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Review on recent advancements in layered double hydroxides application for effective removal of heavy metals and organic micro-pollutants: Challenges and future perspectives

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Abstract

The rapid expansion of agricultural and industrial activities has led to the release of various pollutants, including heavy metals (HMs), organic pollutants (OPs), pharmaceuticals, and emerging contaminants, posing substantial risks to environmental and human health. Traditional remediation methods struggle with questions of efficiency, specificity, and sustainability. This review offers a comprehensive and critical analysis of recent advancements in adsorbent technologies, with a specific focus on the application of layered double hydroxides (LDHs) for the removal of HMs and OPs. LDHs are considered promising materials for pollutant removal because of their notable characteristics, including stable mineralization, low solubility product constants, anionic intercalation capacity, high surface area, and tunable surface chemistry. However, the review also addresses the challenges associated with large-scale LDH applications. While LDHs demonstrate significant potential as alternatives to conventional adsorbents, further research is required to enhance their surface modification, structural design, and post-treatment recovery processes for more effective applications. Finally, this review develops a foundation for future studies on the mechanical features and practical implementation of LDH-based remediation technologies, consolidating current knowledge and identifying critical research gaps.

Keywords: Heavy Metals; LDHs; Organic Pollutants; Wastewater Treatment; Removal of Pollutants

1. Introduction

The ongoing transformation of global society and the economy has resulted in an intensified focus on critical ecological concerns (Farhan et al. 2024; Pelalak et al. 2023). Human activities, such as agriculture, industrial production, and urbanization, release substantial amounts of pollutants into the environment, contributing to considerable ecological and public health risks (Li ChunMei et al. 2019; Bhatt et al. 2021). Among these contaminants, HMs such as cadmium (Cd), zinc (Zn), chromium (Cr), and nickel (Ni), as well as OPs such as pesticides, antibiotics, and dyes, are particularly concerning. Despite their presence at low concentrations, these substances can lead to severe health effects, emphasizing the necessity for effective removal strategies.

Over the past decade, nanotechnology has emerged as a primary strategy for water purification. Among various adsorbents, LDHs have garnered significant attention due to their exceptional physicochemical features, including a high specific surface area, excellent hydrophobicity, efficient ion exchange ability, cost-effectiveness, and a high interlayer negative charge density (Zubair et al. 2021; Lu et al. 2024). Structurally, LDHs are anionic clays characterized

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by a general molecular formula of $\left\{A_{\frac{x}{n}}\right\}n - * mH_2O$. They comprise brucite-like layers in which octahedral metal oxides form the primary lattice, with metal cations occupying octahedral sites (Lu et al. 2016). The molar ratio M^{3+} to $M^{2+} + M^{3+}$ of metal cations typically ranges from 0.2 to 0.4 (Zhang et al. 2016; Zhang, He, et al. 2022). The partial substitution of divalent cations for trivalent metals induces positively charged layers, balanced by intercalated anions. These layers alternate with M^{2+} and M^{3+} ions along the a- and b-axes, while water molecules and neutral anions occupy the interlayer space along the c-axis, forming a well-defined three-dimensional structure (Bai et al. 2024; Zheng et al. 2019).

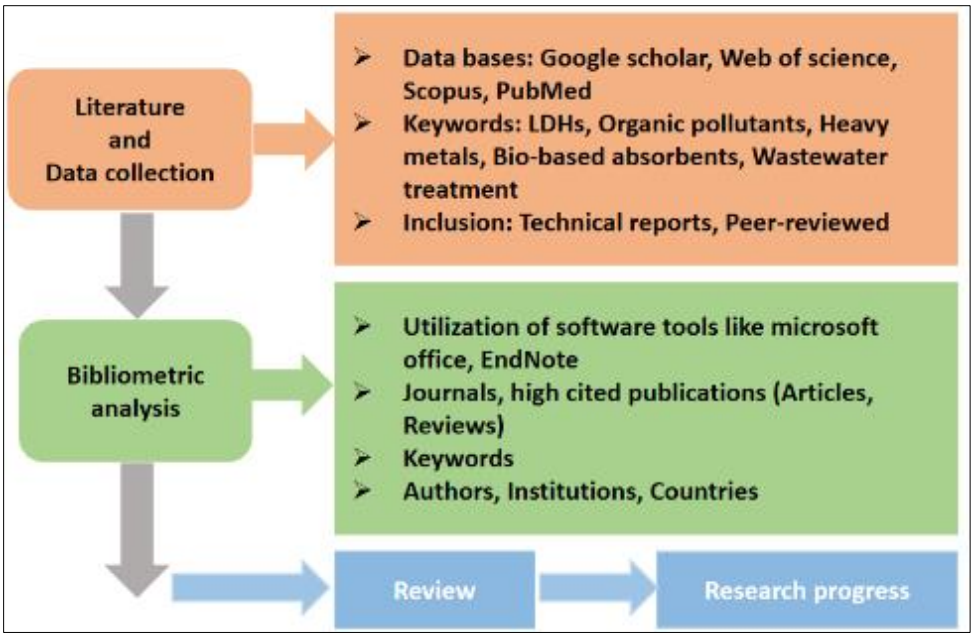

Figure 1 Approach for analyzing LDHs as bio-based absorbents

Table 1 Overview of recent studies on HMs and OPs removal via LDHs

References	Main Subject	Gaps and Contribution
(Sheraz et al. 2024)	Comprehensive assessment of carbon, bio-material, and inorganic-based adsorbents for the removal of the most hazardous heavy metal ions from wastewater.	This paper is the comparative effectiveness of different types of adsorbents in targeting specific HM ions in wastewater.
(Zahara et al. 2023)	LDH Zn/M^{3+} (M^{3+} = Al and Cr) as highly efficient adsorbent of HMs Pb (II).	The paper focuses on Zn-Al and Zn-Cr LDHs as efficient adsorbents for Pb(II) removal.
(Hamimed et al. 2022)	Nanocelluloses for removal of HMs from wastewater.	This paper presents a promising and innovative solution for the removal of HMs from wastewater.
(Mohiuddin et al. 2021)	Starch-Mg/Al LDH composites as an efficient solid phase extraction sorbent for non-steroidal anti-inflammatory drugs as environmental pollutants.	This paper highlights the potential for biocompatible materials to enhance the removal of environmental pollutants.

This review offers a comprehensive overview of LDH applications for the removal of HMs and OPs, providing insight into recent advancements, research trends, and challenges in the research area. The purpose is to implement LDH-based technologies for environmental remediation (Meseguer-Sánchez et al. 2021; Wang, Bai, et al. 2023). To ensure a systematic and effective perspective, this review emphasizes three major objectives: tracing the origin and progression of pollutants, evaluating the efficacy of LDHs in pollutant removal, and identifying current limitations and addressing future research directions. A systematic literature review was conducted using prominent scholarly databases, including Scopus, Web of Science, PubMed, and Google Scholar. Keywords such as "bio-based adsorbents," "LDHs," "OPs," "HMs," and "wastewater treatment" were employed to retrieve peer-reviewed publications, technical reports,

and demonstration projects from the past decade. This approach ensured the inclusion of current and relevant scientific research (Fig. 1). The quality and relevance of the selected literature were evaluated, and duplicates were excluded. The reviewed studies were categorized into key thematic areas, including LDH synthesis, adsorption mechanisms, pollutant removal efficiency, scalability, and environmental impact. Table 1 provides a summary of current research on LDH applications for HM and OP removal.

2. LDHs application benefits

LDHs have gathered significant attention in the recent scientific literature as innovative functional materials for the removal of HMs and OPs (Tian et al. 2024). These materials possess tunable physicochemical characteristics, which include precisely controllable crystal morphology, modifiable interlayer anion configuration, and adjustable molar ratios of host layer cations (Zubair, Syamaladevi, and Ullah 2024; Zubair et al. 2021). LDHs are considered highly promising adsorbents for wastewater treatment, due to their large specific surface area and interlayer anion exchangeability (Guo et al. 2011; Lu et al. 2016; Li et al. 2025). Furthermore, their chemical stability and adaptability make them potential candidates for soil remediation applications (Guan et al. 2022; Zhao et al. 2020).

The Al-Li/ThLDH@CNT nanocomposite, developed by Manea et al. (2022), demonstrated a 98% degradation of malachite green (MG) dye within 45 minutes under visible light irradiation (Manea et al. 2022). Similarly, palladium and tin sulfide (Pd-SnS) nanoparticles containing LDHs exhibited enhanced stability and photocatalytic activity against rhodamine B and hexavalent chromium (Sun, Lee, and Park 2023). Zhang et al. (2022) synthesized a chitosan-LDH composite with high adsorption capacities for various HM ions and organic dyes, operating through diverse adsorption mechanisms (Zhang, Ma, et al. 2022). Additionally, a copper-based oxide/LDH compound was shown to effectively remove tetracycline (TC) and Cr(VI) with a synergistic efficiency of approximately 95%. The copper-based oxide/LDHs-1/15 composite displayed impressive durability and stability during successive photocatalytic cycles in practical applications.

3. Preparation methods of LDHs

LDHs can be efficiently synthesized in laboratory settings due to their favorable thermodynamic properties and the regular interactions of appropriate anions and cations. LDHs are non-toxic and environmentally friendly, as their synthesis involves a series of low-cost, eco-friendly approaches that employ water as a solvent, such as coprecipitation, hydrothermal treatment, and sol-gel methods (Fig. 2). Although LDHs are relatively uncommon, they can also be produced from inexpensive materials (Oh, Hwang, and Choy 2002). The synthesis process is influenced by several factors, including temperature, pH, and reaction time (Zhang et al. 2012). LDH synthesis methods are generally categorized into direct approaches, such as hydrothermal and co-precipitation techniques, and indirect approaches, such as anion exchange (He et al. 2006; Zubair et al. 2017). This review also discusses procedures for synthesizing LDH composites through conventional methods.

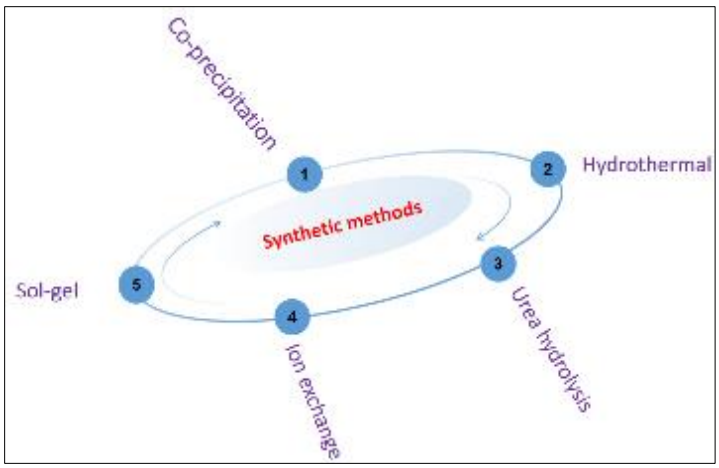

Figure 2 Preparation methods of LDHs

3.1. Co-precipitation

Co-precipitation, also referred to as the salt route or salt-based route, is the most widely applied method for the synthesis of LDHs due to its versatility across a broad pH range (Mittal 2021; dos Santos et al. 2021; Tang et al. 2024). This method involves two types of precipitation: low and high super-saturation, with specific processes employed to adjust the pH (Ng'etich and Martincigh 2021; Evans and Slade 2006). The properties of the resulting LDHs, whether amorphous or highly crystalline hydrotalcite, are influenced by several factors, including aging time, base solution, temperature, metal molar ratios, pH, and cation concentration (Bukhtiyarova 2019; Wang and O'Hare 2012). The process entails the simultaneous precipitation of metal hydroxides from metal salts in deionized water, followed by the insertion of an alkaline solution to enhance the pH (Bukhtiyarova 2019; Ng'etich and Martincigh 2021; Evans and Slade 2006). After sufficient aging, the precipitates are rinsed, filtered, and dried to achieve the final LDH product.

3.2. Hydrothermal

The hydrothermal synthesis reaction is conducted by combining M(II) and M(III) metal salt solutions dissolved in an alkaline solution, exhibiting characteristics akin to those of the coprecipitation process. This reaction occurs in a heated autoclave at temperatures of 100−180°C and a pH range of 8−10 for 10−48 hours (Daud et al. 2016; Mohapi et al. 2020; Bai et al. 2024). The synthesized solids are extracted via centrifugation and subsequently washed with ethanol and deionized water. Hydrothermal synthesis has demonstrated superior efficacy compared to the coprecipitation method in producing LDHs with high crystallinity and distinct morphologies. This method underscores its significance in the preparation of advanced inorganic nanomaterials for contemporary green technologies, facilitating enhanced chemical reactions and temperature conditions (Rao et al. 2007; Wang et al. 2021).

3.3. Urea hydrolysis

Urea hydrolysis typically entails rapid supersaturation with the precipitant (OH^-), leading to the nucleation of mixed hydroxides, independent of Ostwald particle growth, which includes a range of particle sizes (Pang et al. 2019; Karim et al. 2022). Alkaline retarders, such as urea, are used to decouple nucleation from particle formation, thereby enabling aging retardation (Adachi-Pagano, Forano, and Besse 2003). The process of urea hydrolysis occurs in two stages: the initial formation of intermediates that govern the rapid hydrolysis to ammonium carbonate. The rate of hydrolysis is temperature-dependent, and LDHs can be synthesized through various heat treatments. The urea-to-metal salt ratio significantly influences particle size and can produce large sheets and well-crystallized hexagonal LDHs (Ogawa and Kaiho 2002; Benali et al. ; Okamoto, Iyi, and Sasaki 2007).

3.4. Ion exchange

The anion exchange process in LDHs involves dispersing the precursor LDH in an aqueous solution containing the target anion, followed by continuous stirring at room temperature for several hours (Mohapi et al. 2020; Omwoma et al. 2014). The solid sediments are filtered via filtration, repeatedly cleaned with deionized water, and subsequently dried. Additionally, water molecules in the interlayer play a crucial role, with hydrogen bonding being important for their arrangement across the inorganic layer. The high anion exchange capacity of LDHs facilitates interlayer ion exchange, simplifying the synthesis of LDH precursors (Guan et al. 2022; Cui et al. 2023).

3.5. Sol-gel

The sol-gel technique, employing condensation and hydrolysis methods, is considered a straightforward, cost-effective, and efficient moist-chemistry approach for synthesizing highly pure metal oxides from LDH precursors (Prince et al. 2009; Danks, Hall, and Schnepp). In comparison to coprecipitation, sol-gel-derived LDHs exhibit a higher specific surface area and superior thermal stability but are characterized by lower crystallization levels (Aramendía et al. 2002; Elhalil et al. 2019).

4. Modification techniques of LDHs

The electron state of functional groups significantly influences the zeta potential of LDHs, enabling effective material customization through component combinations and synthesis methods. Their composites serve as efficient adsorbents for OPs HMs due to their exchangeable interlayer anions (Dai et al. 2024). Nanosheets exhibit dynamic tunability, with surface bonds that are more reactive than bulk formulations. Minor adjustments in small-scale synthesis can substantially alter adsorption properties (Fig. 3). Consequently, physicochemical modifications are crucial for optimizing performance in adsorbing HMs and OPs (Miyah et al. 2024). Table 2 provides a summary of LDH-based material synthesis and modification strategies, while additional preparation techniques are detailed in Table S1.

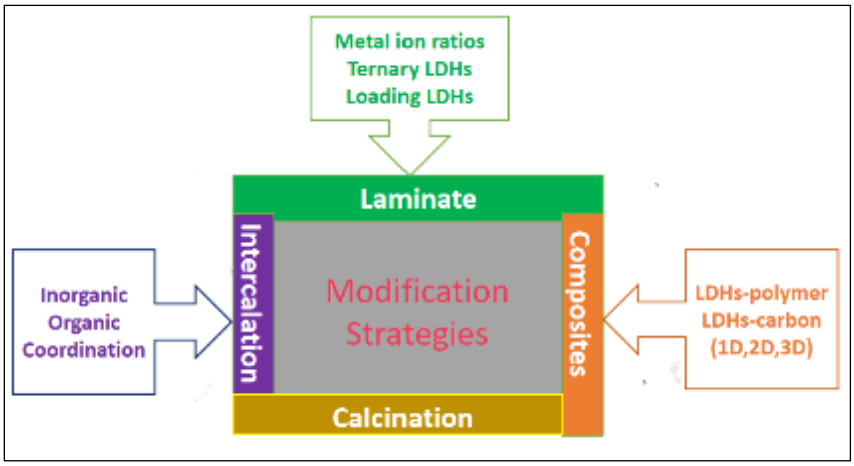

Figure 3 Modification techniques of LDHs

Table 2 Recent utilization of LDH-based components

Material	Modification method	Pollutants	Adsorptive capacity (mg/kg)	Reference
CuFeAl-LDO	Laminate	Tetrabromobisphenol A	99.91%	(Hou et al. 2022)
ZnCr-LDH	Calcination	Pyrophosphate	79.00	(Fu et al. 2021)
Znln-LDH	Calcination	Methylene bleu	98.00%	(Liu et al. 2020)
MgFe-LDHs-AC	Composites	Cu^{2+}	2.03	(Song et al. 2024)
CoAl-LDH	Composites	Ranitidine	97.00%	(Asif, Kang, and Zhang 2022)

4.1. Laminate

4.1.1. Metal ion ratios

The ratio of metal ions significantly influences the efficacy of pollutant adsorption into LDHs. Recent studies have demonstrated that a 5:1 MgAl ratio achieves superior phosphorus removal efficiency (Lee et al. 2019; Deng et al. 2021; Jung et al. 2021). Additionally, research has shown that varying metal ion proportions (2:1, 3:1, 4:1) during LDH preparation impact their performance, with a 4:1 ratio maintaining optimal performance (Li et al. 2016; Wan et al. 2012). While pore capacity decreases with higher metal ion ratios, the pore surface area increases, enhancing pollutant adsorption. The current approach involves dispersing LDHs into biochar (BC) ponds (Vallet-Regı et al. 2004; Montiel-Centeno et al. 2025; Pandey et al. 2021). Furthermore, as Mg/Al ratios increase, the lower charge density facilitates the entry of pollutant ions into larger interlayer spaces, thereby improving adsorption capacities (Li et al. 2016; Wan et al. 2012).

4.1.2. Loading LDHs

ZnO, TiO_2, Cu_2O, and similar semiconductors are recognized for their low cost and excellent photocatalytic performance, though they exhibit poor transport properties (Gao, Yu, and Xu 2018; Hu et al. 2025; Mortaheb et al. 2008). To mitigate these limitations, various metal materials, such as Cu, Ag, and Ni, as well as carbon materials like carbon nanotubes, are employed due to their capacity for electron storage and transport (Li, Liu, et al. 2023). Combining these materials with LDHs enhances visible light absorption and hot carrier performance. For instance, the cadmium sulfide/CoAl-LDHs nanocomposite demonstrated improved light absorption and achieved a bandgap of 2.15 eV (Cai et al. 2017). Additionally, the extended activity of hot carriers in cerium, with its 3.2 eV bandgap, offers a significant advantage. Research in this area has further improved the photodegradation efficiency of phenolic pollutants (Valente, Tzompantzi, and Prince 2011).

4.2. Intercalated LDHs

4.2.1. Inorganic intercalation

LDHs contain a common nanostructure, rendering them highly valuable for environmental remediation (He et al. 2018; Khandaker, Fujibayashi, and Kuba 2025). However, their low selectivity and poor affinity for HMs and OPs stem from the absence of surface functional groups (Chaudhuri and Yun 2022; Ampong et al. 2023; Rojas 2014; Velusamy et al. 2021). Recent studies have focused on enhancing LDHs by introducing sulfonic acid, thiol, and sulfide groups. These molecules significantly improve their selectivity, particularly for soft metal ions, and strengthen their adsorption performance. For example, Rahman et al. (2018) demonstrated that high-retention adsorption can be achieved by intercalating nitrate Mg-Al LDHs without organic anion exchange (Rahman et al. 2018). Similarly, Poudel et al. (2021) synthesized LDH@ through a hydrothermal method, achieving effective removal of chromium (400.40 mg/g) and divalent lead ions (Pb(II), 426.76 mg/g) via mechanisms such as electron migration, isomeric replacement, and surface complexation (**Fig. S1**) (Poudel, Awasthi, and Kim 2021).

4.2.2. Organic intercalation

LDHs are widely selected for modification, particularly for grafting functional groups. Organic molecules, such as ethylenediaminetetraacetic acid (EDTA) (Chen et al. 2024; Shen et al. 2024; Lin et al. 2024; Jasem-Feisal, Amiripour, and Ghasemi 2024), amino acids (Koilraj, Kalusulingam, and Sasaki 2019), thiol carboxylic acids (Jiang et al. 2023), and citric acid (Wang, Zhang, et al. 2023), have been employed for this purpose. For instance, Zhang et al. (2020) utilized MgAl-Cys-LDH for the adsorption of Cd(II), Cu(II), and Pb(II), leveraging the ability of the −SH group to immobilize metal ions into metal sulfide structures (Zhang et al. 2020). Similarly, Chen et al. (2014) synthesized ion-exchanged platinum/ZnTi-LDHs with enhanced surface sites and pore volume (Chen et al. 2014). Further studies are necessary to fully explore the potential of modified LDHs for the adsorption of HMs and organophosphates in environmental applications.

4.3. Composite materials of LDHs

4.3.1. LDHs polymer

The interactivity of LDHs and polymers involves creating nanocomposites with unique structural characteristics, such as gas barrier properties and photostability (Alexandre et al. 2002; Mallakpour and Tabebordbar 2020; Pathak and Singh 2024). LDH production in a mixed polymer solution enhances the interfacial exchange between LDHs and the host polymer. This is achieved by coprecipitating two basic metal salts into a suitable polymer solution (del Valle Ponce et al. 2022; Mallakpour and Tabebordbar 2020). For instance, polyvinylpyrrolidone (PVP) nanocomposites were produced by inserting LDHs into a mixed polymer solution through a polyester substance (Stimpfling et al. 2016). ZnAl-LDH nanocomposites were synthesized via a coprecipitation process in water at a constant pH of 9 (Gaume et al. 2013). Additionally, the proton conductivity of sulfonated polyether ether ketone (SPEEK) was improved by incorporating MgAl-LDH (Kim et al. 2015). Du et al. (2007) produced nylon-MgAl-LDH by melting nylon 6 with organically modified MgAl-LDH intermediate layers (Du, Qu, and Zhang 2007). Similarly, Suresh et al. (2017) employed an internal mixing mechanism to create polystyrene/NiAl-LDH nanocomposites, where the interaction of LDH nanoparticles with polystyrene enhanced material resistance and encouraged thermal degradation (Suresh et al. 2017).

4.3.2. LDHs carbon

Several studies have demonstrated that LDHs can effectively be applied to various carbon-based materials, including graphene (Cao, Li, and Li 2016; Nayak and Parida 2019; Wang et al. 2018; Zhang et al. 2017), graphite carbon (Abazari et al. 2019; Sahoo et al. 2020; Tonda and Jo 2018; Zou et al. 2017), carbon nanotubes (CNTs) (Bhuvaneswari et al. 2021; Fan et al. 2020; Jia et al. 2016; Zhang, Sun, et al. 2019), carbon quantum dots (Koilraj, Kamura, and Sasaki 2017; Rahmanian, Dinari, and Abdolmaleki 2018; Wei et al. 2016), BC (Gholami et al. 2020; Vithanage et al. 2020), and carbon fibers (Fang et al. 2019; Peng et al. 2018; Wang and Guo 2019). These investigations highlight the exceptional features and high conductivity of these materials, which enhance their applicability (Bi et al. 2011; Pourfarzad et al. 2019; Zhu et al. 2015). The combination of LDHs with carbon-based materials has been proven to improve the adsorption and removal efficiency of HMs and OPs, as well as catalytic degradation processes. These materials prevent the aggregation of LDH laminar structures and reduce the recombination of photogenerated carriers (Liang et al. 2019; Daud et al. 2016). For instance, Liang et al. (2019) reported an increased capacity for photocatalytic ciprofloxacin degradation in wastewater under visible light by the integration of graphene oxide (rGO) with LDHs (Liang et al. 2019). Further, Wang et al. (2024) synthesized E-Mg/Al-LDHBC using ethylenediaminetetraacetic acid as the primary inserted substance and evaluated its adsorption capabilities for Cd and Pb (Wang et al. 2024). New prominent patterns associated with Cd and Pb were observed at the E-Mg/Al-LDHBC interface following the adsorption of Pb(II) and Cd(II) (**Fig. 4**). Additional examples of catalytic activity are summarized in F**ig. S2**.

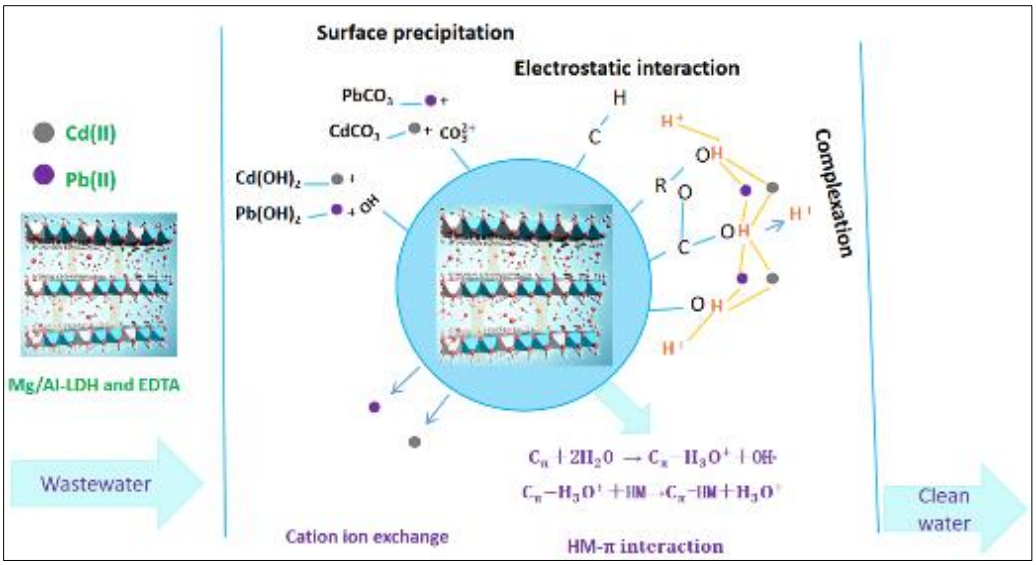

Figure 4 Diagram of pollutants removal mechanism (Wang et al. 2024). Copyright 2024 Wang at al

4.3.3. LDHs calcination

To enhance the efficiency of LDH preparation, recent studies have employed calcined LDH to produce layered double metal oxides (LDOs) (Xu et al. 2023; Shen et al. 2020). These investigations demonstrated that calcination significantly enhanced the surface sites and adsorption characteristics of metal oxides, thus improving the adsorption capacity of HMs. For instance, Yuan et al. (2013) utilized a nanostructured filter to create graphene/LDH for Cr removal from wastewater (Yuan et al. 2019). A calcination temperature of approximately 500°C was applied to produce graphene-LDO with high efficiency for Cr removal. Moreover, LDOs have been found to be promoters that enhance the catalytic degradation of OPs. With band gaps ranging between 2.0 eV and 3.0 eV, LDOs exhibit excellent photocatalytic activity (Zhang, Yan, et al. 2019; Benito et al. 2008). Additionally, catalytic nanocrystals are facilitated by effective electron transfer from high-valence metals (Chen, Zhang, et al. 2019; Chen, Zeng, et al. 2019). For example, Ju et al. (2018) developed a nano-adsorbent capable of degrading bisphenol A at low temperatures by employing calcined ZnAlTi-LDHs at approximately 500°C (Ju et al. 2018). To improve toluene adsorption, calcined MgAl-LDH was integrated into MgAl-LDO (Laipan et al. 2015). Furthermore, the memory effect of LDOs during rehydration allows them to revert to their original structures, enabling reuse in multiple cycles.

5. Utilization of LDHs for the removal of pollutants

The mechanisms underlying the elimination of HMs and OPs are depicted in **Figs. 5** and **6**, respectively, based on prior analyses. The formation of anion-metal complexes and the precipitation of hydroxides on the surface of LDHs occurs due to the presence of hydroxyl groups in these materials. Surface complexation and precipitation are identified as the major mechanisms by which LDHs adsorb HMs (González et al. 2014; Laipan et al. 2020). LDHs demonstrate exceptional ion exchange and adsorption properties, attributed to their exchangeable anions and positively charged layers (Li et al. 2016). Furthermore, chelator-synthesized LDHs have been employed as effective adsorbents for HMs in aqueous solvents, owing to the strong chelating interactions between ligands and HMs (Koilraj, Kalusulingam, and Sasaki 2019; Chen et al. 2021). Functional groups such as aldehyde, carboxyl, and sulfhydryl can form complexes with HMs, thereby enhancing the contaminant removal capacity of LDHs. The interlayer anions can be reduced to less hazardous valence states or equivalent metal forms, while isomeric substitution has been proposed as a pathway for HM stabilization. The removal of OPs is commonly accomplished through three principal advanced oxidation processes (AOPs), including photocatalysis, Fenton-like reactions, and peroxymonosulfate catalysis. The main mechanisms through which LDHs facilitate OP degradation through AOPs include electron transfer, single oxygen generation, and radical formation. Additionally, LDHs have been applied for removing common contaminants, such as malachite green, Cd(II), Cr(VI), and tetracycline, as noted in the bibliometric analysis. Recent studies further highlight the application of LDHs to address these contaminants.

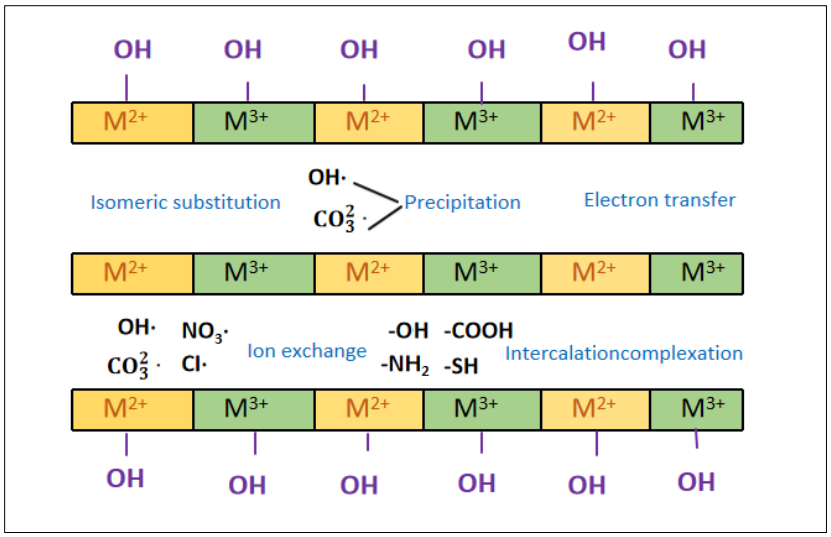

Figure 5 LDHs applications pathways for HMs removal

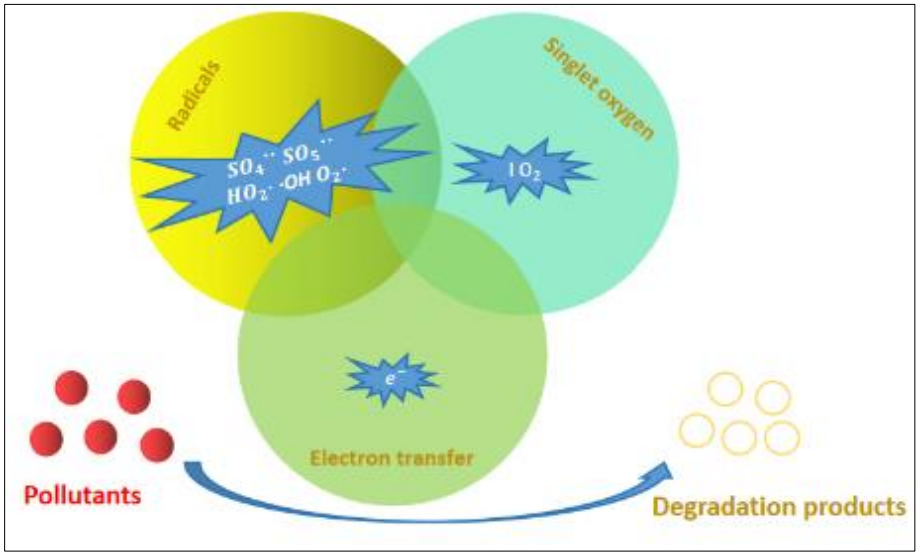

Figure 6 OPs elimination via LDHs

5.1. Chromium (VI)

Hexavalent chromium (Cr (VI)) is identified as one of the most hazardous HMs because of its intense toxicity and tendency to biological aggregation (Bao et al. 2020; Cong et al. 2022; Zhao et al. 2021; Zhou et al. 2022; Li et al. 2024).. Naturally occurring in the environment, Cr exists primarily in two forms: the highly toxic Cr (VI) and the less toxic trivalent Cr (III). Special attention has been devoted to Cr (VI) because of its potential risks. Anionic forms of Cr (VI), such as chromate and dichromate, further complicate its environmental impact. The removal of Cr (VI) usually involves ion exchange, coordination, and redox processes. For example, the MgAl-LDH composite, described by Ma et al. (2017), demonstrates impressive adsorption capabilities, with an efficiency of 130 mg/g and a 93% capture of Cr(VI) (Ma et al. 2017). This reduction of Cr (VI) to Cr (III), a milder Lewis acid, occurs through a heterogeneous redox process. A portion of Cr (III) remains in the interlayer after forming bonds with sulfides. Fourier transform infrared spectroscopy (FTIR) has confirmed the stability of LDHs during these redox processes, indicating that the host layer provides a stable setting for anion exchange. V. Rives (2001) revealed that uncalcined Cl-intercalated LDHs had a more significant positive impact on Cr(VI) removal than their calcined alternatives (Rives 2001). The principal mechanism involves the partial exchange of Cl^- with chromate. Advanced materials, such as a nanofiber film of magnesium aldehyde/polyacrylonitrile (MgAl-LDH/PAN), have also been developed, enabling in situ growth of LDHs coated with boehmite sol (Gore et al. 2016). This approach effectively reduced Cr (VI) to Cr (III), as confirmed by the valence state of adsorbed Cr ions. Additionally, NiCo-

LDH microspheres, synthesized via a single-stage hydrothermal method (Li et al. 2024), demonstrated exceptional Cr(VI) removal efficiency due to their high surface area, positive surface charge, and unique pore structure, achieving an adsorption capacity of 123 mg/g. Similarly, a NiFe-LDH/Polypyrrole pseudocapacitive electrode, created through in situ polymerization, exhibited a Cr(VI) removal rate of 111 mg/g from wastewater (Yang et al. 2024). These advancements underscore the potential of LDH-based materials for addressing Cr (VI) contamination (Fig. 7).

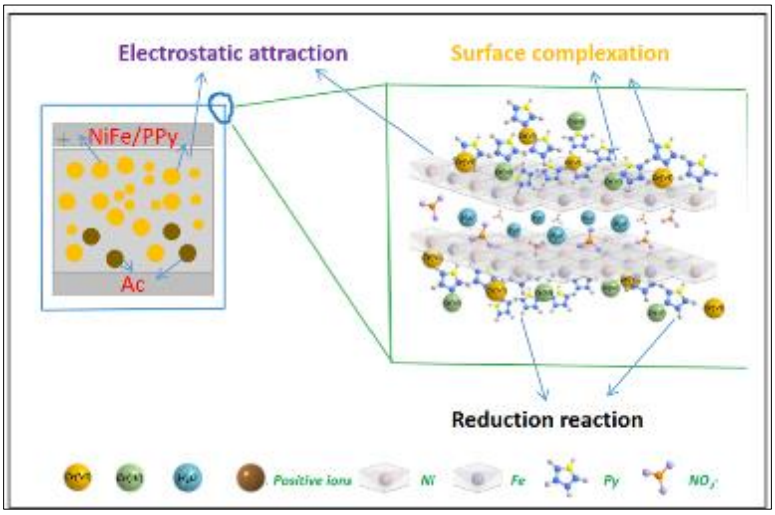

Figure 7 Cr(VI) electrosorption by NiFe/PPy (Yang et al. 2024). Copyright 2024 D Yang et al

5.2. Cadmium (II)

Cadmium ions are highly toxic and persistent HMs that pose significant threats to the environment and human health. LDHs can effectively remove these ions through mechanisms such as complexation, precipitation, interface adsorption, and isomorphic replacement (Asiabi et al. 2017; Zhang, Chen, et al. 2022; Zhao et al. 2023). The mineralization process involving LDHs is notably stable, as demonstrated by experiments (Fig. S3). LDHs are positively charged laminates composed of brucite-like layers stacked and bound by interlayered anions. These structures can be modified through isomorphic substitution, where divalent metal cations are replaced with trivalent ones (Fan et al. 2014). This substitution, combined with the abundance of hydroxide (-OH) groups, enables LDHs to interact with a wide range of inorganic and organic compounds (Bing et al. 2018). Strong coordination of these -OH groups facilitates the removal of contaminants. For instance, Liu et al. (2019) achieved a 99.7% removal rate using calcined MgZnFe-LDH (CMZF) as an adsorbent (Liu et al. 2019). Additionally, metal ions in LDH laminates can exchange with metal ions in other metal salts. Kong et al. (2021) demonstrated efficient removal of cadmium ions through the mineralization of CaAl-LDH, achieving a high adsorption capacity of 592 mg/g and a rapid adsorption rate of 5 minutes (Kong et al. 2021). The efficiency of CaAl-LDH immobilization on soil exceeded 96.9%. The isomorphic substitution of CaAl-LDH to CdAl-LDH during adsorption further enhanced the stability of the mineralized product. This consistency was corroborated by density functional theory simulations, confirming the resilience of the process.

5.3. Tetracycline

Tetracycline (TC), a highly chemically stable antibiotic, is released into the environment through urine and feces and cannot be fully absorbed by the body (Yuan et al. 2022; Zhang, Meng, et al. 2022; Zhang, Cheng, et al. 2022). AOPs, including peroxymonosulfate catalysis, Fenton-like effects, and photocatalysis, are employed for antibiotic degradation using LDH-based composites (Xie et al. 2021). Under light irradiation, LDH-based materials typically generate reactive species, initiating redox processes as photoelectrons transfer from the valence band (VB) to the conduction band (CB), resulting in the formation of free radicals such as $\cdot O_2^-$ and $^{\bullet}OH$. These radicals efficiently oxidize and degrade antibiotics. LDHs play a critical role in activating peroxymonosulfate (PMS), producing substantial amounts of $^{\bullet}OH$ during Fenton-like reactions, which rapidly inserted antibiotics into smaller molecules. Furthermore, LDHs facilitate PMS reactions, leading to associated reactive radicals. Research by Li et al. (2022) demonstrated that persulfate activation, combined with LDHs synthesized via Z-scheme heterojunction mechanisms, effectively degraded TC (Li et al. 2022).

A straightforward hydrothermal method was employed to synthesize MoO_2@CoFe-LDHs Z-type multilayer junction, which was successfully activated by Co-Fe dual-site mechanisms, facilitating tetracycline degradation under visible light (Li, Meng, et al. 2023). The results indicated that the synergistic destruction effect of this junction on tetracycline was

3.7 times more effective than that of the multilayer junction alone. Additionally, it was 2.7 times higher than the value reported by Xu et al. (2022) (Xu et al. 2022). The latter applied a hydrothermal process to develop a pH-universal electric Fenton (EF) cathode, which exhibited excellent tetracycline degradation (94.2%) across a broad pH range. Additionally, Fig. S4 illustrates the production of In_2O_3@LDHs.

5.4. Malachite green

The plastic industry, printing, and textiles frequently use malachite green (MG), a dye made from triphenane molecules. Its effectiveness against fungal and protozoan diseases in aquatic species makes it a popular fungicide in aquaculture. However, due to its high toxicity and solubility, MG can harm the liver, kidneys, and lungs of various animals, even at low doses (Vareda 2023; Yuan et al. 2023). Common adsorption mechanisms include chemical bonding, physical adsorption, and hydroxide precipitation. Tang et al. (2023) synthesized magnetic ZnAl-LDH (MZA) for MG adsorption, utilizing molecular intercalation, hydrogen bonding, and electrostatic attraction as the main mechanisms (Tang et al. 2023). MZA maintained a high adsorption capacity over four adsorption-desorption cycles. Manea et al. (2022) developed flower-like Al-Li/ThLDH@CNT nanocomposites for MG photodegradation by combining exfoliated Al-Li/Th LDH nanosheets (**Fig. 8**), with F-CNTs via a hydrothermal method (Manea et al. 2022). The Al-Li/ThLDH@CNT exhibited a maximum adsorption capacity of 172.4 mg/g and achieved 98% MG decolorization in 45 minutes. Gao et al. (2021) created an innovative synthetic adsorbent (LDH@PDA@MPNs) for MG removal using metal complexation and mussel-inspired chemistry in a two-step process (Gao et al. 2021).

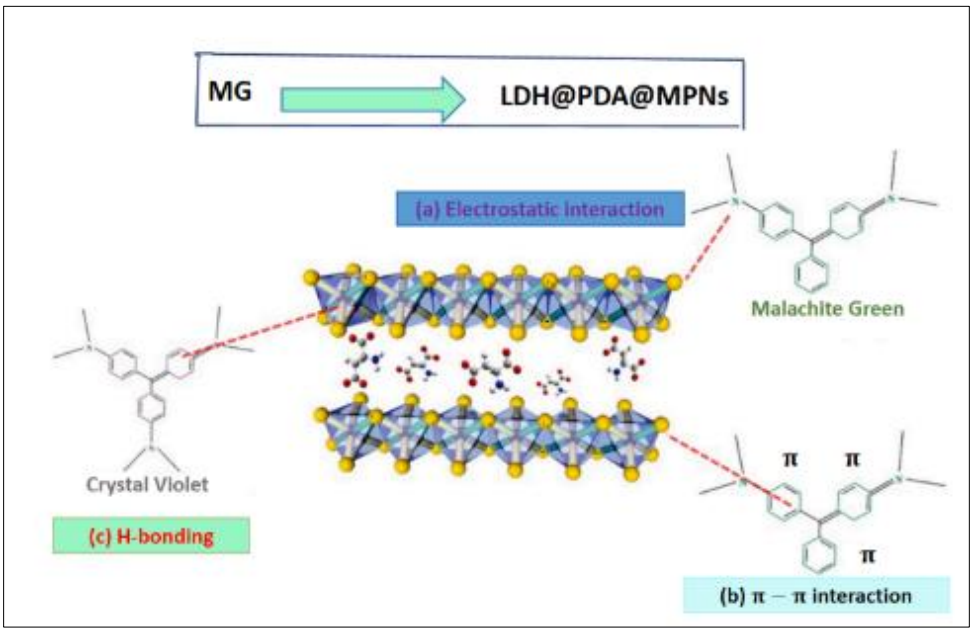

Figure 8 Interaction mechanisms between MG and LDH@PDA@MPNs (Manea et al. 2022)

6. Challenges and futures perspectives

The development of adsorbents for wastewater treatment, particularly for the removal of hazardous or toxic pollutants, remains a critical area of ongoing research. This study reviews recent advancements in the application of LDHs for the adsorption-based removal of various contaminants, including OPs and HMs. The findings indicate that LDHs are highly effective in adsorbing a wide range of organic contaminants.

However, despite significant progress in the application of LDHs for treating HMs and OPs, several challenges continue to hinder their broader implementation:

6.1. Assessment of potential environmental effects

Examining the potential hazardous effects of LDHs and their modified components on the environment is crucial for assessing their applicability in environmental remediation. However, data in this area remain minimal. For example, toxic metals such as Co/Ni frequently occur in LDHs with high catalytic activity, and their production may involve harmful chemicals. Consequently, efforts should prioritize identifying less toxic alternatives and minimizing the

leaching of hazardous compounds. Additionally, studying LDH movement and transformation into natural environments is essential to indirectly assess potential adverse environmental impacts.

6.2. Enhancement of synthesis methods

The molar concentration of metal ions significantly influences the effectiveness of LDH-based components. To enhance pollutant removal through LDHs, researchers should explore modified components incorporating different trivalent cations and divalent ions in various proportions. Additionally, to improve the economic feasibility of LDH composites, more attention should be paid to optimizing preparation techniques. Reaction conditions and preparation methods also play a crucial role in determining the properties of LDHs, with some methods being overly complex, resource-intensive, and unsuitable for large-scale synthesis. Consequently, future research should prioritize the development of innovative, cost-effective, efficient, and environmentally friendly synthesis techniques.

6.3. Emerging pollutants

Emerging pollutants, due to their diverse chemical structures and properties, can be classified into several groups. Each group exhibits distinct characteristics that may influence the adsorption capacity of LDHs. Previous studies introduced LDH-based materials for the removal of emerging contaminants, demonstrating their potential. However, existing research remains insufficient to fully elucidate the underlying mechanisms. Consequently, further research is needed to explore LDH materials capable of selectively adsorbing specific emerging contaminants, alongside efforts to clarify the associated mechanisms.

6.4. Long-term stability analysis

Certain LDHs may release structural components, functional categories, or specific ions into the environment under specific conditions during pollutant removal activities, potentially leading to performance degradation, secondary pollution, and reduced reusability. To ensure the reliability and longevity of LDH-based components in practical applications, researchers must carefully evaluate the materials' structural and chemical stability, as well as their performance under varying conditions. It is possible to achieve long-term stability through isomorphic substitution; however, it is effective for only a limited range of HMs. Moreover, the lack of clear explanations regarding isomorphic substitution in several studies highlights the need for further research to elucidate its precise mechanism.

6.5. Comprehensive mechanistic research

The exact reduction process remains uncertain despite efforts to investigate LDHs' pollution removal mechanisms. This includes studies suggesting that LDHs and their components can convert Cr (VI) into Cr (III). Furthermore, it is crucial to determine whether a specific structure or functional group is essential for Cr (VI) elimination and how LDH compounds influence this process. Consequently, more comprehensive and detailed characterization techniques are necessary. LDH-based catalysts in sulfate radical-AOPs facilitate organic molecules degradation via both reactive and nonradical pathways. Nonradical-dominant systems exhibit superior tolerance to interfering contaminants, whereas the radical pathway often demonstrates better oxidation potential for OPs. While recent studies have focused on identifying reaction pathways, managing the present mechanisms remains a challenge. Therefore, future research should prioritize controlling reaction pathways alongside identifying active chemicals to achieve optimal pollutant degradation efficiency.

6.6. Investigating for soil remediation applications

Several studies have been conducted on the use of HMs and OPs for soil remediation. However, LDH composites exhibit significant removal capacity for both contaminants in sewage treatment. Investigating the potential applications of LDH and its components in soil remediation is crucial, particularly soil amendments that supply elements such as nitrogen and phosphorus. Additionally, researchers aim to recycle LDH composites after adsorption to enhance resource utilization efficiency.

7. Conclusion

This study conducted a comprehensive bibliometric analysis of research advancements, focal points, and trends in the use of LDHs for the removal of HMs and OPs. In recent years, LDH research has expanded rapidly, with significant growth observed in recent academic studies across various countries. This trend highlights the growing relevance of LDHs in diverse scientific applications and the collaborative efforts of researchers worldwide. Keyword analysis, including citation bursts, clustering, and co-occurrence, revealed that initial research primarily focused on using LDH nanoparticles for water purification. Recent studies have identified MG, Cd (II), Cr (VI), and TC as the most prevalent

pollutants, which are expected to remain key areas of focus. To enhance pollutant degradation in AOPs, researchers have increasingly applied LDHs as alternatives to persulfates and photocatalysts. Additionally, the development of LDH-biochar composites has emerged as a prominent topic. These composites, known for their exceptional catalytic degradation capabilities, high anion exchange capacity, superior electrical properties, strong chemical resistance, and versatile interfacial functionalities, are highly effective for pollutant removal.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Abazari, Reza, Ali Reza Mahjoub, Soheila Sanati, Zolfaghar Rezvani, Zhiquan Hou, and Hongxing Dai. 2019. 'Ni–Ti layered double hydroxide@ graphitic carbon nitride nanosheet: a novel nanocomposite with high and ultrafast sonophotocatalytic performance for degradation of antibiotics', Inorganic chemistry, 58: 1834-49.

[2] Adachi-Pagano, Mariko, Claude Forano, and Jean-Pierre Besse. 2003. 'Synthesis of Al-rich hydrotalcite-like compounds by using the urea hydrolysis reaction—control of size and morphology', Journal of Materials Chemistry, 13: 1988-93.

[3] Alexandre, Michaël, Philippe Dubois, Tao Sun, Juan M Garces, and Robert Jérôme. 2002. 'Polyethylene-layered silicate nanocomposites prepared by the polymerization-filling technique: synthesis and mechanical properties', Polymer, 43: 2123-32.

[4] Ampong, Daniel Nframah, Emmanuel Agyekum, Frank Ofori Agyemang, Kwadwo Mensah-Darkwa, Anthony Andrews, Anuj Kumar, and Ram K Gupta. 2023. 'MXene: fundamentals to applications in electrochemical energy storage', Discover Nano, 18: 3.

[5] Aramendía, María A, Victoriano Borau, César Jiménez, José M Marinas, José R Ruiz, and Francisco J Urbano. 2002. 'Comparative study of Mg/M (III)(M= Al, Ga, In) layered double hydroxides obtained by coprecipitation and the sol–gel method', Journal of Solid State Chemistry, 168: 156-61.

[6] Asiabi, Hamid, Yadollah Yamini, Maryam Shamsayei, and Elham Tahmasebi. 2017. 'Highly selective and efficient removal and extraction of heavy metals by layered double hydroxides intercalated with the diphenylamine-4-sulfonate: a comparative study', Chemical Engineering Journal, 323: 212-23.

[7] Asif, Muhammad Bilal, Hongyu Kang, and Zhenghua Zhang. 2022. 'Gravity-driven layered double hydroxide nanosheet membrane activated peroxymonosulfate system for micropollutant degradation', Journal of Hazardous Materials, 425: 127988.

[8] Bai, Jing, Xiangling Zhang, Chen Wang, Xuhao Li, Zhouying Xu, Cheng Jing, Ting Zhang, and Yinghe Jiang. 2024. 'The adsorption-photocatalytic synergism of LDHs-based nanocomposites on the removal of pollutants in aqueous environment: A critical review', Journal of Cleaner Production: 140705.

[9] Bao, Shuangyou, Weiwei Yang, Yingjun Wang, Yongsheng Yu, Yinyong Sun, and Kefei Li. 2020. 'PEI grafted amino-functionalized graphene oxide nanosheets for ultrafast and high selectivity removal of Cr (VI) from aqueous solutions by adsorption combined with reduction: Behaviors and mechanisms', Chemical Engineering Journal, 399: 125762.

[10] Benali, Mona, Jamil Toyir, Liliana Bizo, and Adrian-Ioan DUDU. 'Oxidative Conversion of Biomass into Formic Over Vanadium-and Molybdenum-Modified Mg-Al Mixed Oxide Derived from Hydrotalcite', Available at SSRN 5094272.

[11] Benito, P, M Herrero, C Barriga, FM Labajos, and V Rives. 2008. 'Microwave-assisted homogeneous precipitation of hydrotalcites by urea hydrolysis', Inorganic chemistry, 47: 5453-63.

[12] Bhatt, Pankaj, Saurabh Gangola, Geeta Bhandari, Wenping Zhang, Damini Maithani, Sandhya Mishra, and Shaohua Chen. 2021. 'New insights into the degradation of synthetic pollutants in contaminated environments', Chemosphere, 268: 128827.

[13] Bhuvaneswari, K, G Palanisamy, Kundan Sivashanmugan, T Pazhanivel, and T Maiyalagan. 2021. 'ZnO nanoparticles decorated multiwall carbon nanotube assisted ZnMgAl layered triple hydroxide hybrid

photocatalyst for visible light-driven organic pollutants removal', Journal of Environmental Chemical Engineering, 9: 104909.

[14] Bi, Bo, Lin Xu, Bingbing Xu, and Xizheng Liu. 2011. 'Heteropoly blue-intercalated layered double hydroxides for cationic dye removal from aqueous media', Applied Clay Science, 54: 242-47.

[15] Bing, Weihan, Lei Zheng, Shan He, Deming Rao, Ming Xu, Lirong Zheng, Bin Wang, Yangdong Wang, and Min Wei. 2018. 'Insights on active sites of CaAl-hydrotalcite as a high-performance solid base catalyst toward aldol condensation', ACS Catalysis, 8: 656-64.

[16] Bukhtiyarova, MV. 2019. 'A review on effect of synthesis conditions on the formation of layered double hydroxides', Journal of Solid State Chemistry, 269: 494-506.

[17] Cai, Pingwei, Suqin Ci, Na Wu, Yuan Hong, and Zhenhai Wen. 2017. 'Layered structured CoAl/CdS-LDHs nanocomposites as visible light photocatalyst', physica status solidi (a), 214: 1600910.

[18] Cao, Yong, Guoting Li, and Xinbao Li. 2016. 'Graphene/layered double hydroxide nanocomposite: Properties, synthesis, and applications', Chemical Engineering Journal, 292: 207-23.

[19] Chaudhuri, Haribandhu, and Yeoung-Sang Yun. 2022. 'Synthesis and environmental applications of graphene oxide/layered double hydroxides and graphene oxide/MXenes: A critical review', Separation and Purification Technology, 297: 121518.

[20] Chen, Chao-Rong, Hong-Yan Zeng, Mo-Yu Yi, Gao-Fei Xiao, Run-Liang Zhu, Xiao-Jv Cao, Shi-Gen Shen, and Jia-Wen Peng. 2019. 'Fabrication of Ag2O/Ag decorated ZnAl-layered double hydroxide with enhanced visible light photocatalytic activity for tetracycline degradation', Ecotoxicology and Environmental Safety, 172: 423-31.

[21] Chen, Gong, Xinyi Zhang, Yingjie Gao, Guixian Zhu, Qingfeng Cheng, and Xiuwen Cheng. 2019. 'Novel magnetic MnO2/MnFe2O4 nanocomposite as a heterogeneous catalyst for activation of peroxymonosulfate (PMS) toward oxidation of organic pollutants', Separation and Purification Technology, 213: 456-64.

[22] Chen, Guixiang, Shengming Qian, Xinman Tu, Xiaoyong Wei, Jianping Zou, Lehui Leng, and Shenglian Luo. 2014. 'Enhancement photocatalytic degradation of rhodamine B on nanoPt intercalated Zn–Ti layered double hydroxides', Applied Surface Science, 293: 345-51.

[23] Chen, Mengzhu, Huihui Yuan, Xing Qin, Yiren Wang, Haibing Zheng, Linwen Yu, Yuxin Cai, Qing-feng Liu, Guojin Liu, and Weihua Li. 2024. 'Improve corrosion resistance of steel bars in simulated concrete pore solution by the addition of EDTA intercalated CaAl-LDH', Corrosion Science, 226: 111636.

[24] Chen, Shangqing, Xiaonan Yang, Zheng Wang, Jiayin Hu, Senjian Han, Yafei Guo, and Tianlong Deng. 2021. 'Prussian blue analogs-based layered double hydroxides for highly efficient Cs+ removal from wastewater', Journal of Hazardous Materials, 410: 124608.

[25] Cong, Yanqing, Lidong Shen, Baimei Wang, Jianlai Cao, Zixuan Pan, Ziyu Wang, Kai Wang, Qiangbiao Li, and Xuchun Li. 2022. 'Efficient removal of Cr (VI) at alkaline pHs by sulfite/iodide/UV: Mechanism and modeling', Water Research, 222: 118919.

[26] Cui, Shihao, Yutao Peng, Xiao Yang, Xing Gao, Chung-Yu Guan, Beibei Fan, Xue Zhou, and Qing Chen. 2023. 'Comprehensive understanding of guest compound intercalated layered double hydroxides: Design and applications in removal of potentially toxic elements', Critical Reviews in Environmental Science and Technology, 53: 457-82.

[27] Dai, Chenglong, Xiangci Wu, Qiang Wang, Yuchen Bai, Dan Zhao, Jianfeng Fu, Bingfeng Fu, and Hui Ding. 2024. 'Layered double hydroxides for efficient treatment of heavy metals and organic pollutants: Recent progress and future perspectives', Separation and Purification Technology: 12,82,77.

[28] Danks, AE, SR Hall, and Z Schnepp. "The evolution of 'sol–gel'chemistry as a technique for materials synthesis, Mater. Horiz. 3 (2016) 91–112." In.

[29] Daud, Muhammad, Muhammad Shahzad Kamal, Farrukh Shehzad, and Mamdouh A Al-Harthi. 2016. 'Graphene/layered double hydroxides nanocomposites: a review of recent progress in synthesis and applications', Carbon, 104: 241-52.

[30] del Valle Ponce, María, Mariel Cina, Carlos López, and Soledad Cerutti. 2022. 'Synthesis and evaluation of a Zn–Al layered double hydroxide for the removal of ochratoxin A. Greenness assessment', Analytical Methods, 14: 2841-48.

[31] Deng, Yu, Min Li, Zhan Zhang, Qiao Liu, Kele Jiang, Jingjie Tian, Ying Zhang, and Fuquan Ni. 2021. 'Comparative study on characteristics and mechanism of phosphate adsorption on Mg/Al modified biochar', Journal of Environmental Chemical Engineering, 9: 105079.

[32] dos Santos, Grazielle Emanuella de Souza, Pollyanna Vanessa dos Santos Lins, Leonardo Mendonça Tenório de Magalhães Oliveira, Elenara Oliveira da Silva, Ioannis Anastopoulos, Alessandro Erto, Dimitrios A Giannakoudakis, André Ricardo Felkl de Almeida, José Leandro da Silva Duarte, and Lucas Meili. 2021. 'Layered double hydroxides/biochar composites as adsorbents for water remediation applications: recent trends and perspectives', Journal of Cleaner Production, 284: 124755.

[33] Du, Longchao, Baojun Qu, and Ming Zhang. 2007. 'Thermal properties and combustion characterization of nylon 6/MgAl-LDH nanocomposites via organic modification and melt intercalation', Polymer Degradation and Stability, 92: 497-502.

[34] Elhalil, A, R Elmoubarki, M Farnane, A Machrouhi, FZ Mahjoubi, M Sadiq, S Qourzal, M Abdennouri, and N Barka. 2019. 'Novel Ag-ZnO-La2O2CO3 photocatalysts derived from the Layered Double Hydroxide structure with excellent photocatalytic performance for the degradation of pharmaceutical compounds', Journal of Science: Advanced Materials and Devices, 4: 34-46.

[35] Evans, David G, and Robert CT Slade. 2006. 'Structural aspects of layered double hydroxides', Layered double hydroxides: 1-87.

[36] Fan, Guoli, Feng Li, David G Evans, and Xue Duan. 2014. 'Catalytic applications of layered double hydroxides: recent advances and perspectives', Chemical Society Reviews, 43: 7040-66.

[37] Fan, Lipeng, Lan Yang, Yanjun Lin, Guoli Fan, and Feng Li. 2020. 'Enhanced thermal stabilization effect of hybrid nanocomposite of Ni–Al layered double hydroxide/carbon nanotubes on polyvinyl chloride resin', Polymer Degradation and Stability, 176: 109153.

[38] Fang, Kaili, Minfeng Chen, Jizhang Chen, Qinghua Tian, and Ching-Ping Wong. 2019. 'Cotton stalk-derived carbon fiber@ Ni-Al layered double hydroxide nanosheets with improved performances for supercapacitors', Applied Surface Science, 475: 372-79.

[39] Farhan, Ahmad, Aman Khalid, Nimra Maqsood, Sidra Iftekhar, Hafiz Muhammad Adeel Sharif, Fei Qi, Mika Sillanpää, and Muhammad Bilal Asif. 2024. 'Progress in layered double hydroxides (LDHs): Synthesis and application in adsorption, catalysis and photoreduction', Science of the Total Environment, 912: 169160.

[40] Fu, Dun, Tonni Agustiono Kurniawan, Ram Avtar, Pan Xu, and Mohd Hafiz Dzarfan Othman. 2021. 'Recovering heavy metals from electroplating wastewater and their conversion into Zn2Cr-layered double hydroxide (LDH) for pyrophosphate removal from industrial wastewater', Chemosphere, 271: 129861.

[41] Gao, Duoduo, Huogen Yu, and Ying Xu. 2018. 'Direct photoinduced synthesis and high H2-evolution performance of Bi-modified TiO2 photocatalyst in a Bi (III)-EG complex system', Applied Surface Science, 462: 623-32.

[42] Gao, Mingkun, Donghui Xu, Yuhang Gao, Ge Chen, Rongqi Zhai, Xiaodong Huang, Xiaomin Xu, Jing Wang, Xin Yang, and Guangyang Liu. 2021. 'Mussel-inspired triple bionic adsorbent: Facile preparation of layered double hydroxide@ polydopamine@ metal-polyphenol networks and their selective adsorption of dyes in single and binary systems', Journal of Hazardous Materials, 420: 126609.

[43] Gaume, Julien, Sandrine Therias, Fabrice Leroux, Agnès Rivaton, and Jean-Luc Gardette. 2013. 'Exfoliated polymer nanocomposites by in situ coprecipitation of layered double hydroxides in a polymer matrix', Journal of applied polymer science, 129: 1345-49.

[44] Gholami, Peyman, Laleh Dinpazhoh, Alireza Khataee, Aydin Hassani, and Amit Bhatnagar. 2020. 'Facile hydrothermal synthesis of novel Fe-Cu layered double hydroxide/biochar nanocomposite with enhanced sonocatalytic activity for degradation of cefazolin sodium', Journal of Hazardous Materials, 381: 120742.

[45] González, MA, Ivana Pavlovic, Ricardo Rojas-Delgado, and Cristobalina Barriga. 2014. 'Removal of Cu2+, Pb2+ and Cd2+ by layered double hydroxide–humate hybrid. Sorbate and sorbent comparative studies', Chemical Engineering Journal, 254: 605-11.

[46] Gore, Christopher T, Solomon Omwoma, Wei Chen, and Yu-Fei Song. 2016. 'Interweaved LDH/PAN nanocomposite films: Application in the design of effective hexavalent chromium adsorption technology', Chemical Engineering Journal, 284: 794-801.

[47] Guan, Xian, Xingzhong Yuan, Yanlan Zhao, Hou Wang, Hui Wang, Jing Bai, and Ying Li. 2022. 'Application of functionalized layered double hydroxides for heavy metal removal: A review', Science of the Total Environment, 838: 155693.

[48] Guo, Xiaoxiao, Fazhi Zhang, Qing Peng, Sailong Xu, Xiaodong Lei, David G Evans, and Xue Duan. 2011. 'Layered double hydroxide/eggshell membrane: An inorganic biocomposite membrane as an efficient adsorbent for Cr (VI) removal', Chemical Engineering Journal, 166: 81-87.

[49] Hamimed, Selma, Nejib Jebli, Amina Othmani, Rayene Hamimed, Ahmed Barhoum, and Abdelwaheb Chatti. 2022. 'Nanocelluloses for removal of heavy metals from wastewater.' in, Handbook of Nanocelluloses: Classification, Properties, Fabrication, and Emerging Applications (Springer).

[50] He, Jing, Min Wei, Bo Li, Yu Kang, David G Evans, and Xue Duan. 2006. 'Preparation of layered double hydroxides', Layered double hydroxides: 89-119.

[51] He, Xin, Xinhong Qiu, Chenyan Hu, and Yawen Liu. 2018. 'Treatment of heavy metal ions in wastewater using layered double hydroxides: A review', Journal of Dispersion Science and Technology, 39: 792-801.

[52] Hou, Xiangting, Shiqi Liu, Chengze Yu, Likun Jiang, Yingjie Zhang, Guocheng Liu, Chengzhi Zhou, Tao Zhu, Yanjun Xin, and Qinghua Yan. 2022. 'A novel magnetic CuFeAl-LDO catalyst for efficient degradation of tetrabromobisphenol a in water', Chemical Engineering Journal, 430: 133107.

[53] Hu, Zhihui, Shasha Tang, Yan Jia, Zekun Dong, Yu Tang, Yuan Wu, and Yan Zhang. 2025. 'Insight into the mechanism of Bi modified MXene-derived TiO2 for efficient visible-light driven photocatalytic reduction of bromate', Journal of Environmental Chemical Engineering: 115423.

[54] Jasem-Feisal, Ameneh, Fatemeh Amiripour, and Shahram Ghasemi. 2024. 'MOF-derived Co-Al layered double hydroxide modified rice husk biochar nanohybrid for efficient removal of Cu (II) from wastewater', Journal of Water Process Engineering, 64: 105612.

[55] Jia, Gan, Yingfei Hu, Qinfeng Qian, Yingfang Yao, Shiying Zhang, Zhaosheng Li, and Zhigang Zou. 2016. 'Formation of hierarchical structure composed of (Co/Ni) Mn-LDH nanosheets on MWCNT backbones for efficient electrocatalytic water oxidation', ACS applied materials and interfaces, 8: 14527-34.

[56] Jiang, Yimei, Zhengtao Shen, Chao-Sheng Tang, and Bin Shi. 2023. 'Synthesis and application of waste-based layered double hydroxide: A review', Science of the Total Environment: 166245.

[57] Ju, Liting, Pingxiao Wu, Qiliang Yang, Zubair Ahmed, and Nengwu Zhu. 2018. 'Synthesis of ZnAlTi-LDO supported C60@ AgCl nanoparticles and their photocatalytic activity for photo-degradation of Bisphenol A', Applied Catalysis B: Environmental, 224: 159-74.

[58] Jung, Kyung-Won, Seon Yong Lee, Jae-Woo Choi, Min-Jin Hwang, and Wang Geun Shim. 2021. 'Synthesis of Mg–Al layered double hydroxides-functionalized hydrochar composite via an in situ one-pot hydrothermal method for arsenate and phosphate removal: Structural characterization and adsorption performance', Chemical Engineering Journal, 420: 129775.

[59] Karim, Ansaf V, Aydin Hassani, Paria Eghbali, and PV Nidheesh. 2022. 'Nanostructured modified layered double hydroxides (LDHs)-based catalysts: a review on synthesis, characterization, and applications in water remediation by advanced oxidation processes', Current Opinion in Solid State and Materials Science, 26: 100965.

[60] Khandaker, Shahjalal, Megumu Fujibayashi, and Takahiro Kuba. 2025. 'Innovative potassium hexacyanoferrate intercalated into layered double hydroxide adsorbent for efficient cesium removal from seawater', Separation and Purification Technology, 354: 128984.

[61] Kim, Nam Hoon, Ananta Kumar Mishra, Da-Yeong Kim, and Joong Hee Lee. 2015. 'Synthesis of sulfonated poly (ether ether ketone)/layered double hydroxide nanocomposite membranes for fuel cell applications', Chemical Engineering Journal, 272: 119-27.

[62] Koilraj, Paulmanickam, Rajathsing Kalusulingam, and Keiko Sasaki. 2019. 'Arginine and lysine-functionalized layered double hydroxides as efficient sorbents for radioactive Co2+ removal by chelate-facilitated immobilization', Chemical Engineering Journal, 374: 359-69.

[63] Koilraj, Paulmanickam, Yuta Kamura, and Keiko Sasaki. 2017. 'Carbon-dot-decorated layered double hydroxide nanocomposites as a multifunctional environmental material for co-immobilization of SeO42–and Sr2+ from aqueous solutions', ACS Sustainable Chemistry and Engineering, 5: 9053-64.

[64] Kong, Xianggui, Ruixiang Ge, Tian Liu, Simin Xu, Peipei Hao, Xiaojie Zhao, Zhenhua Li, Xiaodong Lei, and Haohong Duan. 2021. 'Super-stable mineralization of cadmium by calcium-aluminum layered double hydroxide and its large-scale application in agriculture soil remediation', Chemical Engineering Journal, 407: 127178.

[65] Laipan, Minwang, Jingfang Yu, Runliang Zhu, Jianxi Zhu, Andrew T Smith, Hongping He, Dermot O'Hare, and Luyi Sun. 2020. 'Functionalized layered double hydroxides for innovative applications', Materials Horizons, 7: 715-45.

[66] Laipan, Minwang, Runliang Zhu, Qingze Chen, Jianxi Zhu, Yunfei Xi, Godwin A Ayoko, and Hongping He. 2015. 'From spent Mg/Al layered double hydroxide to porous carbon materials', Journal of Hazardous Materials, 300: 572-80.

[67] Lee, Seon Yong, Jae-Woo Choi, Kyung Guen Song, Keunsu Choi, Young Jae Lee, and Kyung-Won Jung. 2019. 'Adsorption and mechanistic study for phosphate removal by rice husk-derived biochar functionalized with Mg/Al-calcined layered double hydroxides via co-pyrolysis', Composites Part B: Engineering, 176: 107209.

[68] Li ChunMei, Li ChunMei, Yu SiYu Yu SiYu, Zhang XiaoXu Zhang XiaoXu, Wang Yun Wang Yun, Liu ChunBo Liu ChunBo, Chen Gang Chen Gang, and Dong HongJun Dong HongJun. 2019. 'Insight into photocatalytic activity, universality and mechanism of copper/chlorine surface dual-doped graphitic carbon nitride for degrading various organic pollutants in water'.

[69] Li, Fengrong, Xuezhen Liu, ZhengYi Zhao, Xia An, Yali Du, and Xu Wu. 2023. 'Fabrication of highly dispersed carbon doped Cu-based oxides as superior selective catalytic oxidation of ammonia catalysts via employing citric acid-modified carbon nanotubes doping CuAl-LDHs', Chinese Journal of Chemical Engineering, 63: 185-96.

[70] Li, Jinfeng, Tuo Li, Qianwen Wang, Bo Tian, Zhigang Li, Jianwei Zhang, Wenze Li, Wa Gao, Nan Zhang, and Haifeng Gu. 2025. 'In-situ preparation of HPO42− intercalated NiFe layered double hydroxides for efficient U (VI) removal', Separation and Purification Technology, 354: 129279.

[71] Li, Ming, Xi Chen, Jinjin He, Shucheng Liu, Yi Tang, and Xiaogang Wen. 2024. 'Porous NiCo-LDH microspheres obtained by freeze-drying for efficient dye and Cr (VI) adsorption', Journal of Alloys and Compounds, 976: 173107.

[72] Li, Ronghua, Jim J Wang, Baoyue Zhou, Mukesh Kumar Awasthi, Amjad Ali, Zengqiang Zhang, Lewis A Gaston, Altaf Hussain Lahori, and Amanullah Mahar. 2016. 'Enhancing phosphate adsorption by Mg/Al layered double hydroxide functionalized biochar with different Mg/Al ratios', Science of the Total Environment, 559: 121-29.

[73] Li, Xun, Yue Meng, Jinhua Li, Lianyang Zhang, Bo Xie, Zheming Ni, and Shengjie Xia. 2023. 'The performance and mechanism of persulfate activation boosted MoO2@ LDHs Z-scheme heterojunction for efficient photocatalytic degradation of tetracycline', Journal of Environmental Chemical Engineering, 11: 110257.

[74] Li, Xun, Ziying Yuan, Zhiling Huang, Aoki Koso, Jinhua Li, Bo Xie, Zheming Ni, and Shengjie Xia. 2022. 'The photodegradation property and mechanism of tetracycline by persulfate radical activated In2O3@ LDHs Z–scheme heterojunction', Separation and Purification Technology, 302: 122077.

[75] Liang, Jianxing, Ying Wei, Yan Yao, Xiaoke Zheng, Jing Shen, Guangyu He, and Haiqun Chen. 2019. 'Constructing high-efficiency photocatalyst for degrading ciprofloxacin: three-dimensional visible light driven graphene based NiAlFe LDH', Journal of Colloid and Interface Science, 540: 237-46.

[76] Lin, Tong, Zhuoqun Deng, Tianyang Shen, Haoran Wang, Xinyuan Sun, Ruoxuan Zheng, Wei Chen, Sai An, and Yu-Fei Song. 2024. 'Revisiting the super-stable mineralization mechanism of CaAl-LDHs for Cu2+ and complete removal of Cu2+ by structured CaAl-LDHs', Chemical Engineering Science, 288: 119822.

[77] Liu, Junqin, Pingxiao Wu, Shuaishuai Li, Meiqing Chen, Wentin Cai, Dinghui Zou, Nengwu Zhu, and Zhi Dang. 2019. 'Synergistic deep removal of As (III) and Cd (II) by a calcined multifunctional MgZnFe-CO3 layered double hydroxide: photooxidation, precipitation and adsorption', Chemosphere, 225: 115-25.

[78] Liu, Xiaoxiao, Qian Shao, Yufei Zhang, Xiaojing Wang, Jing Lin, Yuanfa Gan, Mengyao Dong, and Zhanhu Guo. 2020. 'Microwave hydrothermal synthesized ZnIn-layered double hydroxides derived ZnIn-layered double oxides for enhanced methylene blue photodegradation', Colloids and Surfaces A: Physicochemical and Engineering Aspects, 592: 124588.

[79] Lu, Yanfeng, Xianghan Li, Xinbin Jing, Yu Huang, Yi Qiang, Guangzhu Cao, Ronggao Qin, Qiang Cao, Junji Cao, and Shun Cheng Lee. 2024. 'Applications of layered double hydroxide nanomaterials in environmental remediation: synthesis, structural modification and performance enhancement', Surfaces and Interfaces: 104902.

[80] Lu, Zhiyi, Li Qian, Yang Tian, Yaping Li, Xiaoming Sun, and Xue Duan. 2016. 'Ternary NiFeMn layered double hydroxides as highly-efficient oxygen evolution catalysts', Chemical Communications, 52: 908-11.

[81] Ma, Lijiao, Saiful M Islam, Hongyun Liu, Jing Zhao, Genban Sun, Huifeng Li, Shulan Ma, and Mercouri G Kanatzidis. 2017. 'Selective and efficient removal of toxic oxoanions of As (III), As (V), and Cr (VI) by layered double hydroxide intercalated with MoS42−', Chemistry of Materials, 29: 3274-84.

[82] Mallakpour, Shadpour, and Hashem Tabebordbar. 2020. 'Layered double hydroxide polymer nanocomposites for catalysis.' in, Layered Double Hydroxide Polymer Nanocomposites (Elsevier).

[83] Manea, Yahiya Kadaf, Amjad Mumtaz Khan, Ajaz Ahmad Wani, Mansour AS Saleh, Mohsen TA Qashqoosh, Mohammad Shahadat, and Mashallah Rezakazemi. 2022. 'In-grown flower like Al-Li/Th-LDH@ CNT nanocomposite for enhanced photocatalytic degradation of MG dye and selective adsorption of Cr (VI)', Journal of Environmental Chemical Engineering, 10: 106848.

[84] Meseguer-Sánchez, Víctor, Francisco Jesús Gálvez-Sánchez, Gabriel López-Martínez, and Valentín Molina-Moreno. 2021. 'Corporate social responsibility and sustainability. A bibliometric analysis of their interrelations', Sustainability, 13: 1636.

[85] Mittal, Jyoti. 2021. 'Recent progress in the synthesis of Layered Double Hydroxides and their application for the adsorptive removal of dyes: A review', Journal of Environmental Management, 295: 113017.

[86] Miyah, Youssef, Noureddine El Messaoudi, Mohammed Benjelloun, Yaser Acikbas, Zeynep Mine Şenol, Zeynep Ciğeroğlu, and Eduardo Alberto Lopez-Maldonado. 2024. 'Advanced applications of hydroxyapatite nanocomposite materials for heavy metals and organic pollutants removal by adsorption and photocatalytic degradation: a review', Chemosphere: 142236.

[87] Mohapi, Maleshoane, Jeremia Shale Sefadi, Mokgaotsa Jonas Mochane, Sifiso Innocent Magagula, and Kgomotso Lebelo. 2020. 'Effect of LDHs and other clays on polymer composite in adsorptive removal of contaminants: a review', Crystals, 10: 957.

[88] Mohiuddin, Irshad, Aman Grover, Jatinder Singh Aulakh, Ashok Kumar Malik, Sang Soo Lee, Richard JC Brown, and Ki-Hyun Kim. 2021. 'Starch-Mg/Al layered double hydroxide composites as an efficient solid phase extraction sorbent for non-steroidal anti-inflammatory drugs as environmental pollutants', Journal of Hazardous Materials, 401: 123782.

[89] Montiel-Centeno, Kiara, Deicy Barrera, Fátima García-Villén, Sebastian Amaya-Roncancio, César Viseras, and Karim Sapag. 2025. 'Ordered mesoporous silica and carbon as controlled release systems for cephalexin: Influence of surface modification and porosity', Surfaces and Interfaces, 56: 105576.

[90] Mortaheb, Hamid R, Mohammad H Amini, Fateme Sadeghian, Babak Mokhtarani, and Hesam Daneshyar. 2008. 'Study on a new surfactant for removal of phenol from wastewater by emulsion liquid membrane', Journal of Hazardous Materials, 160: 582-88.

[91] Nayak, Susanginee, and KM Parida. 2019. 'Deciphering Z-scheme charge transfer dynamics in heterostructure NiFe-LDH/N-rGO/g-C3N4 nanocomposite for photocatalytic pollutant removal and water splitting reactions', Scientific Reports, 9: 2458.

[92] Ng'etich, Wesley K, and Bice S Martincigh. 2021. 'A critical review on layered double hydroxides: Their synthesis and application in sunscreen formulations', Applied Clay Science, 208: 106095.

[93] Ogawa, Makoto, and Hiroshi Kaiho. 2002. 'Homogeneous precipitation of uniform hydrotalcite particles', Langmuir, 18: 4240-42.

[94] Oh, Jae-Min, Sung-Ho Hwang, and Jin-Ho Choy. 2002. 'The effect of synthetic conditions on tailoring the size of hydrotalcite particles', Solid State Ionics, 151: 285-91.

[95] Okamoto, Kentaro, Nobuo Iyi, and Takayoshi Sasaki. 2007. 'Factors affecting the crystal size of the MgAl-LDH (layered double hydroxide) prepared by using ammonia-releasing reagents', Applied Clay Science, 37: 23-31.

[96] Omwoma, Solomon, Wei Chen, Ryo Tsunashima, and Yu-Fei Song. 2014. 'Recent advances on polyoxometalates intercalated layered double hydroxides: From synthetic approaches to functional material applications', Coordination Chemistry Reviews, 258: 58-71.

[97] Pandey, Prashant, Aparajita Shankar, Michael Biney, and Vipin K Saini. 2021. 'Enhancement in amoxicillin adsorption and regeneration properties of SBA-15 after surface modification with polyaniline', Colloid and Interface Science Communications, 43: 100432.

[98] Pang, Hongwei, Yihan Wu, Xiangxue Wang, Baowei Hu, and Xiangke Wang. 2019. 'Recent advances in composites of graphene and layered double hydroxides for water remediation: a review', Chemistry–An Asian Journal, 14: 2542-52.

[99] Pathak, Jigyasa, and Poonam Singh. 2024. 'Ultrafast catalytic reduction of organic pollutants using ternary zinc–copper–nickel layered double hydroxide', Applied Organometallic Chemistry, 38: e7507.

[100] Pelalak, Rasool, Aydin Hassani, Zahra Heidari, and Minghua Zhou. 2023. 'State-of-the-art recent applications of layered double hydroxides (LDHs) material in Fenton-based oxidation processes for water and wastewater treatment', Chemical Engineering Journal: 145511.

[101] Peng, Xiaoming, Min Wang, Fengping Hu, Fengxian Qiu, Tao Zhang, Hongling Dai, and Zan Cao. 2018. 'Multipath fabrication of hierarchical CuAl layered double hydroxide/carbon fiber composites for the degradation of ammonia nitrogen', Journal of Environmental Management, 220: 173-82.

[102] Poudel, Milan Babu, Ganesh Prasad Awasthi, and Han Joo Kim. 2021. 'Novel insight into the adsorption of Cr (VI) and Pb (II) ions by MOF derived Co-Al layered double hydroxide@ hematite nanorods on 3D porous carbon nanofiber network', Chemical Engineering Journal, 417: 129312.

[103] Pourfarzad, Hamed, Mehdi Shabani-Nooshabadi, Mohammad Reza Ganjali, and Hamideh Kashani. 2019. 'Synthesis of Ni–Co-Fe layered double hydroxide and Fe2O3/Graphene nanocomposites as actively materials for high electrochemical performance supercapacitors', Electrochimica Acta, 317: 83-92.

[104] Prince, Julia, Ascencion Montoya, Gerardo Ferrat, and Jaime S Valente. 2009. 'Proposed general sol– gel method to prepare multimetallic layered double hydroxides: synthesis, characterization, and envisaged application', Chemistry of Materials, 21: 5826-35.

[105] Rahman, Mir Tamzid, Tomohito Kameda, Shogo Kumagai, and Toshiaki Yoshioka. 2018. 'A novel method to delaminate nitrate-intercalated MgAl layered double hydroxides in water and application in heavy metals removal from waste water', Chemosphere, 203: 281-90.

[106] Rahmanian, Omid, Mohammad Dinari, and Mahmood Karimi Abdolmaleki. 2018. 'Carbon quantum dots/layered double hydroxide hybrid for fast and efficient decontamination of Cd (II): The adsorption kinetics and isotherms', Applied Surface Science, 428: 272-79.

[107] Rao, CNR, SRC Vivekchand, Kanishka Biswas, and A Govindaraj. 2007. 'Synthesis of inorganic nanomaterials', Dalton Transactions: 3728-49.

[108] Rives, Vicente. 2001. 'Study of layered double hydroxides by thermal methods', Layered double hydroxides: present and future: 115-32.

[109] Rojas, Ricardo. 2014. 'Copper, lead and cadmium removal by Ca Al layered double hydroxides', Applied Clay Science, 87: 254-59.

[110] Sahoo, Dipti Prava, Kundan Kumar Das, Sulagna Patnaik, and Kulamani Parida. 2020. 'Double charge carrier mechanism through 2D/2D interface-assisted ultrafast water reduction and antibiotic degradation over architectural S, P co-doped gC 3 N 4/ZnCr LDH photocatalyst', Inorganic Chemistry Frontiers, 7: 3695-717.

[111] Shen, Xiaolin, Zhiliang Zhu, Hua Zhang, Guanglan Di, Ting Chen, Yanling Qiu, and Daqiang Yin. 2020. 'Carbonaceous composite materials from calcination of azo dye-adsorbed layered double hydroxide with enhanced photocatalytic efficiency for removal of Ibuprofen in water', Environmental Sciences Europe, 32: 1-15.

[112] Shen, Zhongying, Quanwei Li, Xiaorong Wei, Mengyu Lu, Zhixian Chang, Ruifeng Chong, and Deliang Li. 2024. 'Highly efficient removal of Pb2+ and Cd2+ on MgAl-LDH modified with carbon dots, citric acid and amino silane: Kinetic, isothermal and mechanistic studies', Journal of Environmental Chemical Engineering, 12: 113601.

[113] Sheraz, Nashra, Afzal Shah, Abdul Haleem, and Faiza Jan Iftikhar. 2024. 'Comprehensive assessment of carbon-, biomaterial-and inorganic-based adsorbents for the removal of the most hazardous heavy metal ions from wastewater', RSC advances, 14: 11284-310.

[114] Song, Jingke, Chenyang Li, Xin Zhao, Ruirui Liu, Ruixue Han, Kai Jiang, Meiqing Shi, and Dapeng Wu. 2024. 'Mg Fe-layered double hydroxides (LDHs) modified electrode enhanced capacitive deionization for simultaneous phosphorus recovery and copper ions removal', Journal of Environmental Chemical Engineering, 12: 112145.

[115] Stimpfling, Thomas, Arthur Langry, Horst Hintze-Bruening, and Fabrice Leroux. 2016. 'In situ platelets formation into aqueous polymer colloids: The topochemical transformation from single to double layered hydroxide (LSH–LDH) uncovered', Journal of Colloid and Interface Science, 462: 260-71.

[116] Sun, Hao, Seul-Yi Lee, and Soo-Jin Park. 2023. 'MgAl-layered double hydroxides decorated with Pd-doped SnS nanoparticles: A novel photocatalyst for efficient dye degradation and Cr (VI) reduction in water', Journal of Industrial and Engineering Chemistry, 126: 510-19.

[117] Suresh, Kelothu, Manish Kumar, G Pugazhenthi, and R Uppaluri. 2017. 'Enhanced mechanical and thermal properties of polystyrene nanocomposites prepared using organo-functionalized NiAl layered double hydroxide via melt intercalation technique', Journal of Science: Advanced Materials and Devices, 2: 245-54.

[118] Tang, Lu, Wei Chen, Fan Li, Jiangyan Xu, Yin Shi, and Hongmei Jiang. 2024. 'The formation and adsorption mechanism studies of 3D hydrangea-like ZnFe-LDHs/FeOOH for the highly efficient removal of phosphate', Chemical Engineering Journal, 482: 148410.

[119] Tang, Yuqi, Xiangling Zhang, Xuhao Li, Jing Bai, Chao Yang, Yueling Zhang, Zhouying Xu, Xi Jin, and Yu Jiang. 2023. 'Facile synthesis of magnetic ZnAl layered double hydroxides and efficient adsorption of malachite green and Congo red', Separation and Purification Technology, 322: 124305.

[120] Tian, Yaxin, Guangfei Qu, Rui Xu, Xinxin Liu, and Caiyue Jin. 2024. 'Iron-based materials for immobilization of heavy metals in contaminated soils: a critical review', Journal of Environmental Chemical Engineering: 113741.

[121] Tonda, Surendar, and Wan-Kuen Jo. 2018. 'Plasmonic Ag nanoparticles decorated NiAl-layered double hydroxide/graphitic carbon nitride nanocomposites for efficient visible-light-driven photocatalytic removal of aqueous organic pollutants', Catalysis Today, 315: 213-22.

[122] Valente, Jaime S, Francisco Tzompantzi, and Julia Prince. 2011. 'Highly efficient photocatalytic elimination of phenol and chlorinated phenols by CeO2/MgAl layered double hydroxides', Applied Catalysis B: Environmental, 102: 276-85.

[123] Vallet-Regı, M, JC Doadrio, AL Doadrio, I Izquierdo-Barba, and J Pérez-Pariente. 2004. 'Hexagonal ordered mesoporous material as a matrix for the controlled release of amoxicillin', Solid State Ionics, 172: 435-39.

[124] Vareda, João P. 2023. 'On validity, physical meaning, mechanism insights and regression of adsorption kinetic models', Journal of Molecular Liquids, 376: 121416.

[125] Velusamy, Sasireka, Anurag Roy, Senthilarasu Sundaram, and Tapas Kumar Mallick. 2021. 'A review on heavy metal ions and containing dyes removal through graphene oxide-based adsorption strategies for textile wastewater treatment', The Chemical Record, 21: 1570-610.

[126] Vithanage, Meththika, Ahmed Ashiq, Sammani Ramanayaka, and Amit Bhatnagar. 2020. 'Implications of layered double hydroxides assembled biochar composite in adsorptive removal of contaminants: Current status and future perspectives', Science of the Total Environment, 737: 139718.

[127] Wan, Dongjin, Huijuan Liu, Ruiping Liu, Jiuhui Qu, Shanshan Li, and Jian Zhang. 2012. 'Adsorption of nitrate and nitrite from aqueous solution onto calcined (Mg–Al) hydrotalcite of different Mg/Al ratio', Chemical Engineering Journal, 195: 241-47.

[128] Wang, Fengyi, and Zhiguang Guo. 2019. 'Insitu growth of ZIF-8 on CoAl layered double hydroxide/carbon fiber composites for highly efficient absorptive removal of hexavalent chromium from aqueous solutions', Applied Clay Science, 175: 115-23.

[129] Wang, Peng, Xueqian Zhang, Bin Zhou, Fanpeng Meng, Yishan Wang, and Guangwu Wen. 2023. 'Recent advance of layered double hydroxides materials: Structure, properties, synthesis, modification and applications of wastewater treatment', Journal of Environmental Chemical Engineering: 111191.

[130] Wang, Qiang, and Dermot O'Hare. 2012. 'Recent advances in the synthesis and application of layered double hydroxide (LDH) nanosheets', Chemical reviews, 112: 4124-55.

[131] Wang, Xiangxue, Shuqi Yu, Yihan Wu, Hongwei Pang, Shujun Yu, Zhongshan Chen, Jing Hou, Ahmed Alsaedi, Tasawar Hayat, and Suhua Wang. 2018. 'The synergistic elimination of uranium (VI) species from aqueous solution using bi-functional nanocomposite of carbon sphere and layered double hydroxide', Chemical Engineering Journal, 342: 321-30.

[132] Wang, Xianwen, Xiaoyan Zhong, Jianxiang Li, Zhuang Liu, and Liang Cheng. 2021. 'Inorganic nanomaterials with rapid clearance for biomedical applications', Chemical Society Reviews, 50: 8669-742.

[133] Wang, Yifan, Jianen Li, Liang Xu, Di Wu, Qiaona Li, Yunhe Ai, Wei Liu, Dannan Li, Yutong Zhou, and Boyu Zhang. 2024. 'EDTA functionalized Mg/Al hydroxides modified biochar for Pb (II) and Cd (II) removal: Adsorption performance and mechanism', Separation and Purification Technology, 335: 126199.

[134] Wang, Yue, Yihan Bai, Junfeng Su, Amjad Ali, Zhihong Gao, Tinglin Huang, Meng Cao, and Miqi Ren. 2023. 'Advances in microbially mediated manganese redox cycling coupled with nitrogen removal in wastewater treatment: A critical review and bibliometric analysis', Chemical Engineering Journal, 461: 141878.

[135] Wei, Ying, Xuelei Zhang, Xuanyu Wu, Di Tang, Kedi Cai, and Qingguo Zhang. 2016. 'Carbon quantum dots/Ni–Al layered double hydroxide composite for high-performance supercapacitors', RSC advances, 6: 39317-22.

[136] Xie, Zhi-Hui, Hong-Yu Zhou, Chuan-Shu He, Zhi-Cheng Pan, Gang Yao, and Bo Lai. 2021. 'Synthesis, application and catalytic performance of layered double hydroxide based catalysts in advanced oxidation processes for wastewater decontamination: A review', Chemical Engineering Journal, 414: 128713.

[137] Xu, Mengdie, Jia Wei, Xiujuan Chen, Guoping Pan, Jiamei Li, Luyi Xing, Yifei Zhang, Yanan Li, Zhaoxu Wang, and Jun Li. 2022. 'Satisfactory degradation of tetracycline by a pH-universal MnFe-LDH@ BC cathode in electric Fenton process: Performances, mechanisms and toxicity assessments', Journal of Environmental Chemical Engineering, 10: 108409.

[138] Xu, Wencong, Myrjam Mertens, Thomas Kenis, Elien Derveaux, Peter Adriaensens, and Vera Meynen. 2023. 'Can high temperature calcined Mg–Al layered double hydroxides (LDHs) fully rehydrate at room temperature in vapor or liquid condition?', Materials Chemistry and Physics, 295: 127113.

[139] Yang, Dan, Le Wang, Yanfei Li, Wen Song, Xuguang Li, Tao Yan, and Liangguo Yan. 2024. 'Pseudocapacitive deionization of high concentrations of hexavalent chromium using NiFe-layered double hydroxide/polypyrrole asymmetric electrode', Separation and Purification Technology, 328: 125004.

[140] Yuan, Mingyao, Shangkai Qiu, Mengmeng Li, Zhao Di, Menghan Feng, Changbin Guo, Weilin Fu, Keqiang Zhang, Wenxian Hu, and Feng Wang. 2023. 'Enhancing phosphate removal performance in water using La–Ca/Fe–LDH: La loading alleviates ineffective stacking of laminates and increases the number of active adsorption sites', Journal of Cleaner Production, 388: 135857.

[141] Yuan, Xinxin, Jieyi Yang, Yiyang Yao, Hui Shen, Yue Meng, Bo Xie, Zheming Ni, and Shengjie Xia. 2022. 'Preparation, characterization and photodegradation mechanism of 0D/2D Cu2O/BiOCl S-scheme heterojunction for efficient photodegradation of tetracycline', Separation and Purification Technology, 291: 120965.

[142] Yuan, Zijian, Seong-Min Bak, Pengsong Li, Yin Jia, Lirong Zheng, Yu Zhou, Lu Bai, Enyuan Hu, Xiao-Qing Yang, and Zhao Cai. 2019. 'Activating layered double hydroxide with multivacancies by memory effect for energy-efficient hydrogen production at neutral pH', ACS Energy Letters, 4: 1412-18.

[143] Zahara, Zaqiya Artha, Luna Silaen, Normah Normah, Novie Juleanti, and Neza Rahayu Palapa. 2023. 'Layered double hydroxide Zn/M3+ (M3+= Al and Cr) as highly efficient adsorbent of heavy metal Pb (II)', Indonesian Journal of Material Research, 1: 8-14.

[144] Zhang, Jiyong, Yuhao Ma, Wentao Zhang, Xue Huang, Xiaomeng Wang, Yi Huang, and Peicong Zhang. 2022. 'CuBi2O4/calcined ZnAlBi-LDHs heterojunction: Simultaneous removal of Cr (VI) and tetracycline through effective adsorption and photocatalytic redox', Journal of Cleaner Production, 365: 132810.

[145] Zhang, Lianyang, Yue Meng, Tiantian Dai, Yiyang Yao, Hui Shen, Bo Xie, Zheming Ni, and Shengjie Xia. 2022. 'Fabrication of a coated BiVO4@ LDHs Z-scheme heterojunction and photocatalytic degradation of norfloxacin', Applied Clay Science, 219: 106435.

[146] Zhang, Ning, Xiyu Li, Huacheng Ye, Shuangming Chen, Huanxin Ju, Daobin Liu, Yue Lin, Wei Ye, Chengming Wang, and Qian Xu. 2016. 'Oxide defect engineering enables to couple solar energy into oxygen activation', Journal of the American Chemical Society, 138: 8928-35.

[147] Zhang, Peng, Mingming He, Silu Huo, Fukuan Li, and Kexun Li. 2022. 'Recent progress in metal-based composites toward adsorptive removal of phosphate: Mechanisms, behaviors, and prospects', Chemical Engineering Journal, 446: 137081.

[148] Zhang, Shuwang, Jinyi Chen, Junxia Yu, Qianqian Yu, and Xinhong Qiu. 2022. 'Remediation of Cd-contaminated soil through different layered double hydroxides: The weakness of delamination and mechanism', Journal of Environmental Chemical Engineering, 10: 107815.

[149] Zhang, Tao, Qiurong Li, Haiyan Xiao, Hongxiao Lu, and Yuming Zhou. 2012. 'Synthesis of Li–Al layered double hydroxides (LDHs) for efficient fluoride removal', Industrial and Engineering Chemistry Research, 51: 11490-98.

[150] Zhang, Xue, Liangguo Yan, Jing Li, and Haiqin Yu. 2020. 'Adsorption of heavy metals by L-cysteine intercalated layered double hydroxide: Kinetic, isothermal and mechanistic studies', Journal of Colloid and Interface Science, 562: 149-58.

[151] Zhang, Yu, Dengmiao Cheng, Jun Xie, Yuting Zhang, Yu Wan, Yueqiang Zhang, and Xiaojun Shi. 2022. 'Impacts of farmland application of antibiotic-contaminated manures on the occurrence of antibiotic residues and antibiotic resistance genes in soil: a meta-analysis study', Chemosphere, 300: 134529.

[152] Zhang, Yu, Dongfeng Du, Xuejin Li, Hongman Sun, Li Li, Peng Bai, Wei Xing, Qingzhong Xue, and Zifeng Yan. 2017. 'Electrostatic self-assembly of sandwich-like CoAl-LDH/polypyrrole/graphene nanocomposites with enhanced capacitive performance', ACS applied materials and interfaces, 9: 31699-709.

[153] Zhang, Zhaoran, Liangguo Yan, Haiqin Yu, Tao Yan, and Xuguang Li. 2019. 'Adsorption of phosphate from aqueous solution by vegetable biochar/layered double oxides: fast removal and mechanistic studies', Bioresource technology, 284: 65-71.

[154] Zhang, Zhaoyang, Dejun Sun, Gongrang Li, Bo Zhang, Bei Zhang, Shengmeng Qiu, Yujiang Li, and Tao Wu. 2019. 'Calcined products of Mg–Al layered double hydroxides/single-walled carbon nanotubes nanocomposites for expeditious removal of phenol and 4-chlorophenol from aqueous solutions', Colloids and Surfaces A: Physicochemical and Engineering Aspects, 565: 143-53.

[155] Zhao, Menglan, Yu Wang, Hui Zhao, Zihan Zhang, Juntong Su, Xu Ma, Fanping Kong, Yuan Xie, Zequn Ma, and Qian Zhang. 2023. 'Effective adsorption of heavy metals on layered double hydroxides modify through dithiocarbamate prepared by CS2 and different molecular weight of polyethyleneimine', Separation and Purification Technology, 327: 124886.

[156] Zhao, Shifeng, Zhaosong Li, Haiyan Wang, Hanhan Huang, Caifeng Xia, Derui Liang, Junshan Yang, Qian Zhang, and Zilin Meng. 2021. 'Effective removal and expedient recovery of As (V) and Cr (VI) from soil by layered double hydroxides coated waste textile', Separation and Purification Technology, 263: 118419.

[157] Zhao, Shifeng, Zilin Meng, Xin Fan, Ruisen Jing, Junshan Yang, Yifei Shao, Xijuan Liu, Mi Wu, Qian Zhang, and Aiju Liu. 2020. 'Removal of heavy metals from soil by vermiculite supported layered double hydroxides with three-dimensional hierarchical structure', Chemical Engineering Journal, 390: 124554.

[158] Zheng, Yingqiu, Bei Cheng, Wei You, Jiaguo Yu, and Wingkei Ho. 2019. '3D hierarchical graphene oxide-NiFe LDH composite with enhanced adsorption affinity to Congo red, methyl orange and Cr (VI) ions', Journal of Hazardous Materials, 369: 214-25.

[159] Zhou, Ziyi, Peng Liu, Sheng Wang, Y Zou Finfrock, Zhihang Ye, Yu Feng, and Xiaodan Li. 2022. 'Iron-modified biochar-based bilayer permeable reactive barrier for Cr (VI) removal', Journal of Hazardous Materials, 439: 129636.

[160] Zhu, Xiaolin, Cheng Tang, Hao-Fan Wang, Qiang Zhang, Chaohe Yang, and Fei Wei. 2015. 'Dual-sized NiFe layered double hydroxides in situ grown on oxygen-decorated self-dispersal nanocarbon as enhanced water oxidation catalysts', Journal of Materials Chemistry A, 3: 24540-46.

[161] Zou, Yidong, Pengyi Wang, Wen Yao, Xiangxue Wang, Yunhai Liu, Dongxu Yang, Lidong Wang, Jing Hou, Ahmed Alsaedi, and Tasawar Hayat. 2017. 'Synergistic immobilization of UO22+ by novel graphitic carbon nitride@ layered double hydroxide nanocomposites from wastewater', Chemical Engineering Journal, 330: 573-84.

[162] Zubair, Muhammad, Roopesh Syamaladevi, and Aman Ullah. 2024. 'Challenges and prospects: graphene oxide-based materials for water remediation including metal ions and organic pollutants', Environmental Science: Nano.

[163] Zubair, Mukarram, Muhammad Daud, Gordon McKay, Farrukh Shehzad, and Mamdouh A Al-Harthi. 2017. 'Recent progress in layered double hydroxides (LDH)-containing hybrids as adsorbents for water remediation', Applied Clay Science, 143: 279-92.

[164] Zubair, Mukarram, Ihsanullah Ihsanullah, Hamidi Abdul Aziz, Mohd Azmier Ahmad, and Mamdouh A Al-Harthi. 2021. 'Sustainable wastewater treatment by biochar/layered double hydroxide composites: Progress, challenges, and outlook', Bioresource technology, 319: 124128.