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Synergistic Heavy Metal Remediation Using LDH-Modified Magnetic Biochar and Resistant Microorganisms: A Comprehensive Review

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ABSTRACT

The water and soil contamination by heavy metals such as Cu, Cd, Pb, As and Cr leads to major environmental problems due to their toxic effects, persistent and accumulation in the environment. Traditional removal methods are limited due to high costs, low efficiency of metal removal and generation of secondary sludge. The development of Zn – Al and Mg – Fe **Layered Double Hydroxide** (LDH)-coated magnetic biochar has shown higher efficiency to treat the metal pollutants. Their method of synthesis, structural properties and adsorption mechanisms are discussed. LDH – biochar hybrids perform surface precipitation, surface complexation, ion exchange, and electrostatic interaction to show higher removal efficiency through their synergistic mechanisms. Studies reported the adsorption capacity of Pb (II) and Cd (II) are high as 448-476 mg g^{-1}. Magnetic functionalization enables rapid solid–liquid separation and reusability, while LDH layers enhance stability and enable simultaneous removal of cationic and anionic metal species. The review further highlights the emerging integration of LDH–biochar composites with heavy metal-resistant microorganisms, where biochar provides a protective microbial habitat and LDHs act as nano-bridges to improve metal immobilization, redox transformation, and long-term soil stability. Overall, LDH-modified magnetic biochar–microbe systems represent a promising, low-carbon approach for efficient and sustainable heavy metal remediation.

Keywords: Adsorption; Bioremediation; Circular Bioeconomy: Environmental Remediation; Heavy Metal Resistant Microorganisms: Wastewater Treatment.

INTRODUCTION

The fast growth of industrial and agricultural modernization has resulted in major global environmental issues, mainly described by the widespread pollution of water and soil by heavy metals (Li et al. 2022; Mortada et al. 2023). Metals such as cadmium (Cd), copper (Cu), lead (Pb), arsenic (As), and chromium (Cr) are typical pollutants that result from various human activities such as mining, smelting, electroplating, and chemical production (Li et al. 2022; Hameed et al. 2024). Unlike organic pollutants, heavy metals are non-biodegradable and persistent; they cannot be destroyed but only converted into less toxic oxidation states, resulting in their infinite accumulation within the ecosystem (Priyadarshanee and Das, 2021). Heavy metals are generally described as metallic elements with an atomic density higher than 5 g/cm³ (Abidin et al. 2020). The primary sources of these pollutants include industrial effluents from battery production and paint industries, mining wastes, and the overuse of chemical fertilizers and pesticides in agricultural activities (Oziegbe et al. 2021). They lead to serious threat to aquatic organisms and enter the food chain, absorbed by the human body by metals binding with particulates and accumulating in sediments (Abidin et al. 2020; Amin et al. 2024; Zhou et al. 2019). The toxic effects are disastrous, leads to chronic renal failure, neurological damage, mutagenicity and carcinogenicity (Marzan et al. 2017; Hasan and Karmakar, 2024; Selim & Harun-Ur-Rashid, 2025). Conventional methods such as chemical precipitation, ion exchange, membrane filtration, reverse osmosis, and electrolysis have several limitations (Li et al. 2022; Amin et al. 2024; Priya et al. 2022). These conventional methods are often hampered by high operational and maintenance costs, high energy requirements, and the production of enormous amounts of toxic secondary sludge (Wibowo et al. 2025). Moreover, most of these chemical processes are inefficient in removing metals at low concentrations (usually <100 mg/L), which makes them unsuitable for the treatment of large amounts of diluted industrial effluent (Priya et al. 2022). In the pursuit of finding sustainable solutions, adsorption has been identified as the most viable method owing to its ease of operation, high selectivity, and the possibility of utilizing renewable materials (Magdum et al. 2026; Li et al. 2022).

Biochar, a carbon-rich porous material obtained from the pyrolysis of waste biomass, is considered a suitable alternative as it is carbon-neutral and economical (Huang et al. 2023; Amin et al. 2024). However, raw biochar tends to have low adsorption capacity and stability (Li et al. 2022). Modification of biochar with LDHs, a type of anionic clay mineral with high ion exchange capacity and high surface area, has been found to greatly improve the chemical reactivity and porosity of the material (Li et al. 2022; Huang et al. 2023). The addition of magnetic nanoparticles to LDH-biochar composites has further enhanced the material's applicability by enabling fast solid-liquid separation using an external magnetic field (Wibowo et al. 2025; Fitri et al. 2024). This review aims to discuss the synthesis and application of Zn-Al LDH-coated magnetic biochar as a multi-functional platform for environmental remediation. The main goals are to assess the transition towards a circular bioeconomy by using solid waste resources (such as rice husk, grape stalks, and cow dung) as precursors for the synthesis of high-performance adsorbents. (Phiri et al. 2024)

The main focus of this review article is the combined use of Layered Double Hydroxide (LDH) modified magnetic biochar and synergistic immobilization processes that include surface precipitation, ion exchange, and the use of Heavy Metal-Resistant Bacteria (HMRB) to convert toxic species into stable minerals (Lyu et al. 2024; Selim and Harun-Ur-Rashid, 2025). In addition, it examines the retention durability and stability of these materials in Acid Mine Drainage (AMD) and agricultural soil. Also, it is an sustainable remediation of contaminated water and soils with heavy metals. Special attention is paid to the preparation and properties of Zn-Al and Mg-Fe LDH modified magnetic biochar, adsorption processes, regeneration and reusability, analysis methods and their environmental applications. In addition, the significance of heavy metal resistant microorganisms for improving the efficiency of the remediation by biosorption, bioaccumulation, biomineralization and microbial redox reactions is discussed (Arega et al. 2026). This review combines recent achievements in material science and microbial remediation. The benefits, existing limitations, gaps in research and future perspectives of such LDH-magnetic biochar-microbial systems are reviewed.

REVIEW METHODOLOGY

This review was conducted through a Comprehensive searches were performed across five research databases: Scopus, Web of Science, ScienceDirect, PubMed, and Google Scholar.

Relevant articles published between 2014 and 2026 were identified, as this range reflects the specific data points in the analyzed literature, including early foundational studies and the latest advancements. Identification was achieved using combinations of the following keywords: Layered Double Hydroxide (LDH), magnetic biochar, biochar composites, potentially toxic elements (PTEs), heavy metal remediation, adsorption, heavy metal-resistant microorganisms, wastewater treatment, and soil remediation.

The study considered peer-reviewed research articles and review papers published in English. Specific inclusion criteria focused on LDH-modified biochar, magnetic biochar, microbial-assisted remediation, actual adsorption mechanisms, material stability, and field-scale applicability. To ensure high-quality synthesis, conference abstracts and studies unrelated to the synergistic use of bio-hybrids for metal removal were excluded. After screening titles, abstracts, and full texts, more than 40 relevant publications were critically evaluated to map the transition from laboratory-scale experiments to practical environmental restoration.

HEAVY METALS OF ENVIRONMENTAL CONCERN

Heavy metals are defined as metallic elements with high atomic density more than $5 g/cm^3$, and highly persistent (Abidin et al. 2020). Due to natural and human activities like mining, smelting, and use of chemical fertilizers and pesticides they start to accumulate in the environment (Priyadarshanee & Das, 2021; Xie et al. 2021). Cadmium, lead, chromium, arsenic, copper, and nickel are some of the most dangerous environmental contaminants due to their persistent, toxic, and non-biodegradable characteristics (Abidin et al. 2020). The persistent emission of these contaminants through various processes such as industrialization, mining, and agriculture has created a need for effective and sustainable cleanup processes (Shafiq et al. 2023).

Impact on health and environment

Heavy metals enter the food chain through bioaccumulation and biomagnification due to their ability to accumulate in sediments, they are stable and non-biodegradable (Priyadarshanee & Das, 2021). They can also produce carcinogenic, genotoxic, mutagenic, and teratogenic effects, including chronic organ failure and neurological damage (Selim & Harun-Ur-Rashid, 2025). High levels can inhibit the diversity and activity of soil microbial populations, which can affect important biological processes such as nutrient cycling and organic matter decomposition. In aquatic ecosystems, the presence of heavy metals such as Cr (VI) can cause damage to nuclear membranes and mitochondrial processes of indigenous organisms (Monga et al. 2022; Liu et al. 2023).

Regulatory Limits

To control these risks in the environment, very strict standards have been set worldwide, US-EPA Standards The maximum allowable concentration of drinking water is 0.01 mg/L for Arsenic, 0.005 mg/L for Cadmium, 0.1 mg/L for total Chromium, 0.01 mg/L for Lead, and 0.002 mg/L for Mercury (Priya et al. 2022; Monga et al. 2022). Indian Standards For agricultural soil, the permissible levels are 3-6 mg/kg for Cd, 135-270 mg/kg for Cu, 75-150 mg/kg for Ni, 250-500 mg/kg for Pb, and 300-600 mg/kg for Zn (Priya et al. 2022). In Indonesia, the Ministry of Environment requires that the AMD should not contain more than 7 mg/L of Iron (Fe) and 4 mg/L of Manganese (Mn) (Wibowo et al. 2025). It is for this reason that this paper will discuss LDH-modified magnetic biochar and metal-resistant microorganisms (Lyu et al. 2023; Huang et al. 2023; Campillo-Cora et al. 2025).

BIOCHAR AS AN ADSORBENT MATERIAL

Definition and classification of biochar

Biochar can be described as a porous, solid carbonaceous material produced by the pyrolysis of biomass waste in a reactor under limited oxygen or anaerobic conditions (Amin et al. 2024). Biochar can be generally categorized as a sustainable black carbon material, just like AC, but is more economical and eco-friendlier because it is produced from renewable materials (Huang et al. 2023). Generally, biochar can be categorized depending on the origin of the feedstock material (agricultural, forestry, or municipal waste) or the temperature of thermal decomposition employed during the production of biochar, which is a major factor in determining its final chemical composition (Zhou et al. 2019).

Table 1: Adsorption performance of LDH–biochar composites derived from different biomass feedstocks for heavy metal removal.

Adsorbent Material	**Feedstock Source**	**Target Metal (loid)**	**Max. Capacity (*max*)**	**pH**	**Contact time**	**Dose (g/L)**	**Reference**
MgAl–LDH@RHB	Rice Husk	Cd (II), Cu (II)	125.3, 104.3 mg/g	6.0	1440 min	2.5	(Li et al. 2022)
ZnAl–LDH-BC600	*Solidago canadensis*	Cd (II), Pb (II)	99.8, 128.4 mg/g	6.5	1440 min	0.8-2.0	(Hameed et al. 2024)
MgFe–LDH/PPBC	Pomelo Peel	Cd (II)	448.96 mg/g	5.5	1660 min	1.5	(Huang et al. 2023)
MgFe–LDH/MBC	Camellia Shell	Pb (II)	476.25 mg/g	3.0-6.0	300 min	0.4	(Jia et al. 2019)
MgFe–LDH-RHA	Rice Husk Ash	Pb (II)	682.2 mg/g	5.0	1440 min	0.1-1.0	(Yu et al. 2018)
ZnMgAl–LDH/RHB	Rice Husk	Cu (II), Pb (II)	117.0, 124.0 mg/g	6.0	30/15 min	4.0	(Shafiq et al. 2023)
FeMgAl/RHB	Rice Husk	Pb (II), Cd (II)	205.6, 77.5 mg/g	6.0	15/60 min	2.0-4.0	(Amin et al. 2024)
L2MBC800 (LMBC)	Bamboo	As (III), Cd (II)	206.6, 216.2 mg/g	4.5	50/30 min	1.0	(Lyu et al. 2023)
ZnAl/MBC	Wood Waste	Malachite Green	25.90 mg/g	8.0	70 min	1.0	(Fitri et al. 2024)
BC_MMT_ZnAl LDH	*Avicennia marina*	Mn (II), Fe (II)	99% removal (Mn)	5.5-8.0	7/400 min	0.5	(Wibowo et al. 2025)

Methods of biochar preparation

The step involved in biochar preparation is pyrolysis, Biochar can be produced from a wide variety of biomass feedstocks, including agricultural residues (rice husk, wheat straw, corn stover), forestry residues (wood chips, sawdust), animal-derived biomass (cow dung, poultry litter), municipal wastes (sewage sludge), and microbial biomass such as algae and fungi. The physicochemical characteristics and adsorption performance of biochar depend strongly on the type of biomass and pyrolysis conditions employed, were the biomass is heated between the temperature from 400°C-700°C under oxygen-free or low-oxygen environment (Hameed et al. 2024; Huang et al. 2023; Wang et al. 2026). To produce a specialized product like hydrochar from wet biomass such as sewage sludge, HTC technology is used.

Also, to increase the internal structure of the material processing procedure like torrefaction pretreatment at 180°C or physical and chemical activation with substances like KOH and NaOH are used (Wibowo et al. 2025; Lyu et al. 2023).

Physio-chemical properties of biochar

The characteristics of biochar includes high specific surface area, porous structure, and a stable surface charge (Wibowo et al. 2025). The surface functional groups, including hydroxyl (-OH), carboxyl (-COOH), carbonyl (C=O), and phenolic groups, provide active binding sites for pollutants (Hudcova et al. 2022). Biochar's are amorphous carbon in structure with disordered, turbostratic crystallites with different size depending on the thermal treatment intensity (Li et al. 2026; S. Feng et al. 2026).

Disadvantages of pristine biochar

Due to the poor performance of pristine biochar their application in environment is limited (Li et al. 2022). The pristine biochar exhibits electrostatic repulsion towards anionic pollutants like arsenate [As(V)] because of their surface negative charge and resulting in insufficient removal (Lyu et al. 2024). Moreover, its low number of active functional groups and poor solid-liquid separation properties because of its small and light particles make it less ideal for industrial-scale wastewater treatment applications without additional modifications. Furthermore, the lack of stability and cycling ability of raw biochar may require its combination with materials such as LDHs to improve reusability (Amin et al. 2024).

MAGNETIC BIOCHAR

Magnetic biochar (MBC) is a composite material that aims to address the main limitation of powdered biochar, which is the difficulty of solid-liquid separation in treated wastewater due to the small particle size (Jia et al. 2019). Generally, the small particles were usually discharged together with the sludge, resulting in potential secondary pollution. However, with the introduction of magnetism in MBC, it can be easily separated using an external magnetic field. Moreover, the magnetization step can improve the properties of the material, such as its specific surface area, pore size, and zeta potential, which usually results in enhanced adsorption capacity for various pollutants (Zhou et al. 2019).

Iron-based magnetic materials (Fe_3O_4, $\gamma-Fe_2O_3$)

The magnetic properties are usually introduced by the loading of the iron-based minerals, namely magnetite (Fe_3O_4,) and maghemite ($\gamma-Fe_2O_3$,) into the biochar matrix. Various characterization methods, such as XRD and XPS, have verified that the iron oxides can be successfully loaded onto the surface or within the pores of the biochar skeleton in the form of nanoscale particles (Zhou et al. 2019). In addition to the iron oxides, metal ferrites (MFe_2O_4, where M is Mn, Fe, Co, or Ni) are also used owing to their high saturation magnetization and stability, which are essential for efficient recovery in complex water environments (Mahmoud et al. 2021).

Synthesis methods of magnetic biochar

In-situ chemical co-precipitation method involves the dispersion of biochar in a solution containing divalent (Fe^{2+}) and trivalent (Fe^{3+}) iron salts, followed by the addition of an alkaline agent (such as NaOH or NH_3) to raise the pH to 10-11, resulting in the precipitation of magnetic particles on the carbon matrix (Jia et al. 2019). Pyrolysis of pre-treated biomass is a one-step or two-step process, where the raw biomass is pre-impregnated with iron salts (such as $FeCl_2$ or $FeSO_4$) prior to undergoing pyrolysis at temperatures ranging from 400°C to 800°C in an anaerobic environment. Other advanced methods of synthesis mentioned in the literature include microwave-induced synthesis, ball milling, and hydrothermal carbonization (Li et al. 2022).

Magnetic separation and reusability

The distinctive feature of MBC is its high reusability and cycle capacity, which greatly improves its economic efficiency. After the MBC has adsorbed the heavy metals, it can be easily separated from the aqueous solution by the application of a permanent magnet. Regeneration is usually done by chemical elution with eluents such as NaOH (for the removal of surface precipitates) or mineral acids such as HNO_3 and HCl (to dissolve the adsorbed ions by site competition). It has been found that these magnetic composites retain 60% to 70% of their initial adsorption capacity even after four to five cycles of regeneration (Jia et al. 2019). Under acidic conditions, the stability may loose and result in loss of magnetic property and adsorption due to partial leaching of magnetic particles (Zhou et al. 2019).

LAYERED DOUBLE HYDROXIDES (LDHs)

Structure and General Formula of LDHs

LDHs are inorganic functional clays, with brucite-like layered structure. They are composed of host layers with permanent positive charges and guest counter-anions in the exchangeable interlayer region, as well as water molecules (Amin et al. 2024). The chemical formula of these compounds is generally expressed in equation (1), where M^{2+} stands for divalent metal cations (Mg^{2+}, Zn^{2+}, or Cu^{2+}), M^{3+} stands for trivalent metal cations (Al^{3+}, Fe^{3+}, or Cr^{3+}), and A^{n-} stands for the guest interlayer charge-balancing anions (CO_3^{2-}, Cl^-, or NO_3^-). The molar fraction x, which usually varies between 0.2 and 0.4, represents the amount of trivalent metal ions in the host layers (Hameed et al. 2024).

$$[M_{1-x}^{2+}\,M_x^{3+}(OH_2)]^{x+}\,(A^{n-})_{x/n}.mH_2O \cdots\cdots\cdots\cdots\cdots\cdots (1)$$

Zn–Al LDH: Composition and Properties

Zn-Al LDH is a particular composition of the LDH series, where the divalent and trivalent metal ions are zinc and aluminum, respectively (Wibowo et al. 2025). These compounds have many excellent properties, such as a high specific surface area, high thermal stability, controllable particle size, and a special supramolecular structure. They are highly efficient ion exchangers with excellent biocompatibility and high loading capacity. Moreover, Zn-Al LDHs have been successfully prepared from solid waste materials such as waste aluminum cans and zinc galvanic, making them a cost-effective and sustainable approach for environmental applications (Li et al. 2022).

Synthesis Methods of Zn–Al LDH

The Zn-Al LDH is prepared by chemical co-precipitation method, which requires combination divalent and trivalent metal salts in solution and regulate and maintain the pH around 10, basic agent like NaOH or Na_2CO_3 are used (Mahmoud et al. 2021).In order to enhance the crystallinity and robustness of the obtained material, a hydrothermal process is often used, in which the precipitate is allowed to age in a high-pressure reactor at certain temperatures, usually 160°C or 180°C, for a long period of time. Other methods that have been employed for the preparation of Zn-Al LDH include ion exchange and microwave-assisted hydrothermal treatment (Zhou et al. 2019).

Anion Exchange and Adsorption Mechanisms

LDHs have been shown to remove pollutants from water via three main mechanisms: surface adsorption, interlayer anion exchange, and the special "memory effect," which enables calcined LDHs to re-establish their original layered structure upon exposure to aqueous solutions. As anionic adsorbents, LDHs have been demonstrated to efficiently capture oxyanions such as $PO_4^{3-}$and Cr (VI) ions via ion exchange and intercalation into the layer channels (Hasan & Karmakar, 2024). Moreover, LDHs have been found to remove heavy metal cations via surface precipitation (to form stable minerals such as $CdCO_3$ or $Pb_3(CO_3)_2(OH)_2$, isomorphous substitution, and surface complexation with hydroxyl groups (Li et al. 2022; X. Zhao et al., 2026).

Advantages and Drawbacks of LDHs

The main advantages of LDHs are their low cost, adjustable chemical composition, and high porosity with a large specific surface area (Xue et al. 2026). However, their use is hampered by the tendency of LDHs to form aggregates with a bulk or granular morphology, thereby reducing the number of accessible active adsorption sites (Mahmoud et al. 2021). Additionally, LDHs have poor stability in acidic environments, where the material tends to dissolve or decompose, resulting in a high leaching rate of the metal ions (Li et al. 2022).

Zn–Al LDH COATED MAGNETIC BIOCHAR COMPOSITES

Rationale for LDH–biochar hybrid materials

The LDHs have remarkable properties like high specific surface area, high ion exchange capacity, and strong acid-base buffering capacity, which make them efficient for the removal of both cationic and anionic forms of heavy metals (Hudcová et al. 2022). The use of LDHs is limited by their capacity to form aggregates and leaching during the treatment process (Mahmoud et al. 2021). Biochar can be used to prevent the aggregation of LDHs due to its low cost, porous and stable carbonaceous solid, which provide high reactive surface area (Zhou et al. 2019). Both anionic and cationic pollutants can be removed simultaneously, by Zn-Al LDH which contain positive surface charges and anionic layers (Hudcová et al. 2022).

Coating methods of Zn-Al LDH on magnetic biochar

The Zn-Al LDH-Coated magnetic biochar is prepared by in situ co-precipitation and hydrothermal treatment. The metal salts like divalent (Zn, Mg) and trivalent (Al, Fe) are combined with biochar and with NaOH or Na_2CO_3 the pH is adjusted to alkaline region 10.0. The precipitate is subjected to hydrothermal precipitation in a high-pressure reactor at temperature between 90°C and 180°C for prolonged period of time to enhance the crystallinity and purity of the hydrotalcite phases (Fig. 1) (Hameed et al. 2024). The biomass is pre-impregnated with iron salts (such as $FeCl_2$ or $FeSO_4$) to create the magnetic property prior to pyrolysis or by co-precipitating magnetite nanoparticles during the LDH coating process (Mahmoud et al. 2021; Y. Zhao et al. 2026).

Surface and structure modifications after coating

The modification causes substantial changes, particularly in the massive increase in the specific surface area (SSA) due to the presence of nano-LDH flakes or platelets attached to the carbon structure (Li et al. 2022). The LDH material is significantly enhanced in its chemical reactivity through surface complexation, ion exchange, and surface co-precipitation, facilitating the immobilization of hazardous materials such as arsenic and cadmium in stable minerals (Lyu et al. 2023). In the context of soil, the LDH material can be used as a "nano-bridge," enabling the composite material to bond effectively with soil colloids and enhancing the stability of the material against environmental conditions such as acid rain (Lyu et al. 2024). Lastly, incorporating magnetic materials such as Mn-ferrite or Fe_3O_4 enables rapid separation of the solid-liquid mixture using a magnetic force field, thus facilitating easy recovery of the material, minimizing secondary pollution, and facilitating recycling of the material for repeated use (Hasan & Karmakar, 2024).

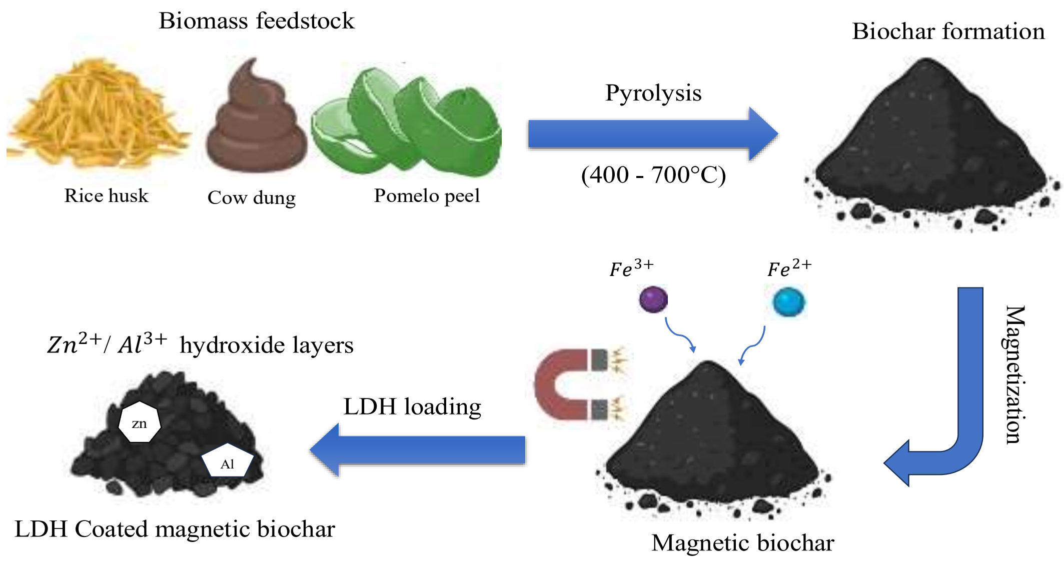

Fig. 1: Schematic representation of Zn – Al LDH coated magnetic biochar synthesis

CHARACTERIZATION TECHNIQUES

X-ray diffraction (XRD)

XRD analysis is used to detect the purity and crystalline nature of the synthesized phases. For biochar, the diffraction patterns are broad and weak, indicating the amorphous nature of carbon (Huang et al. 2023; Li et al. 2022). In contrast, the LDH-modified composites display sharp peaks at specific 2 values, indicating the basal planes of the hydrotalcite structure, including (003), (006), and (009). After the adsorption of heavy metals, new peaks emerge, indicating the formation of stable heavy metal carbonate precipitates such as cadmium carbonate ($CdCO_3$), lead carbonate ($Pb_3(CO_3)_2(OH)_2$), or copper carbonate ($CuCO_3$) (Li et al. 2022).

Fourier transform infrared spectroscopy (FTIR)

FTIR spectroscopy is used to determine the surface functional groups participating in the chemical bonding of contaminants. (Li et al. 2022; Wibowo et al. 2025) Pure biochar usually shows characteristic peaks for hydroxyl (–OH) and carboxyl (–COOH) functional groups. The successful incorporation of LDHs is evidenced by the presence of metal-oxygen (M– O) lattice vibration modes and interlayer nitrate (NO^{3-}) or carbonate (CO_3^{2-}) stretching vibration modes. (Li et al. 2022) Peak shifts or absorbance decrease after adsorption, such as a hydroxyl peak shift, suggest that these functional groups have undergone surface complexation or ion exchange with heavy metal ions (Wibowo et al. 2025).

Scanning and transmission electron microscopy analysis (SEM/TEM)

Surface morphology analysis by SEM shows that the surface texture, which ranges from smooth to wrinkled, is now coated with nano flakes or nano platelets of LDH, making the structure rough and hierarchical (Li et al. 2022). While SEM offers a lower resolution, TEM provides more details and shows that the nanoparticles of LDH create "nano-bridge", allowing for improved bonding between the biochar and soil colloids (Lyu et al. 2024). Combined with Energy Dispersive X-ray (EDX), all three techniques show uniform distribution of chemical elements such as Zn, Al, Mg, and Fe on the surface of the mixture (Wibowo et al. 2025).

BET analysis

BET analysis is done to measure the surface area, porosity, and pore size of the adsorbents based on nitrogen adsorption-desorption isotherms (Wibowo et al. 2025). With the presence of LDHs, the SSA of the composites would be considerably enhanced due to their nano-platelets that contain more active sites than pure carbon matrix (Li et al. 2022). These adsorbents usually exhibit IUPAC Type IV or Type V isotherms, which confirm the mesoporous nature of the adsorbents with pore sizes usually in the range of 2-50 nm (Wibowo et al. 2025; Gururani et al. 2026).

Vibrating sample magnetometer (VSM)

VSM is employed to determine the magnetic properties of the composites, which give a typical S-shaped hysteresis curve (Jia et al. 2019, Fitri et al. 2024). The parameters such as saturation magnetization (Ms) can be used to determine the ease of separation of the material from an aqueous solution by an external magnetic field. Although the biochar matrix is responsible for the stability, the LDH layer sometimes acts as a barrier, (Jia et al. 2019) resulting in a slight reduction in the net magnetic moment compared to the pure magnetic nanoparticles (Mahmoud et al. 2021, Fitri et al. 2024).

pHpzc and surface charge analysis

The point of zero charge (pHpzc) is the pH of the solution at which the surface charge of the adsorbent is neutral (Li et al. 2022). At pH values above pHpzc, the surface of the composite turns negatively charged due to deprotonation, which helps in the electrostatic attraction of cationic pollutants such as Cd^{2+} and Pb^{2+}. However, at pH values below pHpzc, the surface charge turns positive, which may repel cationic heavy metals but help in the adsorption of anionic pollutants (Huang et al. 2023).

HEAVY METAL REMOVAL PERFORMANCE

Adsorption mechanism

The heavy metal removal process using Zn-Al LDH-coated biochar composites is a complex process involving various chemisorption and physisorption mechanisms. The major mechanisms involved include surface precipitation resulting in the formation of stable minerals such as $CdCO_3$ or $Pb_3(CO_2)_2(OH)_2$, and ion exchange, where metal ions displace divalent cations such as Li^+ or Zn^{2+} in the LDH structure. Surface complexation is also an important mechanism, which involves the interaction of metal ions with oxygen-containing functional groups such as hydroxyl (-OH) and carboxyl (-COOH) groups on the biochar and LDH surfaces (Li et al. 2022). Isomorphic substitution (e.g., Cd (II) replacing Fe (III)) and electrostatic attraction between the negatively charged surface of the adsorbent and metal cations are also involved in the sequestration process (Fig. 2) (Huang et al. 2023; Guo et al. 2024). For a particular composite, the LDH can serve as a "nano-bridge" that improves the binding between biochar and soil colloids to facilitate effective immobilization (Li et al. 2026).

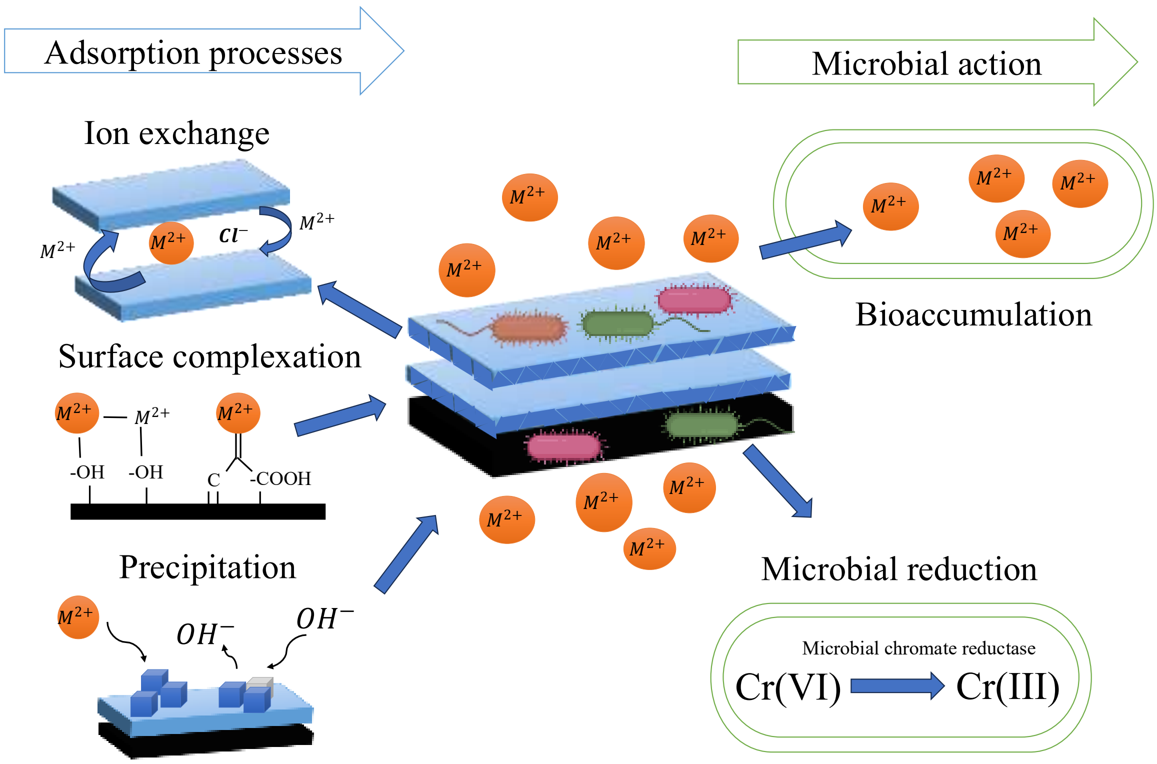

Fig. 2: Schematic illustration of synergistic heavy metal removal mechanisms using LDH – magnetic biochar and microorganisms.

Effect of pH, Contact Time, Dosage, and Initial Concentration

Solution pH is a critical parameter that influences the surface charge of the composite and metal ion speciation (Wibowo et al. 2025; Jia et al. 2019). Adsorption is generally low at pH < 3.0 because of the high concentration of H^+ ions, which compete with adsorbates for surface sites, and the protonation of surface functional groups, resulting in a repulsive force. Efficiency increases with pH, usually reaching a maximum at pH 5.0-8.0, where deprotonation increases electrostatic attraction. (Li et al. 2022). Adsorption kinetics involve a fast initial stage (which may account for 80% to 90% adsorption in the first 15-30 minutes) and a slower stage as the active sites become saturated. Equilibrium is usually attained between 15 and 120 minutes, depending on the metal and the composite material (Shafiq et al. 2023). A higher dose of the adsorbent is generally beneficial for removal efficiency, as it increases the number of active sites, but can result in a reduction in adsorption capacity (mg/g) because of site saturation or agglomeration (Amin et al. 2024). A higher initial concentration offers a greater concentration gradient as a driving force, hence a greater amount of metal adsorbed until the maximum capacity is attained (Li et al. 2022).

Adsorption Isotherms

The equilibrium concentration-adsorption capacity relationship is most commonly modelled using the Langmuir and Freundlich equations. The Langmuir equation generally offers a better fit for LDH-biochar composites, indicating a monolayer adsorption process on a homogeneous surface with fixed binding sites. The maximum adsorption capacities (q_{max}) for these adsorbents have been given as high as 448-476 mg/g for Pb and Cd (Jia et al. 2019). The Freundlich equation is generally employed to interpret the heterogeneous multilayer adsorption, which takes place in certain complex composite systems (Amin et al. 2024). Other equations, such as Temkin (concerned with heat of adsorption) and Dubinin-Radushkevich (D-R) (distinguishing between physical and chemical adsorption), are employed to interpret the surface energy and heterogeneity (Shafiq et al. 2023).

Adsorption Kinetics

The kinetics of heavy metal adsorption always obey the PSO kinetic equation (Li et al. 2022). The high correlation coefficients ($R^2 > 0.99$) obtained with the PSO equation always verify that the chemisorption process is the rate-controlling step, which involves the sharing/exchange of electrons between the adsorbent and the metal ions (Wibowo et al. 2025). Intra-particle diffusion model analysis may show multiple linear segments, suggesting that although the process is fast on the surface, it is also affected by diffusion in the liquid film and the slow diffusion of ions into the pores of the biochar matrix (Li et al. 2022; Pathak et al. 2024).

Thermodynamic Studies

Thermodynamic parameters usually show that the adsorption of heavy metals on these composites is a spontaneous and endothermic process (Jia et al. 2019). Negative values of Gibbs free energy (ΔG^o) confirm the spontaneity of the process, which becomes more favorable with increasing temperature. Positive values of enthalpy change (ΔH^o) indicate that the process is endothermic, often due to the dehydration of metal ions prior to adsorption (Wibowo et al. 2025). Positive values of entropy change

(ΔS^o) indicate an increase in randomness at the solid-liquid interface, often due to the release of water molecules or changes in the structure during metal sequestration (Wibowo et al. 2025). Moreover, the estimation of the mean free energy (E) of D-R models may indicate the presence of a physical adsorption process when the values are below 8 kJ/mol (Shafiq et al. 2023).

HEAVY METAL RESISTANT MICROORGANISMS

Heavy metal resistant microorganisms

Metal-resistant microorganisms have a vital complementary role in the LDH modified magnetic biochar systems in improving heavy metal removal using biological processes (Mounaouer et al. 2014; Magdum et al. 2026). HMRB like *Pseudomonas aeruginosa, Bacillus cereus, Staphylococcus aureus,* and *Klebsiella pneumoniae* have been isolated from contaminated auto-mechanic workshops and industrial areas (Marzan et al. 2017; Bilyaminu et al. 2025). Besides the physical and chemical sorption offered by the biochar-LDH system, the microorganisms work through bio-sorption, bio-accumulation, biomineralization, EPS production, enzyme reduction and detoxification of toxic metal species (Mounaouer et al. 2014). This combination of biological and physicochemical processes helps in improving metal immobilization, bioavailability reduction, and stability of metal contaminated soil and wastewater treatment systems. (Xie et al. 2021; X. Feng et al. 2026).

Biochar as a microbial support material

Biochar (BC) is a remarkably efficient medium for microbial cultivation due to its extensive porosity and high surface area, which provide sheltered habitats for the development of microbes (Lyu et al. 2023; Selim & Harun-Ur-Rashid, 2025). The porous structure of biochar allows for a convenient vehicle that prevents the aggregation of other agents while providing a favorable environment for microbial growth. Biochar contains valuable minerals and sources of organic carbon necessary for microbial metabolism, particularly in soils that lack essential elements (Lyu et al. 2024; Campillo-Cora et al. 2025). Moreover, the alkaline nature and buffer capacity of biochar help mitigate the adverse influence of an acidic medium on microbial survival (Hudcová et al. 2022; Abbas et al., 2024). The immobilization of microbes on the surface of biochar reduces their mobility within the soil, leading to efficient bioremediation of the site (Priya et al. 2022; Lyu et al. 2024).

Combined effectiveness of microorganisms and biochar mixtures

The mixture of HMRB with biochar that has been designed is termed BCMC and functions much better than individual components in capturing contaminants like Cd and Pb (Raut et al. 2025). The "nano-bridge" function of the layered double hydroxide (LDH) component in these composites can better immobilize biochar to soil colloids, thus improving the stability of the microbial habitat. This synergy brings together the physical adsorption and ion exchange properties of the biochar/LDH matrix with the active metabolic transformation and bioaccumulation properties of the microorganisms (Lyu et al. 2024). For instance, the addition of biochar can shield phosphate-solubilizing bacteria from metal ions, enabling them to continue producing chelating agents that help immobilize additional metal ions (Selim & Harun-Ur-Rashid, 2025).

Interaction between microorganisms and LDH-magnetic biochar

Further improvement in the effectiveness of LDH-modified magnetic biochar results from its combination with microorganisms resistant to heavy metals (Gururani et al. 2026). The biochar framework with its porous structure serves as a favorable microenvironment for attachment, growth, and biofilm formation of microbes, while the LDH coating ensures sufficient surface area for adsorption and ion-exchange reactions leading to lowering the mobility of metal ions. Production of EPS, proteins, and organic acids by microorganisms facilitates the process of metal complexing and stabilization of metals that are immobilized on the surfaces of LDH-modified biochar particles (Y. Zhao et al. 2026). In this way, synergistic interactions enable simultaneous processes of physicochemical adsorption and biological decontamination, which leads to better remediation results than using separate components of the composite material. Excess amounts of heavy metals and presence of magnetic nanoparticles could negatively affect the metabolic activities of microorganisms. Hence, an optimization of composition, quantity of nanomaterials, and environment is necessary to preserve microbial viability.

Microbial reduction and immobilization of metals

Microorganisms are also important in the immobilization of metal ions via valence transformation and biomineralization (Selim & Harun-Ur-Rashid, 2025). pointed out that bacteria like *Bacillus* and *Pseudomonas* can reduce highly toxic Hexavalent Chromium [Cr (VI)] to the less mobile and less toxic Trivalent Chromium [Cr (III)] (Fig. 3). Another critical process is MICP, in which ureolytic bacteria promote the precipitation of calcium carbonate crystals that entrap and immobilize heavy metal ions in the soil (Kang et al. 2016). SRB also play a role in the immobilization of heavy metals by precipitating soluble metal sulfates as insoluble metal sulfides, thereby sequestering contaminants such as Cd and Sb in the soil (Selim & Harun-Ur-Rashid, 2025). In FLBC-treated soils, ferric reduction has been demonstrated to facilitate the re-oxidation of As (III) to the less toxic As (V), which then precipitates as stable compounds with Calcium or Iron (Table 2) (Lyu et al. 2024).

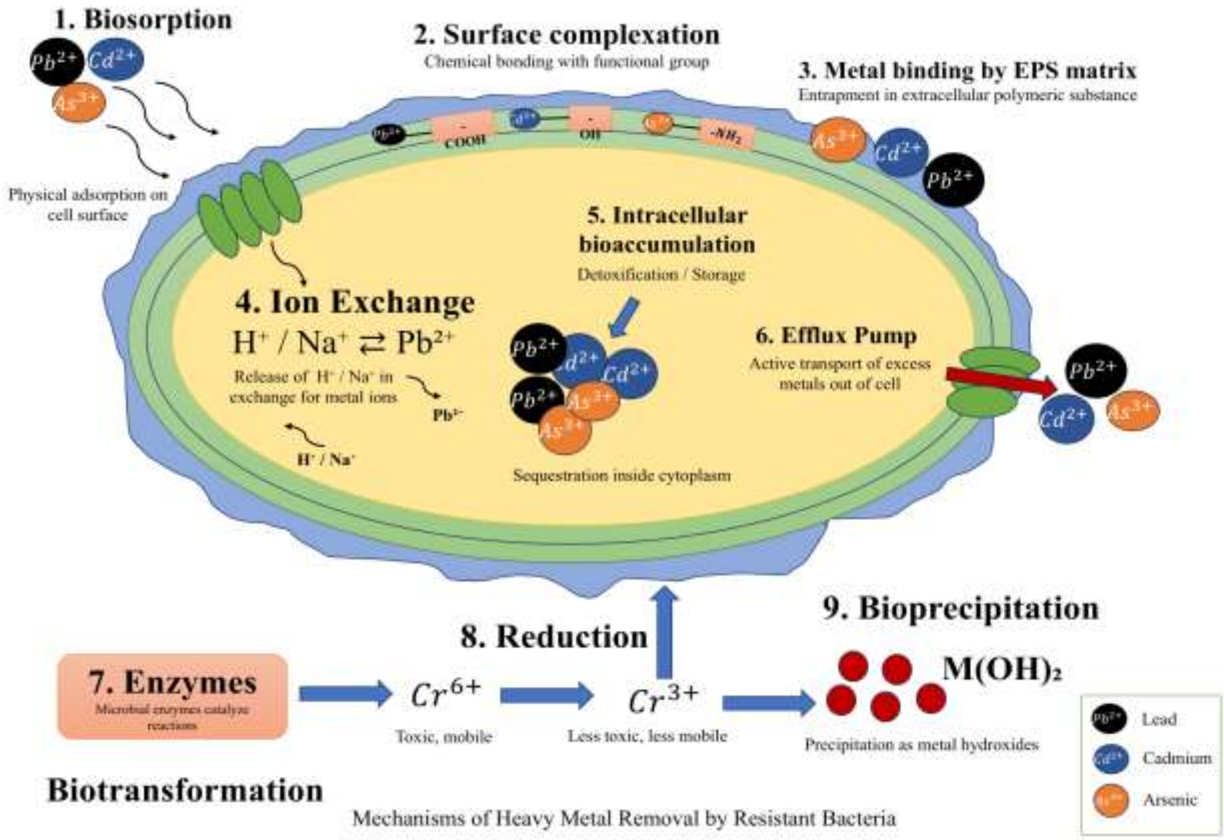

Fig. 3: Mechanism of Heavy Metal Removal by Resistant Bacteria

Challenges in biochar – microbe systems

Despite the promise of biochar-microbe systems, several challenges must be overcome for their widespread use, including the toxicity of heavy metals, which can be beyond the tolerance range of the introduced microbe strains. The microbial species introduced may have to compete heavily with the native species, which are better suited to the local environmental conditions. The bioavailability of heavy metals is also a concern, as heavy metals bound to soil particles may not be available to the microorganisms for degradation. Also, environmental variability in terms of pH and redox potential may lead to the re-mobilization of heavy metals, making it necessary to study the stability of these systems for a long period (Lyu et al. 2024). Finally, scaling up of the system from laboratory scale to field scale is yet to be achieved technologically (Wibowo et al. 2025). Apart from the issues mentioned above, the long-term survival and activity of heavy metal-tolerant microbes in the LDH-doped magnetic biochar system will also depend on the physicochemical characteristics of the composite and environmental conditions. Though biochar serves as an excellent medium for the development of microbial colonies, higher amounts of heavy metals and continuous exposure to the magnetic nanoparticles and LDH compounds can hamper microbial development, enzymatic actions, and metabolic activities (X. Zhao et al. 2026). The environmental conditions such as pH, temperature, moisture, competing ions, and interaction with indigenous microbial flora can impact the efficiency of the bioremediation process. Hence, proper optimization of composite formulation, microbial immobilization, and operational parameters becomes

Biochar/ composite material	Microorganism	Target metal(s)	Synergistic mechanism	Removal immobilization performance	pH / Time / Dose	Matrix type	Reference

crucial for effective and efficient bioremediation. Besides, pilot plant studies and field-level trials are required to examine the ecological safety, stability, and techno-economic feasibility of such hybrid systems prior to their actual implementation.

Table 2: Synergistic interaction between biochar-based composites and microorganisms for heavy metal removal and immobilization.

Rice husk biochar	*Pseudomonas aeruginosa*	Cu^{2+}, Pb^{2+}	Biosorption + microbial efflux	Cu: 97.5%, Pb: 76.5%	pH 7.0 / 96 h / Batch	Auto-mechanic soil	Bilyaminu et al. 2025
Cow dung biochar	*Bacillus cereus*	Cd^{2+}	Surface adsorption + biomineralization	>85% immobilization	pH 6.0–8.0 / 48 h / Variable	Tannery effluent	Marzan et al. 2017
Magnetic biochar	*Klebsiella pneumoniae*	Cr (VI)	Adsorption + microbial reduction to Cr (III)	>90% reduction	pH 7.0 / 3–5 days / 400 ppm	Urban creek sediment	Monga et al. 2022
LDH–biochar composite	Phosphate-solubilizing bacteria	Cd^{2+}, Pb^{2+}	Ion exchange + chelation by organic acids	Enhanced retention	pH 3.5–5.5 / 20 days / Variable	Wastewater / Soil	Selim & Harun-Ur-Rashid, 2025
Biochar-supported fungi	*Penicillium janthinellum*	Cd^{2+}	Cell wall binding + IAA production	High Cd tolerance	300 mg/L Cd / Incubation / Variable	Contaminated soil	Xie et al. 2021
FLBC(LDH–biochar)	Indigenous microbial consortia	As, Cd	Nano-bridge stabilization + redox transformation	Long-term immobilization	pH 7.0–8.0 / 60 days / 5 wt%	Phaeozem & Krasnozem soil	Lyu et al. 2024
Biochar+ SRB	Sulfate-reducing bacteria	Cd^{2+}, Sb^{3+}	Sulfide precipitation + adsorption	>85% stabilization	pH 6.3 / Seasonal / Field spray	Mixed metal farmland	Selim & Harun-Ur-Rashid, 2025

SUSTAINABLE BIOCHAR ENGINEERING

Desorption and Regeneration Methods

Removal of heavy metals and rejuvenation of active sites of adsorbents can be achieved through chemical or thermal methods. Chelating agents such as EDTA-2Na are very effective in desorbing heavy metals such as Cd (II) and Cu (II) from LDH-biochar composites (Li et al. 2022). Mineral acids such as HNO_3 and HCL are widely used as eluents to dissolve adsorbed metal ions by competing with protons (H^+) for binding sites (Priyadarshanee & Das, 2021). On the other hand, alkaline solutions are used to regenerate adsorbents by reacting with surface precipitates, such as lead carbonate, to release the metal into the liquid phase without damaging the chemical structure of the biochar (Jia et al. 2019). Thermal regeneration has also been successfully used to regenerate biochar, where the exhausted biochar is heated to 500°C for one hour to decompose the adsorbed organic molecules, thereby clearing the pores for reuse (Hasan & Karmakar, 2024).

Reusability Cycles

LDH-modified biochar's typically have better cyclic performance than pure biochar, which tends to degrade quickly in terms of surface functional groups (Li et al. 2022; Hameed et al. 2024). For example, MgAl-LDH@RHB composite materials can be recycled up to four cycles, although the adsorption capacity for Cd (II) ions could decrease from 79 mg/g to 25 mg/g over that time (Li et al. 2022). Notably, some Zn-Al LDH composite materials have been observed to increase their capacity after the first regeneration cycle (e.g., from 400 to 430 mg/g) because of the high-temperature transformation of LDHs into LDO, which have a "memory effect" (Hasan & Karmakar, 2024). Other magnetic biochar/LDH composites have been shown to retain a removal capacity of over 211 mg/g for Pb (II) even after five cycles (Jia et al. 2019).

Structural Stability and Metal Leaching

The integrity of the LDH component is a major concern, as it tends to dissolve in an acidic environment ($pH < 3$) (Li et al. 2022, Zhou et al. 2019). During the As(V) adsorption process, there has been a substantial increase in leaching, which in some cases has been found to double at higher concentrations of pollutants, thus confirming the progressive conversion of the LDH into an amorphous form (Hudcová et al. 2022). Although ions are leached into the solution, trivalent ions such as Al^{3+} or Fe^{3+} often remain in the solution to help and maintain the layered structure (Li et al. 2022). Moreover, the magnetic parts of these composites, such as Fe_3O_4, can partially dissolve during the acidic regeneration process, thus causing a progressive loss of magnetic and adsorption properties (Zhou et al. 2019).

Environmental Safety Considerations

The application of these composites in practical conditions requires proper handling to avoid secondary pollution. During the treatment process, various cations such as and, can be leached into the aqueous phase; hence, the treated water should not be released until the concentration of these ions is within the permissible limits (Li et al. 2022). To provide long-term safety, exhausted biomass needs to be disposed of through lined systems or processed through thermal desorption to inhibit the remobilization of metals in soil or groundwater (Priyadarshanee & Das, 2021; Selim & Harun-Ur-Rashid, 2025). Moreover, for contaminants that can be biologically transformed into gas phases, such as mercury or arsenic, the treatment process needs to be restricted to closed reactors to prevent air pollution (Selim & Harun-Ur-Rashid, 2025; Mayer Pushpa Latha et al. 2026).

COMPARISON WITH OTHER ADSORBENTS

Traditional adsorbents

Activated carbon (AC) is traditionally known as the most effective traditional adsorbent since it has an enormous specific surface area as well as high adsorption capacity of organic dyes and toxins (Zhou et al. 2019; Mahmoud et al. 2021).Nevertheless, the use of AC is greatly impeded by its high production and maintenance costs and the fact that it is usually fossil fuel-derived, hence less sustainable compared to carbon-neutral materials. Moreover, AC usually poses great challenges in the regeneration of the substrate after use (Mahmoud et al. 2021). In addition, zeolites and modified zeolites are also efficient modern technologies for the removal of heavy metals. Nevertheless, their efficiency may be impeded by low efficiency in diluted solutions and the complexity of recovering powdered materials from wastewater (Ukachi et al. 2026). Although AC and zeolites are efficient, biochar (BC) has been demonstrated to possess comparable or superior properties for metal removal with a more cost-effective and environmentally sustainable profile (Zhou et al. 2019). High-performance synthetic materials like CNTs, graphene, and MOFs have been shown to have high removal efficiency rates for various pollutants, but their high costs can be a major drawback for their application on an industrial scale (Mahmoud et al. 2021).

Metal oxide and polymer-based composites

However, despite MnO_2-polyacrylic acid and other metal oxide-based adsorbents demonstrating impressive selectivity towards such toxic elements as lead, the chemical reactions required for modification can involve either acidic or basic media that can produce toxic waste products (Li et al. 2022). Biological macromolecules such as cellulose, chitosan, and lignin are preferred thanks to their renewability and biocompatibility, yet they can suffer from a lack of active sites suitable for adsorption, making them inferior to hybrid structures in terms of their potential capacity (Jia et al. 2019; Mahmoud et al. 2021). In addition, many polymer materials have complicated production processes, and their inability to provide stability for regeneration is another disadvantage.

Comparison of performance of LDH-based materials

When biochar is used in combination with LDHs, it performs better than both raw biochar and traditional adsorbents, since such a combination provides an efficient platform characterized by high chemical reactivity (Shafiq et al. 2023; Li et al. 2022). For instance, a Zn-Al LDH-modified biochar showed a maximum adsorption capacity for methyl orange of 400 mg/g, which is a substantial improvement over the raw biochar's capacity of 212 mg/g (Hasan & Karmakar, 2024). In another case, the modification of magnetic biochar with MgFe-LDH resulted in a sevenfold increase in the lead adsorption capacity of the biochar, which reached a maximum of 476.25 mg/g (Jia et al. 2019). These LDH-biochar composites take advantage of a "win-win" effect where the biochar scaffold inhibits the flake-like aggregation of LDH nanoparticles, and the LDH addition provides high ion exchange and surface complexation properties (Hameed et al. 2024; Lyu et al. 2023). Moreover, the LDH-biochar hybrids, such as FLBC, have a more durable retention capability in soil conditions and retain high removal efficiencies even after several regeneration cycles owing to the special "memory effect" of the LDH framework (Lyu et al. 2024; Hasan & Karmakar, 2024). Unlike traditional materials, these hybrids offer a stable, efficient, and cost-effective approach for the treatment of complex effluents containing multiple toxic components (Jia et al. 2019).

Evaluation of the LDH-biochar system

Despite the superior adsorption properties of the LDH-functionalized magnetic biochar when compared with many conventional adsorbents, there are several factors that limit its widespread use. The main disadvantage of activated carbon is the lower cost-effectiveness due to the higher cost of production and regeneration, but it provides an advantage in terms of the higher specific surface area. Another problem is that zeolites have great ion-exchange properties, but they are not effective in multi-metal removal processes. Graphene- and carbon nanotube-based adsorbents provide efficient adsorption, but the synthesis process is costly and the production of such material on a large scale is complicated. In turn, the use of waste-derived biomass as the feedstock and provision of good regeneration and magnetic recovery makes LDH-modified magnetic biochar more cost-effective than other adsorbents. Nevertheless, the instability of the LDH layers in acidic environment, possible metal ion leaching during the repeated regeneration cycles and decrease in adsorption efficiency in presence of competitive ions in real wastewater or soil samples are important issues. Moreover, most of the published works use synthetic solutions under controlled laboratory conditions.

CHALLENGES AND RESEARCH GAPS

Scalability and Real Wastewater Application

There is a large gap in the technology between the laboratory-scale batch process and the industrial-scale application of Zn-Al LDH-coated magnetic biochar composites (Priyadarshanee & Das, 2021; Selim & Harun-Ur-Rashid, 2025). Although the composites have excellent performance in the laboratory, the treatment of real industrial effluent is more complicated because of the tons of effluent discharged, which demands shorter contact times and may cause early saturation of the biosorbent surface (Priyadarshanee & Das, 2021). Moreover, although the magnetic separation process makes the recovery of powdered adsorbents from wastewater easier, the cost of production of these high-performance magnetic materials is still higher than that of the conventional adsorbents, creating a barrier to their commercialization (Fitri et al. 2024). The design of the batch reactors to treat high volumes of dynamic environmental conditions is still a focus of future research (Priyadarshanee & Das, 2021).

Long-term Stability and Toxicity Issues

The LDH phase is highly prone to dissolution and degradation under acidic conditions (usually pH < 3) (Li et al. 2022). Studies have found that higher levels of specific contaminants, such as arsenate [As(V)], can cause the promotion of Mg leaching and even induce the LDH to change into an amorphous form, which may affect the long-term efficiency of the composite (Hudcová et al. 2022). Moreover, changes in environmental pH, redox potential, and temperature can cause the re-leaching of already immobilized heavy metals, which may again pose a threat of secondary pollution (Lyu et al. 2024; Selim & Harun-Ur-Rashid, 2025). To avoid further environmental hazards, the treated water needs to be tested for the presence of cations (Mg^{2+}, Al^{3+}), which should comply with regulations, and the spent biomass needs to be disposed of in lined systems or through thermal desorption (Li et al. 2022).

Limited Studies on Microbe–LDH–Biochar Systems

Although individual studies on biochar-microbe and LDH-biochar models are on the rise, studies on the combined application of all three components in a unified remediation approach are scarce (Hudcová et al. 2022). There is a lack of integrated information to grasp and predict the complex interactions between the carbon-based material, the mineral layers, and the biological components (Amin et al. 2024). Moreover, non-native microbial strains used in bioaugmentation approaches may also experience strong competition from native microbial strains, which are better suited to the soil conditions, possibly impairing the survival and performance of the "super strains" in the integrated system (Selim & Harun-Ur-Rashid, 2025).

Need for Field-level Validation

Most of the existing knowledge has been obtained from controlled systems, and there is an urgent need for multi-year field studies to confirm the agronomic performance outputs, such as crop yield and food safety indicators. The conclusions obtained from particular biochar materials may not have universal applicability because biochars from different sources are highly different in their performance. Future studies should aim at developing "choose-by-constraint" decision support systems and reporting templates regarding dose, residence time, and speciation parameters to ensure that these materials can be effectively used in various real-world terrestrial and aquatic systems (Selim & Harun-Ur-Rashid, 2025; Huang et al. 2023).

FUTURE PERSPECTIVES

Green synthesis approaches

In addition, the non-native microbial strains employed in bioaugmentation strategies could also face intense competition from native microbial strains, which are more adapted to the soil environment, possibly affecting the survival and efficacy of the “super strains” in the integrated system (Selim & Harun-Ur-Rashid, 2025). A large amount of existing knowledge has been gained from controlled systems, and there is an urgent need for long-term field experiments to verify the agronomic performance output values, such as crop yield and food safety parameters (Montreemuk et al. 2026). The results derived from specific biochar materials may not be universally applicable because biochars from different materials are very different in their properties. Future research should focus on the development of “choose-by-constraint” decision support systems and reporting templates on dose, residence time, and speciation parameters to ensure that these materials can be used effectively in different real-world terrestrial and aquatic systems (Selim & Harun-Ur-Rashid, 2025; Huang et al. 2023).

Biochar-based composites with multifunctional applications

Recent research efforts have been made towards developing new approaches based on biochar, MMT, and Zn-Al LDH to develop a novel system by integrating features of high specific surface area, porosity, and ion-exchange ability through a distinctive method (Wibowo et al. 2025). Such composite materials can be further optimized using biological macromolecules like cellulose or magnetic nanomaterials like Mn-ferrite to facilitate the removal of existing contaminants such as methylene blue dye and Hg ions (Mahmoud et al. 2021). These materials are not only acting as a medium, but the LDH component acts as a “nano-bridge” to increase the binding affinity of biochar to the soil colloids and enhance the physical stability of the material (Li et al. 2022).

Synergy between adsorption and bioremediation processes

Another promising frontier in environmental engineering science is integrating adsorption and bioremediation techniques into one system. Bioengineered biochars may be employed as efficient carriers of microorganisms that resist heavy metals, creating protective environments that support their life and activity (Ouyang *et al.* 2023). This technology may be applied to microorganism-assisted phytoremediation, where fungi resistant to cadmium, such as *Penicillium janthinellum ZZ-2*, are used to synthesize phytohormones promoting plant growth, while the adsorbent is utilized to immobilize hazardous ions (Xie et al. 2021). In addition, bioengineered biochars may be employed to conduct redox reactions directly in place, for example, the re-oxidation of less toxic As(V) from As (III), which subsequently may precipitate as more stable compounds with iron and calcium minerals available in the composite (Lyu et al. 2024).

Applications for industry and environment

In order to ascertain that these interactions are not only successful in laboratories but also in practical situations, further investigation will need to be undertaken involving pilot testing within practical aquatic and terrestrial environments (Wibowo et al. 2025; Selim & Harun-Ur-Rashid, 2025). These applications provide great benefits for carbon sequestration, soil fertility enhancement, and sustainable rehabilitation of mining and industrial areas (Lyu et al. 2024). Nevertheless, their extensive use in industry needs comprehensive techno-economic and life-cycle assessment analyses to ensure that the processes remain low-cost and low-carbon (Selim & Harun-Ur-Rashid, 2025). Eventually, standardized rehabilitation programs need to incorporate common reporting formats regarding metal speciation, dose-response parameters, and stability to ensure that these materials are not affected by environmental factors such as the leaching effects of acid rain (Lyu et al. 2024).

CONCLUSIONS

LDH-functionalized magnetic biochar is a promising and environmentally friendly multipurpose material for the removal of heavy metals from water and soils. Numerous studies utilizing characterization methods, such as X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy combined with energy-dispersive X-ray spectroscopy (SEM–EDS), Brunauer–Emmett–Teller (BET) method, and vibrating sample magnetometry (VSM), have shown that the in situ co-precipitation and hydrothermal approaches ensure the efficient loading of LDH nanoparticles into the porous structure of biochars, which increases the specific surface area, surface functionality, adsorption capacity, structural stability, magnetic recovery ability, and reuse of the nanocomposites. The combination of biochar, LDHs, and magnetic components ensures effective adsorption and separation of heavy metals, whereas heavy metal-resistant microorganisms contribute to the improved remediation through biosorption, bioaccumulation, biomineralization, EPS formation, and microbial redox reactions. As a result, the enhanced contaminant immobilization and environmental sustainability are achieved. Based on the analysis of existing literature, it can be concluded that these nanomaterials represent an environmentally friendly approach to multiple heavy metals removal from the environment within the framework of circular bioeconomy concept. Nevertheless, challenges related to large-scale production, long-term stability under varying environmental conditions, regeneration efficiency, potential metal leaching, and field-scale validation remain. Future research should focus on optimizing composite design, elucidating microbe–material interactions, conducting pilot- and field-scale investigations, and evaluating techno-economic feasibility to facilitate the practical implementation of these hybrid systems for sustainable environmental remediation.

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Author contributions

Poojasri Sowndarajan: Conceptualization, investigation, writing – original draft; Sai Sakthi Sridevi Kumaran: Data curation, writing review and editing, validation; Deepthi Sri Sathiyamurthy: Data curation, writing review and editing, validation; Bhuvaneswari Shanmugam: Supervision, writing – review and editing, validation.

Conflict of interest statement

The authors declare no conflict of interest.

Data availability statement

Data availability is not applicable, as this did not involve the generation or analysis of any datasets.

Consent

All authors listed in the manuscript have consented to authorship and participation. All authors have read and approved the final version of the manuscript.

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