastics adsorption capacity: 360 mg/g	(Sun et al., 2023)
Biochar@Co-Ni-Al LDH	Crosslinked with chitosan/PVA beads	Levofloxacin: 1795 mg/g; Removal efficiency: ~98%	(Mosaffa et al., 2025)
Poplar Biochar-LDO (CL-800)	Co-precipitation followed by pyrolysis	Congo red: 4841 mg/g; Ciprofloxacin: 744 mg/g	(Yu et al., 2025b)
MgZnFe-LDHs/PBC	Porous biochar infused with MgZnFe LDH	Cd^{2+} adsorption: ~293 mg/g	(Yu et al., 2023)
MnAl-LDH/KOH Biochar	In-situ co-precipitation onto KOH-activated biochar	Tetracycline adsorption: ~1477 mg/g	(Fan et al., 2024)
Fe-Cu-LDH/Biochar Composite	Hydrothermal synthesis combined with sonocatalysis.	~97% removal efficiency for cefazolin sodium in 80 minutes.	(Gholami et al., 2020)
Mg/Al-LDH and LDO Biochar Composite	Simultaneous pyrolysis of LDH-pretreated biomass at 500°C to form LDO-coated biochar.	Adsorption capacity of 795 mg/g for Congo red dye.	(Mai et al., 2021)
Biochar-Supported Calcined Mg/Al-LDO Composite	Pre-treated biomass loaded with Mg/Al LDHs, followed by slow pyrolysis.	Adsorption capacity of ~1118 mg/g for tetracycline at 318 K.	(Xiaofei Tan et al., 2016)
MgFe-LDH/Biochar Composite	Incorporation of MgFe-LDH particles onto biochar through liquid-phase deposition.	~25 mg/g adsorption capacity for Cd^{2+}.	(Tan et al., 2019)

LDH-BC Composite	Precipitation of LDHs onto biochar, followed by pyrolysis	~52 mg/g adsorption capacity for phosphate using Anion exchange and surface complexation.	(Yang et al., 2019)
Biochar/MnAl-LDH	Co-precipitation of MnAl-LDH on biochar, followed by drying and grinding	~4 mg/g adsorption capacity for Cu^{2+}. Adsorption follows the Langmuir and pseudo-second-order models.	(Wang et al., 2018)
Mg-Fe LDH on Rice Husk Biochar	LDH assembly on rice husk ash-derived biochar via a co-precipitation process.	Adsorption capacity of 682 mg/g for Pb^{2+} with high selectivity for heavy metals.	(Yu et al., 2018)
CuFe-LDH on Date Palm Biochar	Co-precipitation of CuFe-LDH on biochar from date palm waste.	Adsorption capacity of ~565 mg/g for Eriochrome Black T dye.	(Zubair et al., 2021a)
Biochar-Mg-Al LDO Composite	Co-pyrolysis at 500°C of biochar and MgAl-LDH precursor.	Adsorption capacity of ~97% for phosphate.	(Lee et al., 2019)
Electro-Assisted Fe_3O_4 Biochar-LDH Composite	Two-step electro-assisted modification for Caragana korshinskii biochar-Mg-Al LDH.	The maximum phosphate adsorption capacity is ~252 mg/g.	(Cui et al., 2019)
Fe-Cu LDH Biochar	Hydrothermal synthesis of Fe-Cu LDH on biochar for sonocatalysis.	~97% degradation efficiency for cefazolin sodium within 80 minutes.	(Gholami et al., 2020)
Ni/Mg/Al LDO	Calcination at 600°C to transform LDH to LDO.	Adsorption capacities of 1250 mg/g for Congo red and ~103 mg/g for Cr(VI).	(Lei et al., 2017)

Vegetable Biochar-LDOs	Horizontal lamellar particles prepared with cabbage biochar and Mg-Al LDO.	95% phosphate removal within 5 minutes.	(Z. Zhang et al., 2019a)
Magnetic Biochar-LDO	LDO nanosheets integrated with biochar from pinewood sawdust.	Adsorption capacity of ~591 mg/g for Pb^{2+} and ~330 mg/g for CrO_4^{2-}.	(H. Wang et al., 2020a)
Biochar-Mg-Al LDO	Precipitation of Mg-Al LDOs on palm-derived biochar.	Achieved ~28 mg/g for nitrate and ~177 mg/g for phosphate.	(Alagha et al., 2020)
Cocoa Pod Husk Biochar with LDO	One-step NaOH activation to embed LDOs in biochar.	Efficient adsorption of multiple dyes in simulated wastewater.	(Córdova et al., 2020)
Biochar-LDO Composite	Layer-by-layer assembly of biochar and Mg-Al LDO.	Maintained removal efficiencies above 90% across pH 2-10.	(Z. Zhang et al., 2019a)
Biochar-MgO-LDO Nanocomposites	MgO nanoparticles loaded onto nitrogen-doped biochar via pyrolysis	Adsorption capacity of 893 mg/g for Pb and rapid removal within 10 minutes	(Ling et al., 2017)

The combined LDH/LDO-biochar materials exhibit unique properties that significantly enhance their ability to remove pollutants from wastewater. These materials leverage the synergistic effects of biochar's porous structure and LDH/LDO's layered composition, resulting in superior adsorption efficiency, ion exchange capacity, and structural stability (**Figure 6**). Biochar's porous structure offers an extensive surface for adsorption, while LDH/LDO introduces additional active sites through its layered structure. Studies have demonstrated that LDH/biochar composites achieve adsorption capacities of up to 400 mg/g for certain pollutants, such as heavy metals, which is considerably higher than the capacities of either pristine biochar or LDH alone (Dos Santos et al., 2021). Furthermore, functional groups such as -OH, -COOH, and C=O on biochar strongly interact with contaminants, while LDH contributes hydroxide layers and interlayer anions, enhancing chemisorption and complexation mechanisms. These properties make LDH/LDO-biochar composites particularly effective for removing heavy metals and dyes from wastewater (Yang et al., 2016).

Figure 6. Material characteristics

Another critical feature of these composites is their high ion exchange capacity. LDH's intercalated anions enable the exchange with pollutants such as phosphate, nitrate, and ammonium, while biochar offers moderate cation exchange capacity. This synergy allows the efficient removal of a diverse range of contaminants. For example, engineered biochars have demonstrated phosphate removal efficiencies of up to 95% under controlled conditions (Shakoor et al., 2021). Furthermore, the combined buffering capabilities of biochar and LDH ensure stable adsorption performance across a wide range of pH levels, which is critical for treating wastewater under varying environmental conditions (Mittal, 2021).

The structural stability and regeneration potential of these composites are also noteworthy. Biochar contributes mechanical durability, while the “memory effect” of LDOs allows the material’s structure to regenerate upon hydration. This combination enables long-term use and reusability of the materials. For instance, LDH/biochar composites have demonstrated over 80% regeneration efficiency after multiple adsorption and desorption cycles (Daud et al., 2019). This durability ensures that these materials are not only efficient but also cost-effective and environmentally sustainable.

Moreover, LDH/LDO-biochar composites offer dual functionality for both water treatment and soil remediation. The materials can adsorb pollutants and simultaneously release nutrients, such as ammonium and phosphate, into the soil, making them suitable for agricultural applications. Such versatility is exemplified by studies on LDH-modified biochars, which recover valuable nutrients from wastewater for reuse as fertilizers (Wei et al., 2018). This adaptability highlights their potential to address environmental challenges sustainably. Table 2 also summarises the advantages of combining LDH or LDO in biochar for treating wastewater.

Table 2. Contribution of materials in the removal of pollutants

Characteristics	**Biochar contribution**	**LDH/LDO contribution**	**Synergic effect**
High surface area	Porous structure	Layered structure	Enhanced adsorption capacity
Functional groups	-OH, -COOH, C=O	Hydroxide layers, interlayer anions	Strong chemisorption and complexation
Ion exchange capacity	Limited	High anion exchange capacity	Efficient removal of cationic/anionic metals
pH buffering	Moderate	High	Stable adsorption across pH ranges
Structural stability	Durable	Memory effect (LDO)	Regeneration and reuse potential
Selective adsorption	Porosity and functional groups	Layered structure and chemistry	Targeted removal of specific metals
Adsorption kinetic	Rapid diffusion	High surface area	Faster adsorption rates

Sustainability	Renewable biomass	Cost-effective synthesis	Low-cost, eco-friendly adsorbent
Dual-functionalization	Adsorption	Nutrient release	Soil remediation and water treatment
Versality	Broad pollutant range	Specific ion selectivity	Effective for diverse contaminants

3.4 Modification and Functional Tuning

The modification of biochar using LDOs and LDHs has become a highly researched approach to significantly enhance biochar's environmental remediation capabilities, particularly in CO_2 capture and phosphate removal. Although biochar itself has a carbon-rich and porous structure, which makes it a viable adsorbent, it is often limited by a low surface area and relatively few functional groups for pollutant interaction. Integrating LDOs or LDHs into the biochar matrix addresses these limitations, improving both its structural and chemical properties for adsorption applications. For instance, a notable improvement in CO_2 adsorption is seen in cellulose-derived biochar when modified with magnesium-aluminum LDOs (Mg-Al LDOs), where an increase of up to threefold in CO_2 capture is attributed to a higher number of basic sites created by the LDOs post-calcination (Taher et al., 2023). This synthesis and subsequent application of biochar-LDO and biochar-LDH composites present compelling advancements in pollutant adsorption. In addition, for easy understanding of the different characteristics of these materials, Figure 7 shows the common comparison of biochar-LDH and biochar-LDO.

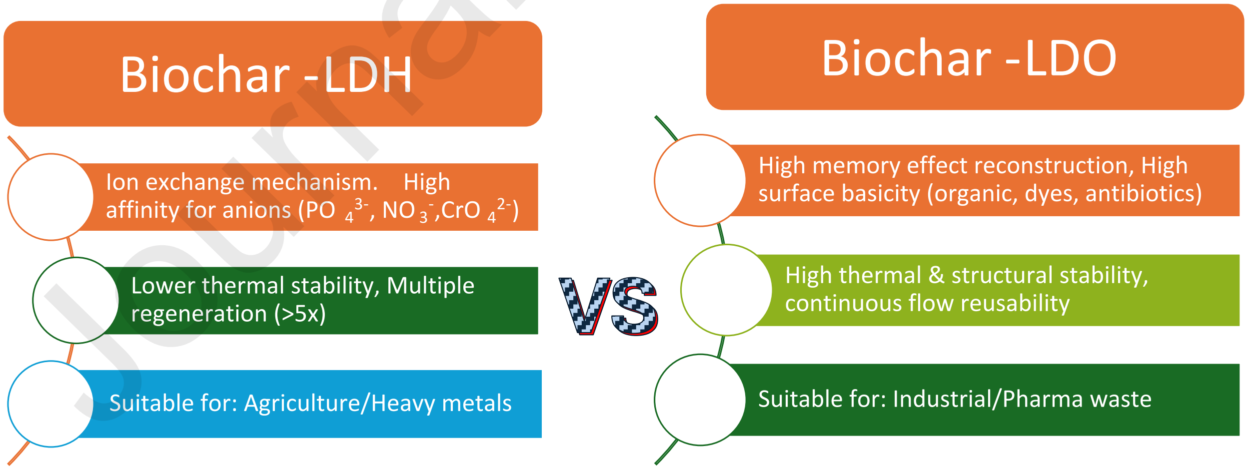


Figure 7. Comparative Overview: Biochar-LDH vs Biochar-LDO in Water Treatment

Biochar-LDO composites, especially those modified with Mg-Al LDOs, demonstrate enhanced CO_2 adsorption due to the calcination process, which transforms LDHs into LDOs and leads to increased surface basicity. This change optimizes biochar for CO_2 chemisorption, where the acidic

CO_2 molecules interact strongly with the basic sites on the LDOs. The high surface basicity of Mg-Al LDOs, generated through this calcination process, makes biochar-LDO composites especially suitable for CO_2 adsorption, an area of significant interest in climate change mitigation efforts (Taher et al., 2023). In addition, using advanced characterization techniques like scanning electron microscopy (SEM) and Fourier transform infrared (FTIR) spectroscopy allows for detailed analysis of these basic sites, further confirming the functional improvement in CO_2 capture capabilities (Taher et al., 2023).

In contrast, biochar-LDH composites are modified primarily for aqueous pollutant removal due to their unique layered structure and anion exchange capacity. For example, vegetable biochar modified with Mg-Al LDHs has shown considerable efficiency in phosphate removal. LDHs, with their hydroxide sheets bearing positive charges balanced by anions in the interlayer spaces, are highly conducive to anion exchange. Studies demonstrate that Mg-Al LDH biochar composites can reach over 92% phosphate removal efficiency across a range of pH values, achieving rapid adsorption kinetics and equilibrium within minutes (Z. Zhang et al., 2019a). The adsorption efficiency in these composites arises from a combination of mechanisms, including electrostatic attraction, surface complexation, and the capacity for anion exchange. Here, the LDH's lamellar structure is integral, as it provides high porosity and multiple functional sites for adsorption, making biochar-LDH composites highly effective for aqueous applications like phosphate removal.

The distinctions between biochar-LDO and biochar-LDH composites underscore the importance of understanding both structure and adsorption mechanisms in targeting specific pollutants. Biochar-LDO composites, with their enhanced surface basicity post-calcination, are ideally suited for CO_2 capture as they favor chemisorption processes for acidic gases. Biochar-LDH composites, however, retain their layered structure and interlayer anions post-synthesis, which is crucial for adsorbing anionic pollutants such as phosphates through what is known as the “memory effect.” This memory effect allows LDHs to reconstruct their original layered structure in the presence of water, enabling consistent anion exchange and reuse across multiple adsorption cycles without significant loss in adsorption performance (Z. Zhang et al., 2019a). Thus, while both biochar-LDO and biochar-LDH composites demonstrate broad potential in environmental applications, their differences in adsorption mechanisms make them complementary solutions, adaptable depending on whether gaseous or aqueous pollutants are the target.

Comparing modified biochar with other adsorbents, such as activated carbon and zeolites, reveals further advantages in terms of sustainability and cost. Biochar can be produced from waste biomass, making it an economically feasible and sustainable alternative to more costly materials like activated carbon. Activated carbon, though effective, involves resource-intensive production processes, while zeolites, another commonly used adsorbent, can pose environmental concerns related to extraction and synthesis. In contrast, biochar modification through LDOs and LDHs can yield a highly effective material for pollutant removal without the extensive energy demands of traditional adsorbents (Mohit, 2024; Wang et al., 2021). The multifunctionality of modified biochar extends beyond pollutant adsorption, as composites like KOH-modified biochar have demonstrated catalytic potential in biodegradation, significantly enhancing the removal of contaminants such as tetracycline and chromium when compared to unmodified biochar (Q. Wang et al., 2023). These advantages underscore the potential for modified biochar to serve as a cost-effective and versatile alternative to conventional adsorbents, particularly in areas where resource sustainability is a concern.

The durability and reusability of biochar-LDH composites also contribute to their appeal for practical applications. Studies have shown that these composites maintain their adsorption efficiency over multiple cycles, a critical factor for long-term use in water treatment facilities where continuous operation is required. For instance, a previous study highlighted the regeneration capabilities of biochar-LDH composites, demonstrating minimal loss of adsorption capacity even after multiple reuse cycles, which is essential for the economic feasibility of large-scale wastewater treatment systems (Amri, 2023; Zhang et al., 2018). This regeneration ability not only supports cost-effective water treatment but also minimizes waste production associated with single-use adsorbents, further solidifying biochar's role in sustainable remediation practices.

Furthermore, modification with LDHs can impart unique structural stability to biochar, making it more resilient under variable environmental conditions. This stability allows BIOCHAR-LDH composites to perform effectively in diverse scenarios, from highly acidic to moderately alkaline conditions, which often challenge the structural integrity of traditional adsorbents (Siregar et al., 2021). In particular, Mg/Al-LDH-modified biochar has shown stability in environments with fluctuating pH and high ionic strength, maintaining a high capacity for phosphate and nitrate removal in real-world water treatment contexts (S. Li et al., 2021; Ma et al., 2022). By comparison, other adsorbents may experience reduced efficacy or structural degradation under similar conditions, underscoring the advantages of LDH modifications in biochar's adaptability and long-term effectiveness.

Finally, exploring modifications with both LDOs and LDHs introduces flexibility in customizing biochar composites to specific pollutant profiles. For instance, the versatility of LDHs allows for the incorporation of various metal ions, enabling researchers to tailor the adsorbent's properties for specific applications. A previous study investigated ZnCr/C-LDH nanocatalysts and observed that metal variations could even extend applications to photocatalytic functions, thus broadening biochar-LDH composites' functionality beyond adsorption to include potential roles in photocatalysis and environmental remediation (Zarewa and Muhammad, 2022). This ability to adjust the composition and structure of LDHs facilitates the development of targeted adsorbents, capable of addressing a wide array of environmental contaminants.

Thus, the modification of biochar with LDOs and LDHs enables the creation of composites with enhanced adsorption properties tailored to specific environmental challenges. While LDO-modified biochars, with their high surface basicity, are optimized for CO_2 capture, LDH-modified biochars excel in aqueous pollutant removal through effective anion exchange mechanisms. By presenting sustainable and multifunctional alternatives to traditional adsorbents, these modified biochars represent an innovative and versatile approach to pollution control across different environmental media. Future research should continue to optimize synthesis methods, improve stability, and explore further applications, ensuring these materials remain at the forefront of sustainable water and air purification technologies.

3.5 Head-to-Head Performance Comparison with Case-based Insights

The performance comparison between biochar-LDH and biochar-LDO composites underscores their distinctive features, operational advantages, and pollutant-specific affinities, positioning each as a viable but context-dependent material in water pollution control. Both composites exhibit promising adsorption behaviors, but their differences in structural chemistry, regeneration potential, and target pollutant profiles enable tailored applications. **Table 3** summarises the several properties in biochar-LDH vs. biochar-LDO according to published papers.

Table 3. Biochar-LDH vs. biochar-LDO comparison in several features

Properties	Biochar-LDH	Biochar-LDO
Target pollutants	Heavy metals (Pb^{2+}, CrO_4^{2-}), phosphate, nitrate, dyes, antibiotics (Alagha et al., 2020; H. Wang et al., 2020b)	Nanoplastics, dyes, and antibiotics (Sun et al., 2023; Yu et al., 2025b)
Adsorption Mechanisms	Anion exchange, complexation, redox reactions, electrostatic interaction (Alagha et al., 2020)	Memory effect (reconstruction into LDH), π–π interactions, hydrogen bonding, electrostatic attraction (Sun et al., 2023)
Typical Adsorption Capacity	Pb^{2+}: ~591 mg/g, CrO_4^{2-}: ~330 mg/g, Phosphate: up to 178 mg/g (Alagha et al., 2020; H. Wang et al., 2020b)	Nanoplastics: up to 360 mg/g, Congo red: up to 4841 mg/g (Sun et al., 2023; Yu et al., 2025b)
Regeneration and Reuse	Good recyclability, effective across multiple cycles (Alagha et al., 2020)	Excellent repeatability and continuous use demonstrated in column studies (Yu et al., 2025b)
Stability & Structure	Stable in water; electrostatic sites susceptible to fouling (Alagha et al., 2020)	More robust due to calcination; stable structure with high surface area (Sun et al., 2023)

Biochar-LDH composites demonstrate robust removal capacities for heavy metals and anions due to their intrinsic LDH structure. The intercalated anions within LDH layers can be exchanged readily with contaminant ions such as phosphate, nitrate, and chromate, facilitating efficient anion capture. For instance, biochar-LDH has shown high performance in removing Pb^{2+} (~591 mg/g), CrO_4^{2-} (~330 mg/g), and phosphate (up to 178 mg/g), even in the presence of competing anions (Alagha et al., 2020; H. Wang et al., 2020b). This high selectivity is attributed to electrostatic interactions, anion exchange, and complexation mechanisms inherent in the LDH structure. Moreover, LDH composites have demonstrated stable performance across wide pH ranges, further supporting their versatility in complex wastewater matrices.

In contrast, biochar-LDO composites obtained by calcining LDH exhibit higher surface area, increased basicity, and enhanced thermal stability, making them suitable for catalytic and oxidative degradation processes. These features are especially advantageous for the removal of dyes, antibiotics, and nanoplastics. For example, LDO-based composites exhibited exceptional adsorption capacity for Congo red (~4841 mg/g) and ciprofloxacin (744 mg/g), along with nearly complete pollutant removal in real wastewater (Sun et al., 2023; Yu et al., 2025b). The elevated performance is attributed to the "memory effect," which allows LDOs to reconstruct their layered structure in aqueous environments, enhancing reusability and regeneration. In column studies, biochar-LDOs sustained their adsorption capacity over extended cycles, offering significant benefits for continuous treatment systems.

While biochar-LDH systems show better performance in heavy metal removal and phosphate capture, biochar-LDOs excel in treating complex organics and emerging contaminants. The distinction extends to dyes: while LDH composites achieved 266 mg/g for Congo red, LDO composites reached as high as 795 mg/g, showcasing LDO's superiority in dye adsorption (Mai et al., 2021). Similarly, LDO systems demonstrated higher efficacy in removing organic compounds like antibiotics and nanoplastics, with documented capacities of 360 mg/g for polystyrene nanoplastics and over 4800 mg/g for Congo red, quantitatively outperforming LDH systems by a significant margin. **Table 4** showed the performance comparison for both biochar-LDH and biochar-LDO according to the previous research.

Table 4. Performance comparison of materials

Pollutants	**Biochar-LDH**	**Biochar-LDO**	**References**
Heavy metals (Pb^{2+}, CrO_4^{2-})	Pb^{2+}: ~519 mg/g CrO_4^{2-}: ~330 mg/g	Less studied for heavy metals	(H. Wang et al., 2020b)
Phosphate (PO_4^{3-})	177.97 mg/g (Langmuir capacity).	>92% removal efficiency across pH 2–10	(Alagha et al., 2020; Z. Zhang et al., 2019b)

	High selectivity even in presence of competing ions		
Nitrate (NO_3^-)	~28 mg/g (Langmuir capacity). Competing Cl^- and PO_4^{3-} reduce efficiency slightly	N/A	(Alagha et al., 2020)
Dyes (Congo red, methylene blue)	MB: ~92 mg/g CR: 266 mg/g (LDH–SB composite)	N/A	(Alagha et al., 2020)
Antibiotics (e.g. Ciprofloxacin)	N/A	CR: ~4841 mg/g CIP: ~744 mg/g Removal in real wastewater: 99% (CR), ~89% (CIP)	(Yu et al., 2025b)
Nanoplastics	N/A	Polystyrene nanoplastics: 360 mg/g. High selectivity predicted and validated by QSAR modeling	(Sun et al., 2023)
Organic pollutants (e.g. Diclofenac)	SDS-LDH/BC: 169 mg/g (DFS), 81% removal at pH 8.0	SDS-LDO/Bio: 36% DFS removal	De Jesus et al., 2024)
Phenol (with biochar support)	~86% removal using wood-derived biochar (non-specific to LDH/LDO)	Same system achieved enhanced methanogenesis with phenol removal and bioelectronic advantages	(Pan et al., 2021)

In terms of reusability, both composites show promise. However, LDO's enhanced structural rigidity post-calcination renders it more durable under varied operational conditions. While LDH composites are slightly more prone to fouling due to electrostatic interactions with charged contaminants, they still maintain adsorption efficiency over multiple regeneration cycles, with some studies reporting over 80% efficiency retained after five cycles (Alagha et al., 2020). This makes both systems economically viable, although the longevity and continuous operation potential of LDO systems may provide additional operational value in industrial-scale implementations.

Several case studies have reported the successful application of both biochar-LDH and biochar-LDO composites in real wastewater environments. For instance, column experiments using biochar-LDO demonstrated sustained pollutant removal over multiple cycles, indicating excellent operational stability and regeneration performance (Yu et al., 2025b). Similarly, batch and continuous systems employing biochar-LDH materials have shown consistent removal efficiencies for heavy metals and anions in complex matrices, including municipal and agricultural wastewater (Alagha et al., 2020). These experimental findings support the comparative insights derived from the literature and underscore the practical relevance of these materials in field-scale applications. Overall, the comparative analysis suggests that biochar-LDH composites are optimal for applications targeting anionic pollutants (e.g., phosphate, chromate, nitrate) and heavy metals, particularly under conditions where rapid ion exchange and broad pH tolerance are necessary. In contrast, biochar-LDO composites are more suitable for removing organic pollutants, nanoplastics, and pharmaceuticals, especially in settings requiring high thermal or chemical stability and prolonged operational reuse.

Therefore, material selection should be guided by the specific pollutant profile, operational environment, and treatment objectives. Future studies should explore hybrid systems that integrate the anion exchange capacity of LDH with the catalytic stability of LDO, offering synergistic removal pathways. In addition, the development of composite systems tailored for multifunctional pollutant removal, including simultaneous heavy metal, dye, and pharmaceutical treatment, remains a promising direction to enhance wastewater treatment sustainability and efficiency. Incorporating these case-based examples helps reinforce the validity of this literature-driven analysis and underscores the practical potential of both material classes under real-world environmental conditions. However, scaling up poses certain challenges, including the need for consistent material quality, efficient regeneration methods, and integration into existing infrastructure. The synthesis of LDH or LDO-modified biochars must also be optimized for bulk production, potentially through low-temperature co-pyrolysis or pelletization techniques. Transport, backpressure management, and leaching risks must be considered in full-scale applications. Nevertheless, the use of locally available biomass and the adaptability of these materials into modular adsorption columns offer a promising pathway for decentralized and cost-effective treatment, particularly in rural or resource-limited regions. Future work should focus on techno-economic assessments and lifecycle evaluations of these systems to guide policy and industrial adoption.

Despite the promising regeneration capabilities of both biochar-LDH and biochar-LDO composites, several challenges can affect their long-term stability, especially under real wastewater conditions. Studies have shown that prolonged exposure to complex wastewater matrices rich in competing ions, organic matter, and microbial activity can gradually reduce adsorption efficiency (Vithanage et al., 2020b; Zubair et al., 2021c). For example, fouling of the LDH surface by organic pollutants or biofilms may block active sites, while repetitive ion exchange cycles can lead to partial delamination or loss of interlayer integrity (Alagha et al., 2020). In the case of LDOs, although their calcined structure offers enhanced durability, repeated hydration and regeneration may weaken the "memory effect" or result in the leaching of constituent metal ions, particularly when exposed to extreme pH or aggressive chemical regenerants (De Jesus et al., 2024; Mai et al., 2021). These issues underscore the importance of assessing adsorbent performance in dynamic and continuous-flow systems beyond controlled batch studies. Future research should thus emphasize pilot-scale evaluations, investigate stabilization strategies (e.g., polymer coating or secondary doping), and explore novel regeneration protocols that preserve the structural integrity of the materials while maintaining high removal efficiency across cycles.

3.6 Removal Mechanism

The removal mechanisms of biochar-LDO and biochar-LDH composites in water pollution control represent a complex interplay of adsorption, ion exchange, and chemical interactions. These materials, which combine the high surface area and porosity of biochar with the ion-exchange and pollutant-specific affinities of LDOs and LDHs, have shown notable efficacy in capturing both organic and inorganic contaminants. Such composites are particularly effective in the removal of phosphorus compounds, heavy metals, and other prevalent industrial and agricultural pollutants, addressing critical challenges in water treatment. The removal mechanisms of these composites draw upon biochar's natural adsorptive properties enhanced by LDO and LDH modifications, resulting in highly efficient, multifunctional adsorbents.

The structure and chemical characteristics of biochar-LDO composites make them particularly well-suited for capturing anionic pollutants like phosphates. Biochar, a porous, carbon-rich material produced via pyrolysis, already serves as a powerful adsorbent due to its high surface area, but when modified with LDOs, its adsorptive potential is significantly increased. The incorporation of LDOs creates more basic sites, which have a high affinity for acidic molecules like CO_2, as well as for negatively charged ions, especially in nutrient-rich wastewater containing phosphorus compounds. Biochar-LDOs remove pollutants mainly through surface adsorption and ion exchange, a process whereby phosphate ions displace hydroxide ions in the LDO layers, harnessing the "memory effect" of LDOs. This phenomenon allows for rehydration and structural restoration of the LDO's layered configuration, facilitating continuous ion-exchange interactions (Taher et al., 2023). Electrostatic attraction between the negatively charged phosphate ions and the positively charged metal centres in the LDO layers further enhances the material's pollutant removal efficiency, making biochar-LDO composites a potent tool in water treatment, particularly in preventing eutrophication caused by excess phosphates in aquatic systems (Z. Zhang et al., 2019a).

In addition to their effectiveness in phosphate removal, biochar-LDO composites exhibit broad adsorptive capabilities for a wide range of other pollutants, including heavy metals, organic pollutants, and ions like nitrate and fluoride. The layered structure of LDOs confers high selectivity for anionic and weakly acidic contaminants, which are prevalent in industrial wastewater. This selectivity arises from the ion-exchange capabilities of the LDO layers, which can accommodate a variety of contaminant ions. The biochar component, with its extensive porosity and high surface area, enhances the diffusion of pollutants into the material's matrix, thereby improving adsorption kinetics and allowing the composite to reach adsorption equilibrium quickly (Z. Zhang et al., 2019a). This combination of rapid kinetics and high adsorption capacity has established biochar-

LDOs as valuable for applications in wastewater treatment, where a mixed contaminant profile is often present.

The removal mechanisms of biochar-LDH composites also leverage the unique properties of LDHs, materials characterized by a layered structure and substantial anion exchange capacities. LDHs are particularly adept at capturing anionic pollutants like phosphates, nitrates, and heavy metals, complementing biochar's high surface area and porosity. For instance, biochar-LDH composites exhibit an ion-exchange mechanism where anionic contaminants, such as phosphates, replace interlayer anions (e.g., carbonate or hydroxide ions) within the LDH structure. This ion exchange is crucial to the material's high affinity for anionic pollutants, facilitating their effective capture from aqueous environments. Furthermore, studies have shown that Mg/Fe-LDH modified biochar, due to the LDH layers' ability to intercalate phosphate ions, offers superior phosphate adsorption capacity, making it suitable for water pollution control, especially in phosphate-laden agricultural wastewater (Ma et al., 2022; Shiriazar et al., 2022).

Besides ion exchange, LDH-modified biochar composites employ surface adsorption and chemical complexation mechanisms for capturing various pollutants. The biochar's carbon-rich structure naturally lends itself to hydrophobic interactions with organic pollutants, making these composites effective in adsorbing dyes, pharmaceuticals, and other industrial contaminants. For example, Mg-Al LDH-modified biochar has been shown to effectively remove methylene blue from water, underscoring its utility in tackling organic pollutants. Hydrophobic interactions between organic molecules and the carbonaceous biochar surface play a key role in this process (Hafiz et al., 2012; Y. Wang et al., 2020). The functional groups introduced during biochar modification with LDHs also enhance interaction with organic pollutants, as these groups facilitate hydrogen bonding and van der Waals interactions that further improve the material's adsorption efficiency.

In addition to adsorption and ion exchange, the role of functional groups on biochar-LDO and biochar-LDH surfaces is significant in the removal of various pollutants. Surface complexation occurs when functional groups on the biochar surface chemically bond with pollutant molecules, forming stable complexes. This is particularly relevant for phosphate removal, where surface functional groups, such as hydroxyl and carboxyl groups, on biochar form complexes with phosphate ions, augmenting the composite's overall adsorption capacity (Taher et al., 2023). Such surface interactions are beneficial in promoting high-throughput water treatment, as the material can capture pollutants effectively with minimal contact time.

Moreover, the structural stability of biochar-LDO and biochar-LDH composites under various environmental conditions enhances their practical utility. LDOs, when integrated into biochar, not only improve the composite's affinity for pollutants but also enhance its durability in diverse conditions, such as varying pH and ionic strength levels. This stability is essential in real-world applications where wastewater conditions can fluctuate, affecting the performance of many adsorbents. Additionally, the memory effect of LDOs, wherein their layered structure is restored upon hydration, allows these composites to maintain consistent pollutant capture performance over multiple adsorption-desorption cycles, highlighting their potential for sustainable use in water treatment systems (Wang, 2024; Zhu et al., 2020).

Biochar-LDH composites similarly exhibit strong structural stability, which is vital for their long-term application in wastewater treatment. The layered structure of LDHs not only provides a stable platform for adsorbing pollutants but also allows the composite to regenerate after use. Studies indicate that biochar-LDH composites can withstand multiple adsorption cycles without significant loss of capacity, an attribute essential for wastewater treatment, where continuous operation is required (Adelagun et al., 2021; Shiriazar et al., 2022). This structural resilience makes biochar-LDH composites economically viable for long-term applications, reducing the need for frequent adsorbent replacement and lowering operational costs.

The versatility of biochar-LDO and biochar-LDH composites extends to the removal of specific organic pollutants, including complex substances like dyes and pharmaceuticals. The carbon-rich biochar in these composites can adsorb organic molecules through hydrophobic interactions. At the same time, the LDO and LDH components provide additional active sites for adsorption, further broadening the spectrum of pollutants that can be targeted. Previous study illustrated the composite's efficacy in removing methylene blue, a common dye pollutant, from water, underscoring its adaptability to various water treatment challenges. Functional groups added during biochar modification improve the binding with organic pollutants, increasing removal efficiencies (Cruz et al., 2023).

A sophisticated combination of adsorption, ion exchange, and surface complexation drives the removal mechanisms in biochar-LDO and biochar-LDH composites. These composites, leveraging the unique properties of LDOs and LDHs, can effectively capture a wide range of pollutants from aqueous environments. Their ability to reach adsorption equilibrium rapidly, coupled with high regeneration potential, positions them as economically viable and sustainable solutions for large-scale water pollution control. Moving forward, optimizing the synthesis and exploring new applications of biochar-LDO and biochar-LDH composites will be crucial in advancing water treatment technologies tailored to diverse environmental contaminants.

3.7 Isotherm, Kinetics and Thermodynamics of Materials

The adsorption behaviors of biochar-LDH and biochar-LDO composites have been characterized using isotherm, kinetic, and thermodynamic models. These models help reveal the underlying mechanisms of adsorption, evaluate adsorption efficiencies, and assess how factors like temperature and contaminant concentration influence the adsorption processes. As biochar-LDH and biochar-LDO composites are increasingly used for environmental remediation, understanding these parameters enables more targeted applications, optimizing pollutant removal performance and guiding further material design.

Isotherm models provide insight into how contaminants interact with the surfaces of biochar composites, defining whether adsorption takes place as a monolayer or as a multilayer. The two most frequently applied models, the Langmuir and the Freundlich models, illustrate the nature of adsorption sites and predict maximum adsorption capacities under various conditions.

The **Langmuir isotherm model** assumes monolayer adsorption at specific homogeneous sites on the adsorbent surface, implying a finite number of identical sites without interaction between adsorbed molecules. The Langmuir equation is defined as:

$$q_e = \frac{q_m K_L C_e}{1 + K_L C_e}$$

Where (q_e) represents the pollutant adsorbed per unit weight of the adsorbent, (q_m) is the maximum adsorption capacity, (K_L) is the Langmuir constant related to binding affinity, and C_e is the equilibrium concentration of the pollutant. For biochar-LDH composites, the Langmuir model typically fits well, indicating a monolayer adsorption process. This is attributed to the LDH structure's uniform sites, facilitating effective electrostatic attraction and ion exchange for anions such as phosphates. Studies, for example, show that Mg-Al LDH-modified biochar achieves a high monolayer adsorption capacity for phosphates, as LDH layers enable consistent adsorption across homogeneous sites (Z. Zhang et al., 2019a).

In contrast, biochar-LDO composites often exhibit deviation from the Langmuir model. Due to the heterogeneity introduced by the calcined oxide structure of LDOs, adsorption in these composites can involve a combination of physical and chemical interactions rather than a single uniform process. This heterogeneity is better represented by the Freundlich isotherm model, which applies to surfaces with varied affinities and suggests multilayer adsorption. The Freundlich equation is expressed as:

$$q_e = K_F C_e^{1/n}$$

where (K_F) is the Freundlich constant indicative of adsorption capacity, and ($1/n$) is a measure of adsorption intensity. The Freundlich model is particularly suited for biochar-LDO composites, where the larger surface area and porosity facilitate multilayer adsorption, making them adaptable for capturing various contaminants. For instance, biochar-LDO composites' structural diversity allows a range of pollutants to adhere through both physisorption and chemisorption, enhancing their suitability for complex water treatment contexts (Taher et al., 2023).

Kinetic models elucidate the rates and mechanisms controlling the adsorption process, distinguishing between physisorption and chemisorption as predominant adsorption modes. The pseudo-first-order and pseudo-second-order kinetic models are commonly applied to evaluate the adsorption behaviors of biochar composites.

The pseudo-first-order model suggests that the adsorption rate is proportional to the number of unoccupied sites. The linear form of this model is:

$$\log(q_e - q_t) = \log q_e - \frac{k_1}{2.303} t$$

where (q_t) is the amount of pollutant adsorbed at time (t), (k_1) is the rate constant, and (q_e) represents the adsorption capacity at equilibrium. For biochar-LDH and biochar-LDO composites, the pseudo-first-order model generally does not provide a satisfactory fit, suggesting that adsorption in these systems is not governed by simple physisorption. Instead, the adsorption in biochar composites is typically driven by more complex interactions that the pseudo-second-order model better describes (Taher et al., 2023).

The pseudo-second-order model is more appropriate for biochar-LDH and biochar-LDO composites as it assumes that adsorption is controlled by chemisorption, where the rate depends on the availability of adsorption sites and the formation of chemical bonds. This model is expressed as:

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e}$$

where (k_2) is the pseudo-second-order rate constant. This model often accurately describes the adsorption kinetics of both biochar-LDH and biochar-LDO, indicating that chemisorption is dominant. For biochar-LDH composites, adsorption involves ion exchange and electrostatic interactions, where anions like phosphates are attracted to the positively charged sites within the LDH layers. In biochar-LDOs, chemical bonding with surface functional groups facilitates pollutant removal. For example, the pseudo-second-order model aligns with the phosphate adsorption rates observed in biochar-LDH composites, reflecting efficient contaminant capture through ion exchange mechanisms and electrostatic interactions (Z. Zhang et al., 2019a).

Thermodynamic parameters, namely Gibbs free energy (ΔG), enthalpy (ΔH), and entropy (ΔS), are essential for understanding the spontaneity, heat exchange, and disorder associated with adsorption in biochar composites. These parameters help determine whether the adsorption process is endothermic or exothermic and provide insights into how temperature affects pollutant capture.

Gibbs free energy change (ΔG) indicates the spontaneity of the adsorption process, calculated as:

$$\Delta G = -RT \ln K_c$$

where (R) is the gas constant, (T) is the temperature, and (K_c) is the equilibrium constant. Negative (ΔG) values for both biochar-LDH and biochar-LDO systems confirm that the adsorption process is spontaneous. This spontaneity suggests that pollutant capture by these composites is thermodynamically favorable, making them suitable for practical applications in water treatment where rapid and effective adsorption is desired.

The enthalpy (Delta H) and entropy (Delta S) of the adsorption process can be derived from the Van't Hoff equation:

$$\ln K_c = \frac{\Delta S}{R} - \frac{\Delta H}{RT}$$

A positive (ΔH) signifies an endothermic process, typical in biochar-LDH and biochar-LDO systems, where adsorption capacity increases with temperature. In LDH-modified biochar, the higher (ΔH) values indicate more substantial chemisorption, as ion exchange and binding within the LDH structure involve energy uptake. In comparison, the thermodynamic favorability of biochar-LDO composites is also linked to increased randomness at the solid-solution interface, signified by positive (ΔS) values. This increase in disorder is particularly evident in multilayer adsorption systems, where biochar-LDO composites effectively capture a variety of ions and molecules from solution, consistent with adsorption of multi-species ions like phosphates (Taher et al., 2023). **Table 5** showed the materials' performance and their sorption characteristics, including kinetic, isotherm models and thermodynamic.

Table 5. Material performance and sorption characteristics

Material	Performance	Kinetic	Isotherm	Thermodynamic	Ref
Magnetic Biochar/MgFe-LDH	Adsorption capacity up to ~476 mg/g at 25°C	Follows pseudo-second-order model.	Langmuir	Spontaneous and endothermic adsorption.	(Jia et al., 2019)
Vegetable Biochar/LDO Composite	Over 95% removal within 5 minutes.	pseudo-second-order	Langmuir and the Freundlich models.	N/A	(Z. Zhang et al., 2019a)
MgFe-LDO Biochar	Sorption capacity up to ~152 mg/g	Elovich kinetic mode	Langmuir model	pH-dependent adsorption affected by competing ions.	(Yang et al., 2019)
Biochar/MgAl-LDH	Sorption capacity up to ~302 mg/g.	Pseudo-second-order model	Langmuir model.	N/A	(Zubair et al., 2020)
CaFe/LDH-Biochar	Adsorption Capacity: ~99 mg/g at 55°C.	Freundlich model.	Pseudo-n order model.	N/A	(Missau et al., 2022)
Ramie Biomass-Derived Biochar/LDO	N/A	Film-diffusion and intra-particle diffusion	Freundlich model.	Spontaneous and endothermic adsorption.	(Xiao-fei Tan et al., 2016)
MgAl-LDH/Biochar	Adsorption Capacity: ~26 mg/g at 40°C.	Pseudo-first-order model ($R^2 = 0.95$).	Redlich–Peterson model ($R^2 > 0.99$).	Endothermic adsorption.	(Dos Santos Lins et

					al., 2019)
Fe_3O_4/Mg-Al-LDH		Pseudo-second-order model.	Langmuir equation.	Endothermic and spontaneous adsorption.	(Shan et al., 2015)
Biochar-LDO Composite	Adsorption Capacity: ~177 mg/g for phosphate	Pseudo-second-order model.	N/A	pH-dependent, endothermic adsorption.	(Alagha et al., 2020)
Kiwi Biochar/MgFe-LDH	Adsorption Capacity: ~25 mg/g	Pseudo-second-order model.	N/A	Favorable at low ionic strength.	(Tan et al., 2019)
Biochar-LDH	N/A	Elovich kinetic model.	Langmuir model.	Nonspontaneous adsorption.	(Amin et al., 2022)

Thus, biochar-LDH and biochar-LDO composites exhibit distinct isotherm and kinetic behaviors, with the Langmuir model fitting biochar-LDH monolayer adsorption and the Freundlich model capturing the multilayer adsorption of biochar-LDO composites. The pseudo-second-order model consistently describes the kinetics of adsorption in both composites, highlighting chemisorption as the primary mechanism. Thermodynamically, the negative Gibbs free energy indicates that the adsorption processes for both biochar composites are spontaneous, with positive enthalpy and entropy changes, further confirming the chemisorption-dominated, endothermic nature of adsorption, especially at elevated temperatures. Understanding these models not only validates the efficacy of biochar-LDH and biochar-LDO composites for water treatment but also guides future optimizations for enhanced pollutant capture across diverse environmental conditions.

3.8 Environmental Benefits and Economic Analysis

Biochar-LDH and biochar-LDO composites provide substantial environmental and economic benefits, particularly in pollution control, resource recovery, and climate mitigation. These composites, produced from renewable biomass, offer sustainable alternatives to conventional adsorbents, addressing various environmental challenges, such as nutrient pollution, greenhouse gas emissions, and heavy metal contamination. The following synthesis explores the environmental and economic implications of biochar-LDO and biochar-LDH composites.

3.8.1 Environmental Benefits

The application of biochar-LDO composites in pollutant removal has notable environmental benefits. Due to their high adsorption efficiency for phosphates and other anions, biochar-LDOs can significantly mitigate nutrient pollution in water bodies, which is a major cause of eutrophication and harmful algal blooms. By removing these nutrients from wastewater, biochar-LDOs play a key role in preserving aquatic ecosystems and promoting biodiversity. The research emphasize that the removal of phosphates through biochar-LDOs is crucial for preventing ecosystem degradation and maintaining water quality, particularly in regions affected by intensive agriculture and industrial waste discharges (Z. Zhang et al., 2019a).

Biochar-LDO composites are also made from renewable biomass, making them a sustainable choice over traditional adsorbents that rely on non-renewable resources. This renewable production process reduces dependency on synthetic adsorbents, which are often associated with toxic byproducts and energy-intensive manufacturing. The biochar component contributes to carbon sequestration, and when integrated with LDOs, it creates a high-performing material that extends its life cycle and lowers the need for frequent replacements. As a result, biochar-LDO composites help capture and store CO_2, supporting climate mitigation efforts aligned with global initiatives to reduce greenhouse gas emissions. Taher et al. highlight that the CO_2 adsorption capabilities of biochar-LDOs align with climate goals, enhancing these composites' contribution to environmental sustainability (Taher et al., 2023).

The environmental benefits extend to biochar-LDH composites as well. LDHs improve the contaminant removal efficiency of biochar, particularly for pollutants such as heavy metals and arsenic, which pose long-term risks to both ecosystems and human health. The ion exchange and adsorption properties of biochar-LDH composites make them highly effective in water treatment applications, providing a low-cost, eco-friendly solution for wastewater remediation. This functionality supports efforts to protect water resources and reduce pollution load in natural ecosystems, positioning biochar-LDH composites as essential materials for environmental cleanup (Fang et al., 2021; Zhang et al., 2022).

3.8.2 Economic Analysis and Cost-Effectiveness

Economically, biochar-LDO and biochar-LDH composites are promising due to their low production costs, effectiveness, and regenerative capabilities. Biochar can be derived from inexpensive, widely available biomass sources, such as agricultural residues, making it an economically viable raw material for large-scale production. LDOs, particularly those based on magnesium-aluminum (Mg-Al) combinations, are also cost-effective, and combining them with biochar results in composites that are both affordable and highly efficient. This combination produces adsorbents that achieve high pollutant removal capacities at a fraction of the cost compared to conventional materials like activated carbon or synthetic ion-exchange resins. The study underscores that the affordability of biochar-LDO composites makes them ideal for industries requiring economical yet effective pollution control solutions (Z. Zhang et al., 2019a).

One of the economic advantages of biochar-LDO composites is their regenerability. These materials can retain their adsorption efficiency over multiple cycles, which reduces the need for frequent replacement and associated disposal costs. Regeneration techniques, such as simple washing and desorption, allow biochar-LDOs to be reused in water treatment processes, making them particularly valuable for industries that handle large wastewater volumes. This regeneration capability is essential for minimizing operational expenses, and the ability to perform effectively across various pH levels and water conditions broadens the applications of biochar-LDOs across sectors like agriculture, industry, and municipal water treatment, enhancing their economic impact (Taher et al., 2023).

Another potential economic benefit of biochar-LDO composites lies in the byproduct recovery opportunities they offer. Phosphates adsorbed onto biochar-LDOs can be desorbed and repurposed as agricultural fertilizers, establishing a closed-loop system that recycles nutrients from wastewater into valuable resources. This recovery not only minimizes waste but also generates economic returns by providing a marketable product in the form of recovered phosphates. As global concerns about phosphate shortages rise, this capability contributes to resource efficiency and aligns with circular economy principles by transforming waste into value. Previous research highlights that such resource recovery strategies from biochar-LDOs can create a sustainable revenue stream, adding economic value to environmental remediation efforts (Taher et al., 2023).

In evaluating the economic feasibility of biochar-LDH and biochar-LDO composites for large-scale wastewater treatment, it's essential to consider their production costs relative to conventional adsorbents. As illustrated in **Table 6**, the estimated costs for biochar-LDH and biochar-LDO composites range from \$1.00 to \$25.00 per kilogram, depending on synthesis methods and raw materials. In comparison, activated carbon and ion exchange resins are priced between \$0.50 to \$3.50 and \$0.75 to \$2.00 per kilogram, respectively. While the initial costs of biochar-based composites may be higher, their advantages such as the utilization of low-cost biomass feedstocks, potential for regeneration, and multifunctional pollutant removal capabilities can offset expenses over time. Moreover, the possibility of resource recovery, like phosphate reclamation, adds economic value, enhancing their appeal for sustainable wastewater treatment solutions.

Table 6. Comparative cost analysis of materials for wastewater treatment

Adsorbent	**Estimated cost**	**Remarks**
Biochar-LDH	\$1.00 – \$25.00	Cost varies based on synthesis methods and raw materials.
Biochar-LDO	\$1.00 – \$25.00	Similar to LDH composites, the cost is influenced by calcination processes.
Activated carbon	\$0.50 – \$3.50	Widely used; price depends on source material and activation method.

Ion exchange resin	\$0.75 – \$2.00	Prices vary based on resin type and application.

Note: The actual cost of adsorbent materials may vary significantly between countries and regions depending on raw material availability, local labor and energy costs, manufacturing scale, and regulatory factors.

3.8.3 Scalability and Market Opportunities

The scalability of biochar-LDO composites is another important factor in their economic viability. The production processes for these composites are relatively simple, often involving low-temperature pyrolysis and minimal chemical inputs. These conditions make biochar-LDO composites suitable for both decentralized, small-scale production and large-scale industrial manufacturing. With growing demand for sustainable pollution control technologies, biochar-LDO composites have potential market opportunities in areas such as wastewater treatment, soil remediation, and air purification. Their versatility also makes them attractive for industries that prioritize sustainable solutions. Zhang et al. note that engineered biochar composites are increasingly popular in environmental remediation, presenting considerable economic opportunities as governments and industries invest in eco-friendly technologies (Z. Zhang et al., 2019a).

Biochar-LDO and biochar-LDH composites deliver extensive environmental benefits by addressing pollution control needs sustainably. Their economic advantages stemming from low-cost production, high efficiency, and regenerative potential make them feasible for various applications. Additionally, the ability to recover and repurpose adsorbed contaminants aligns with circular economy principles, potentially generating additional revenue streams while enhancing resource efficiency. These characteristics position biochar-LDO and biochar-LDH composites as effective, scalable solutions for sustainable environmental remediation, supporting a transition to greener, cost-effective pollution control technologies.

3.9 Environmental Implications of Scaling Production

Scaling the production of biochar, particularly in its integration with LDH and LDO, presents significant environmental opportunities alongside notable challenges. Biochar, a carbon-rich material produced via pyrolysis of biomass, has been extensively studied for its applications in water treatment, carbon sequestration, and soil enhancement. However, the expansion of biochar production systems and their integration with LDHs and LDOs necessitates a critical examination of environmental impacts to maximize benefits while mitigating risks.

The environmental performance of biochar is heavily influenced by its production process. Pyrolysis, the primary method for biochar production, involves heating biomass under low oxygen conditions. Critical parameters such as pyrolysis temperature, feedstock type, and residence time dictate the physicochemical properties of the resulting biochar, directly impacting its adsorption capacity and long-term environmental stability (Bayartsengel et al., 2021; Domenico, 2024; Harvey et al., 2012). Higher pyrolysis temperatures, for instance, enhance biochar's surface area and carbon stability, rendering it more effective in water pollution control and carbon sequestration

(Cordovil et al., 2019; Shimabuku et al., 2016). Furthermore, the incorporation of LDHs and LDOs amplifies biochar's adsorption capabilities, enabling the removal of diverse pollutants through synergistic mechanisms such as ion exchange, surface adsorption, and catalytic degradation (Hong et al., 2021; Osman et al., 2022). While this integration offers significant promise, scaling production introduces challenges related to emissions, resource use, and waste management.

One key environmental benefit of biochar is its potential to mitigate greenhouse gas (GHG) emissions. Biochar applied to soils has been shown to reduce emissions of nitrous oxide (N_2O) and methane (CH_4), two potent GHGs, by improving soil aeration and altering microbial activity (Nsamba et al., 2015; Pereira et al., 2016). N_2O, with a global warming potential 296 times greater than CO_2, poses a significant climate risk, making biochar's mitigation capacity particularly critical (Pereira et al., 2016). Additionally, biochar enhances soil health by improving water retention, nutrient availability, and overall fertility, which can boost agricultural productivity in degraded soils (Singh et al., 2023; Xu et al., 2012). Such applications align with global efforts to enhance climate resilience and food security, particularly in regions facing resource constraints (Pandao, 2023; Woolf et al., 2010). However, achieving these benefits at scale requires the development of efficient production technologies that balance environmental benefits with economic feasibility.

Despite its benefits, the large-scale production of biochar introduces several environmental challenges. Pyrolysis processes can generate air pollutants, including particulate matter (PM), volatile organic compounds (VOCs), and other by-products, which pose health risks and contribute to air pollution if not properly controlled. (Pourhashem et al., 2018; Sparrevik et al., 2014). The choice of biomass feedstock also plays a pivotal role in determining the overall environmental footprint of biochar. For example, comparative studies in Belgium revealed significant differences in emissions and energy use between biochar produced from willow and pig manure, highlighting the importance of feedstock selection in optimizing environmental outcomes (Hamedani et al., 2019). To minimize these impacts, the adoption of standardized production practices and emission control technologies is crucial, along with life cycle assessments (LCAs) to identify hotspots of environmental burdens (Kamaruddin, 2019; You et al., 2017).

The integration of biochar with LDHs and LDOs enhances its sustainability by improving resource efficiency and reducing waste. LDHs and LDOs can synergistically interact with biochar, enabling enhanced adsorption of heavy metals, phosphates, and organic contaminants (Hong et al., 2021; Osman et al., 2022). Such combinations reduce the need for additional treatment agents, thereby lowering the environmental and economic costs associated with water pollution control. Furthermore, biochar-LDH and biochar-LDO systems align with circular economy principles by utilizing agricultural and forestry waste as feedstocks and enabling nutrient recovery from treated water. For example, phosphates adsorbed onto biochar-LDO composites can be desorbed and repurposed as fertilizers, creating a closed-loop system that minimizes waste while enhancing resource recovery (Pandao, 2023; Singh et al., 2023).

Socio-economic factors also play a significant role in the environmental implications of scaling biochar production. The use of agricultural residues and forestry by-products as feedstocks can promote rural development by creating economic opportunities in biochar production and application (Nsamba et al., 2015; Sparrevik et al., 2014). However, supportive policies and frameworks are essential to ensure that scaling efforts align with environmental and social goals. Policymakers must prioritize investments in clean production technologies, research and development, and public-private partnerships to address barriers such as high initial costs and limited market access (Pourhashem et al., 2018; Singh et al., 2023)

Furthermore, scaling the production of biochar and its integration with LDHs and LDOs offers a transformative approach to addressing environmental challenges in water treatment, climate mitigation, and resource management. While the environmental benefits of biochar, such as GHG reduction and soil enhancement, are well-documented, addressing production-related emissions and resource constraints is essential to ensure its sustainability. Future efforts should focus on optimizing production technologies, developing innovative applications, and fostering supportive policies that bridge environmental benefits with socio-economic gains. Through these strategies, biochar-LDH and biochar-LDO systems can play a pivotal role in advancing sustainable development goals and promoting environmental resilience.

3.10 Case Studies in Real World Applications

The integration of biochar with LDH and layered LDO has emerged as a promising solution for addressing global challenges in environmental pollution, particularly in water treatment, soil remediation, and carbon capture. The ability of these materials to combine adsorption, catalytic, and anion-exchange properties makes them versatile for removing contaminants such as heavy metals, phosphates, and organic pollutants. This section synthesizes findings from experimental studies and case applications to illustrate the effectiveness and adaptability of these composites in real-world contexts.

In water pollution control, biochar-LDH composites have demonstrated substantial efficiency in removing both inorganic and organic contaminants. Their high surface area, functional groups, and the anion-exchange capabilities of LDHs enable dual functionality in pollutant adsorption. For instance, studies have shown that Mg/Fe-LDH biochar derived from apple tree residues can effectively remove arsenate from aqueous solutions, achieving high removal rates while maintaining adsorption stability under varying pH conditions (Shiriazar et al., 2022). Similarly, a polyporous biochar-LDH composite developed for agricultural runoff treatment was capable of capturing both inorganic nitrogen and heavy metals, addressing non-point source pollution with significant efficiency (Zhang et al., 2018). This dual capability is crucial for mitigating eutrophication caused by nutrient-rich discharges into water bodies. Moreover, biochar-LDH composites have proven effective for the removal of phenolic compounds and other organic pollutants from wastewater, demonstrating versatility in industrial effluent management (Amri, 2023).

LDO-based composites extend these applications by offering enhanced adsorption performance due to their calcined structure, which creates higher surface basicity and porosity. For instance, biochar-LDO systems prepared through one-step calcination have been reported to triple CO_2 adsorption capacity compared to unmodified biochar, emphasizing their potential for carbon capture and sequestration applications (Taher et al., 2023). In phosphate removal, vegetable-based biochar combined with Mg-Al-LDOs has shown removal efficiencies exceeding 95% in wastewater systems while exhibiting stability across a broad pH range, making these composites particularly valuable for mitigating eutrophication risks (Z. Zhang et al., 2019a). This enhanced performance stems from the structural "memory effect" of LDOs, which allows for the reconstruction of their layered structure in the presence of anions, significantly increasing adsorption efficiency (He et al., 2010).

Another significant application lies in soil remediation, where biochar-LDO and biochar-LDH composites have been used to immobilize heavy metals and improve soil fertility. For example, bamboo-based biochar modified with LDHs demonstrated the ability to adsorb cadmium and lead while simultaneously providing nutrients through the gradual release of intercalated phosphates (Sujana, 2018). The recovery of these nutrients positions these composites as dual-function materials capable of pollution mitigation and agricultural enhancement. Furthermore, by utilizing agricultural residues as feedstocks, these systems align with circular economy principles, converting waste into high-value materials while promoting carbon sequestration (Taher et al., 2023).

Despite these promising outcomes, challenges remain in scaling these technologies for widespread implementation. Variations in feedstock, production methods, and environmental conditions can affect the adsorption efficiency of biochar-LDH and biochar-LDO composites, requiring standardized production protocols (Kumkum, 2024). Regeneration and reusability are also critical for maintaining economic and environmental viability. At the same time, biochar-LDO composites exhibit strong regeneration potential due to the "memory effect," but degradation over multiple adsorption cycles remains a limitation (Z. Zhang et al., 2019a). Addressing these issues through optimized design and policy support will be crucial for advancing their practical applications.

Biochar-LDH and biochar-LDO composites have shown exceptional promise across diverse environmental applications, including water treatment, soil remediation, and carbon capture. Their ability to efficiently remove a broad range of contaminants while aligning with sustainability goals highlights their potential as next-generation materials. Future research should focus on overcoming scalability challenges and enhancing their long-term stability to fully realize their transformative impact in addressing global environmental challenges.

3.11 Comparison with Other Adsorbents

The comparison of biochar-LDH and biochar-LDO composites with other adsorbents reveals their unique advantages in water pollution control, particularly in removing heavy metals, organic pollutants, and other contaminants. These composites combine the inherent porosity and functional group chemistry of biochar with the anion exchange, layered structure, and high adsorption capacity of LDHs and LDOs, making them highly efficient and versatile for environmental applications.

One of the most significant advantages of biochar-LDH and biochar-LDO composites over conventional adsorbents lies in their superior ability to target specific pollutants. For example, biochar modified with LDHs has demonstrated exceptional adsorption capacities for heavy metals such as lead (Pb^{2+}) and cadmium (Cd^{2+}), surpassing unmodified biochar and traditional adsorbents like activated carbon (Shen et al., 2017; Wu et al., 2019). The layered structure of LDHs enables anion exchange, which enhances pollutant binding efficiency through mechanisms such as electrostatic attraction and complexation (Liu et al., 2020). A study by Wu et al. highlighted the enhanced performance of LDH-modified biochar derived from spent mushroom substrate for Pb^{2+} adsorption, achieving significantly better results than activated carbon under similar conditions

(Wu et al., 2019). This ability to adsorb a diverse range of contaminants while maintaining cost-effectiveness and sustainability distinguishes biochar-LDH composites as highly competitive in the field of water treatment.

Compared to other advanced adsorbents, biochar composites offer distinctive versatility. Zhu et al. demonstrated that embedding biochar with molybdenum disulfide (MoS_2) achieved high adsorption capacities for Pb^{2+}, highlighting the potential of biochar as a platform for functionalization with diverse materials (Zhu et al., 2018). Furthermore, dual chemical modification of biochar, such as in studies targeting chromium (Cr(VI)) removal, has proven to enhance adsorption performance beyond that of conventional adsorbents (Yang et al., 2021). These findings suggest that while activated carbon and zeolites are effective for certain pollutants, the tunability and multifunctionality of biochar composites enable broader applicability, particularly when LDHs or LDOs are integrated.

Compared to other advanced materials such as metal-organic frameworks (MOFs) and covalent organic frameworks (COFs), biochar-LDH and biochar-LDO composites offer several practical advantages. While MOFs and COFs exhibit exceptionally high surface areas and tunable pore structures, they often face challenges related to hydrothermal instability, high synthesis cost, and limited scalability in aqueous environments. In contrast, biochar-based composites can be synthesized from low-cost biomass with relatively simple procedures, and demonstrate robust stability in real wastewater conditions. Moreover, biochar-LDH/LDO materials provide dual benefits of ion exchange and catalytic degradation, which can match or exceed the performance of MOFs or COFs in specific applications such as phosphate and dye removal.

For instance, ZIF-67/LDH@C, a composite of MOF and LDH, demonstrated superior adsorption capacities for Pb^{2+}, malachite green, and Congo red, with maximum adsorption capacities of ~662 mg/g, ~1729 mg/g, and ~526 mg/g, respectively (Cai et al., 2023). Similarly, COFs have shown excellent adsorption performance due to their low mass densities and ease of pore structure tailoring, which provide more options for the selective elimination of target pollutants (Liu et al., 2021).

The mechanisms underlying the adsorption processes further underscore the unique advantages of biochar-LDH and biochar-LDO composites. Functional groups on biochar surfaces interact synergistically with the adsorption properties of LDHs and LDOs, facilitating multiple mechanisms, including ion exchange, surface complexation, and pH-dependent electrostatic attraction (Gai et al., 2014; S. Wang et al., 2023). For instance, adsorption of Pb^{2+} onto biochar-LDH composites increases as pH rises, enhancing the biochar's negative surface charge and its affinity for positively charged metal ions (Wu et al., 2019). This adaptability to environmental conditions provides an edge over other adsorbents that may have fixed or limited response ranges. Moreover, biochar-LDO systems, due to their calcined nature, offer enhanced porosity and surface basicity, which improve their capacity for adsorbing CO_2 and other pollutants (Taher et al., 2023).

Sustainability considerations also elevate biochar-LDH and biochar-LDO composites over conventional adsorbents. While activated carbon and zeolites often require non-renewable raw materials and energy-intensive production processes, biochar is derived from biomass waste, aligning with circular economy principles (Feng et al., 2021). Its production not only offers a low-cost alternative but also contributes to carbon sequestration, thus supporting climate change mitigation efforts (Cao et al., 2019). Furthermore, the integration of LDHs or LDOs with biochar enhances their environmental compatibility by creating adsorbents that are renewable, efficient, and cost-effective. For example, Qi et al. demonstrated that the sustainable production of biochar from agricultural residues combined with LDHs significantly reduced production costs while maintaining high pollutant removal efficiencies (Qi et al., 2021).

Despite their many advantages, biochar-LDH and biochar-LDO composites face challenges that limit their widespread application. Variability in adsorption capacities can arise due to differences in feedstock, production methods, and pollutant types, requiring further standardization of synthesis processes (An et al., 2020). Additionally, the regeneration and reuse of these composites remain critical concerns. While LDH and LDO components contribute to higher stability and potential reusability, repeated adsorption cycles may reduce their efficiency due to structural degradation or leaching of contaminants (Zhao et al., 2017). This issue highlights the need for ongoing research to improve the durability and regeneration processes of biochar composites.

The regeneration capability of adsorbents is crucial for their sustainable application. LDO-based composites exhibit a unique "memory effect," allowing them to reconstruct their original LDH structure upon hydration in the presence of anions. This rehydration process is governed by parameters such as pH, ionic strength, and the type of regenerating solution. For example, MgAl-LDO demonstrated efficient regeneration through structural rehydration, enhancing active site regeneration (Han et al., 2025). Similarly, MnO_2/MgFe-LDO composites showed excellent regeneration ability over five adsorption/desorption cycles, maintaining high adsorption capacities for Pb^{2+} (Huang et al., 2023)

Thus, biochar-LDH and biochar-LDO composites represent an innovative class of adsorbents with distinct advantages over traditional materials. Their high adsorption capacities, tunable properties, and sustainability make them ideal for addressing complex water pollution challenges. While challenges in scalability and regeneration persist, continued advancements in composite design and production methods are likely to expand their applicability, providing eco-friendly and efficient solutions for water treatment in diverse environmental contexts.

3.12 Future Research and Recommendation

The continued development of biochar-LDO composites for environmental remediation, particularly in water pollution control and carbon capture, holds significant promise. However, further research is necessary to improve their adsorption capacities, stability, and applicability across a diverse range of contaminants. The following recommendations, based on recent studies, outline essential directions for future research to enhance biochar-LDO composites' potential in real-world applications, ensuring they evolve as practical, sustainable solutions for environmental challenges.

Firstly, optimizing the synthesis methods of biochar-LDO and biochar-LDH composites remains a primary research focus. Current synthesis approaches, including co-precipitation and calcination, have demonstrated efficacy in creating composites with high adsorption capacities. However, refining these methods by adjusting synthesis parameters such as temperature, precursor materials, and pH could further enhance the structural properties of biochar composites. For example, a study by Ma et al. emphasises that incorporating different metal oxides and hydroxides into biochar can improve its adsorption performance, particularly for removing contaminants like phosphates from wastewater. Similarly, a study by Jaberi et al. suggests that exploring various metal combinations, such as calcium-iron or magnesium-aluminum, could yield composites with higher specificity and efficiency in pollutant removal. Thus, future studies should focus on systematically varying these parameters to produce composites tailored to target specific pollutants in diverse environmental contexts (Jaberi et al., 2019; Ma et al., 2022).

Another vital area for future research is understanding the mechanisms that govern the interactions between biochar and LDO/LDH layers. While studies have highlighted the ion-exchange and electrostatic interactions responsible for adsorption, a more detailed understanding of these mechanisms could reveal ways to enhance their efficacy. Research shows that the type of contaminants and specific LDH or LDO used can influence the adsorption behavior of the composite. Employing advanced characterization techniques, such as X-ray diffraction (XRD) and scanning electron microscopy (SEM), could help elucidate the interactions at a molecular level, providing insights into how different contaminants bind to or exchange with active sites on the composite surface. Such knowledge would inform the design of more effective biochar composites that leverage these mechanisms for high adsorption efficiency across a broader contaminant spectrum (Fang et al., 2021; Yu, 2023).

Additionally, expanding the range of precursor materials used to produce biochar and LDOs is recommended. Currently, conventional biomass sources, such as wood and agricultural residues, are primarily utilized for biochar production, while magnesium-aluminum (Mg-Al) combinations are common in LDOs. However, exploring underutilized biomass sources, such as food waste and invasive plant species, could diversify the feedstock options, leading to a more sustainable and cost-effective biochar production process. Meanwhile, incorporating alternative metals like iron or zinc into LDO structures may improve the composites' adsorption capacity for contaminants like heavy metals, expanding their applicability for various industrial effluents. A study by Zhang et al. discusses how metal substitutions in LDOs, such as iron, can optimize the composite’s performance in wastewater treatment, suggesting that biochar-LDO composites can be tailored to address specific environmental pollutants effectively (Z. Zhang et al., 2019a).

Long-term stability and regeneration studies are also essential to verify biochar-LDO composites' practical viability in continuous water treatment operations. Although these composites have shown promising adsorption capacity in laboratory tests, their stability across multiple adsorption-desorption cycles remains largely unexamined. Future studies should evaluate their long-term stability to assess whether adsorption efficiency is maintained over time and under diverse environmental conditions, including varying pH and ionic strengths. Investigating potential leaching of metal ions from the LDO layers is critical, as such leaching could compromise water quality and the composite's sustainability. Zhang et al. emphasize the importance of developing reliable regeneration techniques to maintain adsorption efficiency while minimizing environmental impact, which would enhance the practicality and cost-effectiveness of biochar-LDO composites for large-scale applications (Z. Zhang et al., 2019a).

Lastly, while biochar-LDO composites have been extensively studied for phosphate and CO_2 adsorption, their effectiveness against emerging contaminants such as pharmaceuticals, personal care products, and pesticides warrants further exploration. Real wastewater contains a complex mix of contaminants, and testing biochar-LDO composites in these complex matrices is essential for understanding their competitive adsorption behaviors. For instance, developing composites that can selectively remove priority contaminants specific to industries such as pharmaceuticals, agriculture, and mining could prove advantageous in addressing diverse water treatment needs. Taher et al. suggest that exploring biochar-LDO composites for a wider range of organic and inorganic pollutants in real wastewater scenarios could provide insights into their scalability and potential for industrial applications (Taher et al., 2023).

Advancing biochar-LDO composite technology requires an interdisciplinary approach combining material science, environmental engineering, and field testing. By focusing on refining synthesis methods, understanding interaction mechanisms, diversifying precursor materials, evaluating long-term stability, and exploring new contaminant applications, researchers can develop versatile, efficient, and sustainable biochar-LDO composites. Such advancements will enable these materials to meet the growing demand for effective and eco-friendly solutions in pollution control and water treatment, contributing to a cleaner, healthier environment.

4. Conclusion

This review critically compared biochar-LDH and biochar-LDO composites for water pollution control, focusing on their synthesis, adsorption mechanisms, material characteristics, and real-world performance. The findings demonstrate that while both materials are effective in pollutant removal, their optimal applications differ based on structure, stability, and target contaminants.

Biochar-LDH composites exhibit strong potential for the removal of anionic species and heavy metals through ion exchange and complexation mechanisms. Their advantages lie in low-temperature synthesis, anion selectivity, and nutrient recovery potential. In contrast, biochar-LDO composites, formed by thermal transformation, offer enhanced surface reactivity, stability, and higher capacity for organic pollutants such as dyes, antibiotics, and nanoplastics, facilitated by the memory effect and catalytic interactions.

Case-based studies confirm that both materials have been successfully deployed in batch and column systems for treating real wastewater, supporting their practical viability. However, scalability challenges such as material regeneration, fouling, and leaching must be addressed through optimized synthesis protocols and system integration. The economic analysis further suggests that although initial synthesis costs can vary, the reusability and dual-functionality of these materials make them promising for sustainable wastewater treatment.

Future research should focus on hybridizing LDH and LDO functionalities, improving long-term operational stability, and conducting lifecycle assessments to evaluate environmental and economic trade-offs. The insights presented in this review provide a foundation for selecting and designing next-generation biochar-based composites tailored for specific wastewater treatment needs, advancing sustainable and effective remediation technologies.

5. Data Availability Statements

There is no data used in this study

6. Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, the author(s) used ChatGPT to improve the readability and fix the grammatical errors. After using these tools/services, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the published article.

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Declaration of interests

✓ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: