Sorpt.Stud. 2(1), June 2026, 20-33

INDONESIAN SCHOLAR SOCIETY

Sorption Studies

Journal homepage: https://journal.solusiriset.com/index.php/ss
e-ISSN: 3123-5697

Review Article

Comparative Heavy Metal Adsorption Using Magnetic, Carbon-Based, and Biopolymer Composite: A Critical Systematic Review

Sultan Napoleon[1], Mayang Fauziah Putri Kuntjahjono[1], Wikrama Sarweswara[1], Nugroho Adi Sasongko[2], Akhmad Rifa'i[2], Nuha Nuha[2], Rahmat Basuki[1]*

[1]*Department of Chemistry, The Republic of Indonesia Defense University, Kawasan IPSC Sentul, Bogor 16810, Indonesia*

[2]*Research Center for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency, Puspiptek Area, Serpong, 15314, Indonesia*

[3]*Energy Security Graduate Program, The Republic of Indonesia Defense University Bogor, 16810, Indonesia*

[4]*Murdoch University, 90 South St, Murdoch Western Australia 6150, Australia*

https://doi.org/10.55749/ss.v2i1.152
Received: 30 Dec 2025; Revised: 1 Jun 2026; Accepted: 13 Jun 2020; Published online: 26 June 2026; Published regularly: 30 Jun 2026

***Abstract*—**The increasing contamination of aquatic environments by heavy metals has driven the continuous development of efficient, sustainable, and reusable adsorbent materials. This systematic review critically compares the adsorption performance of magnetic-, carbon-based-, and biopolymer-based composites used for heavy metal removal from aqueous solutions. The analysis integrates data from various studies published within the last decade, focusing on maximum adsorption capacity (qmax), specific surface area, magnetic properties, and adsorption isotherm models. Carbon-based adsorbents demonstrate high adsorption capacities (4.16 – 491 mg g^{-1}) due to their large surface areas and well-developed porosity, while biopolymer-based materials offer environmental sustainability and functional group diversity but generally exhibit lower adsorption performance unless modified with magnetic or carbon components. Magnetic adsorbents, particularly ferrite-based nanocomposites, exhibit exceptional adsorption capacities (up to 1951.98 mg g^{-1} for Pb(II)) and high removal efficiencies exceeding 95%, with the added advantage of easy magnetic separation and recyclability. However, the long-term stability and regeneration efficiency of magnetic adsorbents remain critical challenges. The bibliometric analysis using VOSviewer further reveals that recent research trends are shifting from fundamental adsorption studies toward the development of multifunctional, hybrid composites that integrate magnetic, carbon, and biopolymer components. These advancements reflect a growing emphasis on enhancing adsorption efficiency, reusability, and environmental compatibility, providing a strong foundation for the design of next-generation adsorbents suitable for industrial-scale wastewater treatment.

Keywords*—Adsorption, Biopolymer, Carbon-based material, Heavy metal, Magnetic composite*

1. INTRODUCTION

The rapid advancement of industrial technologies has provided substantial benefits to human life; however, it has also generated significant negative impacts on the environment. One of the major concerns is the presence of heavy metals in industrial effluents, which can contaminate aquatic ecosystems. Metals such as mercury (Hg), lead (Pb), copper (Cu), cadmium (Cd), arsenic (As), chromium (Cr), nickel (Ni), and iron (Fe) are frequently detected in aquatic environments and are known for their toxic nature. Continuous exposure to heavy metals can lead to various health disorders, including Minamata disease, congenital abnormalities, neurological damage, carcinogenic effects, and impaired immune functions. The bioaccumulation of heavy metals in living organisms, whether in humans or aquatic biota, ultimately poses serious long-term risks to both public health and environmental sustainability [1].

To address these challenges, several conventional methods for heavy metal removal have been developed, including chemical precipitation, ion exchange, solvent extraction, and adsorption. Chemical precipitation is effective in reducing metal concentrations; however, it often produces secondary waste and requires relatively complex chemical treatment [2]. Ion exchange functions

***Corresponding author**.
Email address: rhmtbsq@gmail.com

through the substitution of ions using resins, while solvent extraction employs selective solvents to attract and separate the target element [3, 4]. Among these techniques, adsorption has been widely adopted due to its simplicity, efficiency, and effectiveness in separating metal ions from aqueous solutions. Adsorption is defined as the accumulation of adsorbate molecules on the surface of an adsorbent, driven by intermolecular attractive forces or field effects at the adsorbent surface that can capture molecules in either gaseous or liquid form [5].

Over time, studies have revealed the limitations of single-component adsorbents, particularly in terms of adsorption capacity and selectivity toward specific ions (adsorbates) [6]. This has led to the emergence of new approaches through the development of composite adsorbents. Various types of composite materials have been investigated, including magnetic-, carbon-, and biopolymer-based adsorbents, each offering distinct advantages. Magnetic composites combined with carbon or polymers provide the benefit of easy post-adsorption separation using an external magnetic field [7]. Carbon-based adsorbents are well known for their high surface area and excellent chemical stability, making them highly effective for heavy metal ion removal [8]. Meanwhile, biopolymers are attractive due to their biodegradable and environmentally friendly nature, as well as their abundance of functional groups that enable strong interactions with metal ions [9].

The research trend on composite adsorbents has gained increasing attention, with a growing number of reports demonstrating that the combination of different materials can generate synergistic effects, thereby enhancing adsorption capacity, stability, and operational convenience. However, the outcomes are not always consistent, as variations in synthesis methods, the type of targeted metal ions (adsorbates), and experimental conditions can significantly influence parameters such as maximum adsorption capacity (qmax), surface area, and magnetic properties. These factors highlight the critical importance of conducting systematic reviews, as they allow the diverse data from different studies to be consolidated into a more comprehensive and structured perspective.

Based on this background, the present systematic review aims to compare the maximum adsorption capacity (qmax) and textural parameters, including specific surface area, pore size, and magnetic strength, among magnetic, carbon-based, and biopolymer composite adsorbents for heavy metal removal. Unlike previous review articles that primarily focus on individual adsorbent categories, this study provides a systematic and critical comparative evaluation of these major composite materials within a unified framework. By integrating adsorption performance with physicochemical characteristics, this review seeks to identify the key factors governing heavy metal adsorption efficiency, as well as the advantages and limitations associated with each adsorbent class. The findings are expected to provide new insights into the relationship between material properties and adsorption behavior, while establishing a stronger scientific basis for the design and development of more efficient, environmentally sustainable, and industrially applicable adsorbents.

2. METHOD

This study was conducted using the Systematic Literature Review (SLR) approach, which encompasses the stages of identification, screening, eligibility, and inclusion. Literature searches were carried out through both national and international databases such as Elsevier (ScienceDirect), SpringerLink, ACS Publications, MDPI, and SINTA, employing relevant keywords related to heavy metal adsorption, such as “heavy metal adsorption”, “heavy metal removal”, “adsorbent”, and “biosorbent”. The collected articles were then selected based on specific inclusion criteria, namely publications within the last ten years that explicitly reported the application of adsorbents in heavy metal ion removal. The selected studies were subsequently subjected to data extraction and comparative analysis to evaluate the effectiveness of various adsorbent types in terms of their adsorption capacities and material characteristics.

3. RESULT AND DISCUSSION

3.1. Characterization of Various Adsorbent

The characterization of adsorbent materials is a crucial step in understanding the relationship between their physicochemical properties and adsorption performance. Each type of adsorbent possesses distinct morphology, structure, and functional groups, all of which directly influence the number and strength of active sites involved in the adsorption of heavy metal ions [10].

The analysis of the physical and magnetic properties of adsorbents represents an essential aspect in understanding the relationship between material characteristics and the effectiveness of heavy metal ion adsorption. According to Brunauer-Emmett-Teller (BET) data, the specific surface area is one of the key parameters determining the number of available active sites for interaction with metal ions [11]. Adsorbents with higher surface areas generally exhibit greater adsorption capacities due to the provision of larger contact areas. In addition, pore size distribution plays a vital role in facilitating ion diffusion into the material matrix. Biopolymer-based materials are often reported to possess relatively low surface areas, whereas carbon- and magnetic-based adsorbents typically demonstrate higher surface areas with a combination of micro- and mesopores, which significantly enhances adsorption efficiency.

The analysis of magnetic properties using a Vibrating Sample Magnetometer (VSM) provides several key parameters that are closely related to the performance of an adsorbent, including saturation magnetization (Ms), remanent magnetization (Mr), and coercivity (Hc). A high Ms value is particularly desirable, as it facilitates

the rapid and efficient separation of adsorbents from aqueous solutions through the application of an external magnetic field.

Based on the data presented in **Table 1**, adsorbent materials can be classified into three main groups: carbon-based, biopolymer, and magnetic adsorbents. Carbon-based adsorbents are typically derived from biomass sources such as rice husk, sawdust, and acrylic fabric, which exhibit relatively high specific surface areas (SAA) of 1014.14 $m^2\ g^{-1}$, 696.7 $m^2\ g^{-1}$, and 781.3 $m^2\ g^{-1}$, respectively, whereas carbon derived from tire powder shows a much lower SAA of only 131.6 $m^2\ g^{-1}$. Activated carbon foam, a widely used adsorbent, has an SAA of 458.59 $m^2\ g^{-1}$, which is still lower compared to carbon gels (444–547 $m^2\ g^{-1}$) and mesoporous materials such as P-CMK-3 (1254 $m^2\ g^{-1}$) and O-CMK-3 (970 $m^2\ g^{-1}$). Biochar-based adsorbents, such as those synthesized from peanut shells, demonstrate a wide range of surface areas (4.398–203.978 $m^2\ g^{-1}$), highlighting the critical influence of activation methods and pyrolysis conditions on pore development. Furthermore, surface functionalization can also lead to a reduction in surface area, as observed in Mesoporous Carbon Nitride (MCN-1) with an initial SAA of 506.6 $m^2\ g^{-1}$, which decreases to 102.2 $m^2\ g^{-1}$ after modification with amine groups (MDA-MCN-1). Despite this reduction, the functionalization process enhances chemical affinity toward specific metal ions, thereby compensating for the lower surface area.

Halloysite Nanotubes (HNT), which fall under the biopolymer-based adsorbent group, exhibit a specific surface area (SAA) of 55.51 $m^2\ g^{-1}$. However, upon modification with ball-milled biochar and alganite, the SAA decreases substantially to 16 $m^2\ g^{-1}$ prior to adsorption and further declines to 7.11 $m^2\ g^{-1}$ after the adsorption process. This significant reduction indicates pore blockage or surface coverage caused by interactions between the adsorbed metal ions (adsorbates) and the adsorbent surface. Such behavior also highlights the limited regeneration capacity of polymer-based materials unless further modifications are introduced to enhance their structural stability and reusability.

For magnetic-based adsorbents, the specific surface area (SAA) is generally lower compared to carbon-based materials, typically ranging from 24.67 to 57.66 $m^2\ g^{-1}$. Although the relatively small surface area represents a limitation, the key advantage of these adsorbents lies in their magnetic properties, which allow for facile separation after adsorption using an external magnetic field. As shown in **Table 1**, there are notable differences in saturation magnetization (Ms) values, for example, $NiFe_2O_4$, CFO nanoparticles, and CFO microgranules exhibit Ms values of 56.96 emu g^{-1}, 73.687 ± 0.368 emu g^{-1}, and 133.79 ± 0.669 emu g^{-1}, respectively. The difference in particle size (nanoparticles versus microgranules) strongly influences the magnetic behavior of the materials, as reflected in the remanent magnetization (Mr) of CFO microgranules (96.50 ± 0.483 emu g^{-1}), which indicates a higher tendency to retain magnetization even after the external field is removed. This property, however, also increases the risk of particle agglomeration. In contrast, materials such as $Cu_{0.50}Mg_{0.50}Fe_2O_4@SiO_2$ and $NiFe_2O_4$ not only exhibit Ms values of 37.8 and 56.96 emu g^{-1}, respectively, but also possess low coercivity (Hc) values of 0.03 and 0.01 T. Such low Hc values indicate soft magnetic or superparamagnetic behavior, in which the particles can be easily magnetized during adsorption and subsequently demagnetized without retaining permanent magnetization. This characteristic is particularly advantageous for repeated adsorption–desorption cycles, as it minimizes particle aggregation during magnetic separation.

In **Table 1**, some adsorbents have quite large surface area values, such as P-CMK-3 (1254 $m^2\ g^{-1}$) and O-CMK-3 (970 $m^2\ g^{-1}$). However, the adsorption mechanism in this system does not solely originate from the availability of pore surface area but also involves the presence of functional group density on the adsorbent surface. Groups such as -OH, -COOH, and -C=O play a role as weak to moderate complexation centers on the adsorbent surface with the adsorbate, allowing for electrostatic interactions and coordination bonds with the adsorbate. Therefore, an adsorbent with a sufficiently large surface area but only a few active functional groups does not necessarily exhibit a high adsorption capacity.

While in carbon materials there are those that undergo chemical modification, such as Mesoporous Carbon Nitride. In MDA-MCN-1, the reduction in specific surface area is more than 80%, which can be caused by additional interactions from amino groups, often considered as structural loss. However, the adsorption data shows that this modification can shift the mechanism from being primarily physical to being dominated by chemical interactions. The amino groups act as chelating sites that are quite selective toward metal ions, so the quality of the active sites is more important than their quantity in this system. This indicates that the adsorption process is not always determined by the surface area of the adsorbent.

In biopolymer-based adsorbents, such as HNT and HNT-BC@Alg, there are limitations related to surface area, which can specifically restrict physical contributions. However, similar to amine groups that can promote interactions toward chemical interactions rather than physical ones. Hydroxyl and carboxyl groups in this matrix can form multidentate coordination bonds with the adsorbate, resulting in a more stable surface complex. The decrease in surface area of the adsorbent does not indicate pore blockage but also suggests that strong chemical bonds are formed. This has significant implications, as most biopolymer-based adsorbents only show high adsorption efficiency in a single cycle, but in subsequent cycles, the efficiency decreases due to the strong chemical bonds, making deionization quite difficult and limiting repeated use.

Magnetic-based adsorbents generally have a low surface area, ranging only from 24.67 to 57.66 $m^2\ g^{-1}$, which is quite far below carbon-based adsorbents.

However, the presence of hydroxyl groups on the surface of Ferrite (-Fe-OH), which are amphoteric, allows for relatively strong complexation on the adsorbent surface. Additionally, the heterogeneity of energy on the surface of metal oxides provides adsorption sites that do not depend on surface area. Meanwhile, magnetic parameters such as Ms and Hc do not directly contribute to the interactions occurring in the system but play an important role in maintaining stability and ease of recovery of the adsorbent without reducing the active site capacity.

In addition to the surface area and magnetic parameters of the adsorbent, heterogeneity in the structure of the adsorbent also plays a significant role in the adsorption mechanism. Variations in pore geometry, surface roughness, and the spatial distribution of active sites on the adsorbent can lead to differences in adsorption energy at various locations on the surface. This condition is quite applicable to composite materials, where more than one phase of material exists within a single adsorbent system. Ultimately, this can cause the adsorption process to not occur uniformly, but rather tend to happen at active sites with relatively high energy, which are generally associated with defect regions, functionalized domains.

Additionally, the procedure in synthesizing an adsorbent has a significant impact on the final structural characteristics of a material. Differences in activation methods, calcination temperatures, the precursors used, and modifications can alter pore development and the surface of the adsorbent. For example, chemically activated carbon-based adsorbents generally have a microporous structure, while physically activated ones tend to have larger pores. This also applies to biopolymer adsorbents, which are often synthesized using cross-linking processes that result in a decrease in surface area, but the number of active functional groups used to adsorb adsorbates is higher.

Table 1. Characterization of various adsorbents

Type of Adsorbents	Adsorbent	Specific Surface Area (m^2/g)	Ms (emu g^{-1})	Mr (emu g^{-1})	Hc (T)	Ref
Carbon-based	Carbon-based from Sawdust	696.7	-	-	-	[12]
	Carbon-based from Acrylic Fabric	781.3	-	-	-	[12]
	Carbon-based from Tire Powder	131.6	-	-	-	[12]
	Carbon-based from Rice Husk	1014.4	-	-	-	[12]
	Activated Carbon Foam	458.59	-	-	-	[13]
	AC/Fe_3O_4@SiO_2-NH (1:0.5)	-	-	-	-	[14]
	AC/Fe_3O_4@SiO_2-NH (1:0.25)	48.9	-	-	-	[14]
	AC/Fe_3O_4@SiO_2-NH (1:0.15)	-	-	-	-	[14]
	Biochar (peanut shell)-1	4.398	-	-	-	[15]
	Biochar (peanut shell)-2	91.562	-	-	-	[15]
	Biochar (peanut shell)-2	203.978	-	-	-	[15]
	Biochar (peanut shell)-4	119.855	-	-	-	[15]
	Carbon Gel	444	-	-	-	[16]
	Carbon Gel-0.5 Gaphite Intercalation Compound	466	-	-	-	[16]
	Carbon Gel-1.0 Gaphite Intercalation Compound	485	-	-	-	[16]
	Carbon Gel-2.0 Gaphite Intercalation Compound	547	-	-	-	[16]
	Mesoporous Carbon Nitride (MCN-1)	505.6	-	-	-	[17]
	Mesoporous Carbon Nitride Functionalized with Melamine-based Dendrimer Amine (MDA-MCN-1)	102.2	-	-	-	[17]
	P-CMK-3	1254	-	-	-	[18]
	O-CMK-3	970	-	-	-	[18]
	A-CMK-3	15	-	-	-	[18]
Biopolymer	Halloysite Nanotubes (HNT)	55.51	-	-	-	[19]
	Halloysite Nanotubes and Ball-milled Biochar (HNT-BC@Alg) pre-sorption	16	-	-	-	[19]
	Halloysite Nanotubes and Ball-milled Biochar (HNT-BC@Alg) post-sorption	7.11	-	-	-	[19]
Magnetic	$Cu_{0.50}Mg_{0.50}Fe_2O_4$@$SiO_2$	-	37.8	20.87	0.03	[20]
	$MnFe_2O_4$/GO Nanocomposite	-	28.8	-	-	[21]
	$NiFe_2O_4$	-	56.96	-	0.01	[22]
	Engineering Magnetic Cobalt Ferrite (CFO) Nanoparticles	57.66	73.687 ± 0.368	48.608 ± 0.243	-	[23]
	Engineering Magnetic Cobalt Ferrite (CFO) Microganules	24.67	133.79 ± 0.669	96.50 ± 0.483	-	[23]

3.2. Adsorption for Magnetic, Carbon-Based, and Biopolymer Composites Adsorbent

The adsorption process of heavy metal ions is influenced by various factors, one of which is the maximum adsorption capacity (q_m) of the adsorbent material. This parameter reflects the ability of an adsorbent to accommodate metal ions under optimal conditions and serves as a key indicator in evaluating adsorbent effectiveness [24]. To better understand the surface interactions between metal ions and adsorbents, several isotherm models have been developed, with the Langmuir and Freundlich models being the most widely applied in adsorption studies. The Langmuir model assumes monolayer adsorption on a homogeneous surface with uniform binding energies [25], whereas the Freundlich model describes adsorption on heterogeneous surfaces, allowing for the formation of multilayers [26]. By comparing experimental data with these models, valuable insights can be obtained regarding the physicochemical properties of the adsorbent, the dominant binding mechanisms, and whether the process tends toward physical or chemical adsorption. Such analyses provide a fundamental understanding of both the limitations and the potential for further development of adsorbents in heavy metal wastewater treatment applications.

In addition to maximum adsorption capacity, operational conditions during experiments play a crucial role in determining the effectiveness of an adsorption process. Parameters such as pH, contact time, and temperature are critical variables that influence adsorption performance [27, 28]. The pH not only governs the speciation of metal ions but also determines the surface charge of the adsorbent, thereby strongly affecting electrostatic interactions between the adsorbent and the adsorbate. Contact time is closely related to the rate at which equilibrium is achieved, where adsorbents with larger surface areas may reach equilibrium more rapidly than those with denser structures [27]. Temperature, on the other hand, can influence both the kinetics and thermodynamics of adsorption [29]. Therefore, evaluating adsorbent performance under varying operational conditions provides a more comprehensive understanding of the strengths and limitations of each material.

Different types of adsorbent materials offer distinct advantages. Magnetic adsorbents are readily separated by an external magnetic field after adsorption, making them strong candidates for repeated use. Carbon-based adsorbents, particularly those derived from graphene or activated carbon, provide exceptionally large surface areas and relatively high adsorption capacities, although their synthesis can be costly. Biopolymer-based adsorbents, on the other hand, emphasize sustainability due to their environmentally friendly and biodegradable nature, despite generally lower adsorption capacities. However, the combination of biopolymers with magnetic nanoparticles or carbon materials can significantly enhance their performance, resulting in composite adsorbents with more balanced and versatile properties.

In addition to these advantages, it is also important to consider the limitations of each adsorbent type in order to provide a broader perspective on their potential and challenges. Each adsorbent inevitably possesses both strengths and weaknesses. Carbon-based adsorbents demonstrate superior adsorption capacity, yet their synthesis cost remains relatively high. Magnetic adsorbents are effective and allow easy separation, but their stability tends to decrease after several regeneration cycles. Biopolymer-based adsorbents are environmentally friendly and easy to synthesize; however, they generally require modification with other materials to achieve sufficiently high adsorption capacities. Analysis of publication trends over the past decade reveals a growing interest in the development of composite adsorbents. Nonetheless, challenges remain in real wastewater applications, which are often highly complex, particularly due to the presence of competing ions that can significantly reduce adsorption efficiency.

Based on the data presented in **Table 2**, the maximum adsorption capacity (q_m) of the investigated materials exhibits considerable variation, which is influenced by several factors, including the type of material used, the chemical properties of its surface, and the operational conditions applied during adsorption. Carbon-based adsorbents demonstrate relatively consistent performance, with qm values ranging from 4.16 to 491 mg g^{-1}. This variation largely depends on the carbon source (e.g., sawdust, rice husk, acrylic fabric, tire powder) as well as the type of modification employed (e.g., carbon gel, activated carbon foam, and carbon–graphite intercalation compounds) with variations in experimental conditions among the studies, such as pH solution, contact time, initial solution concentration, temperature, and adsorbent dosage. The highest adsorption capacity was reported for activated carbon foam in the adsorption of Pb(II) ions, with a qm of 491 mg g^{-1}, whereas the lowest was observed for carbon gel in the adsorption of Ni ions, with a qm of only 4.16 mg g^{-1}. However, direct comparison of maximum capacity were obtained under different experimental conditions and different metal ion target. Generally, carbon-based adsorbents fit well with Langmuir or Freundlich isotherm models, indicating that adsorption occurs on both homogeneous and heterogeneous surfaces, with removal efficiencies exceeding 85%. While carbon-based adsorbents show promising performance, similar variations in adsorption characteristics are also observed in biopolymer-based adsorbents, which have been increasingly explored in recent studies.

Table 2, which provides data on adsorption performance, further emphasizes that the maximum adsorption capacity of an adsorbent is not solely based on its structural characteristics. The dominant adsorption mechanism can also influence the maximum adsorption capacity value. The significant difference in maximum adsorption capacity indicates that specific chemical interactions within the system play a much more decisive role than physical parameters.

In addition to the characteristics of the adsorbent, the intrinsic properties possessed by the adsorbent also play a significant role in the maximum adsorption capacity observed. Differences in ion radius, hydration energy, and electronic configuration among heavy metal ions can influence the strength of interactions between the adsorbate and adsorbent. For example, Pb(II) shows relatively consistent adsorption capacity results compared to other divalent ions. This can be attributed to the lower hydration energy of Pb(II) and its relatively strong affinity for active sites on the surface of the adsorbent.

The metals Cd(II) and Cu(II) also exhibit relatively high adsorption capacity, but are more sensitive to environmental conditions and competition among adsorbates. Cu(II) specifically tends to form stable inner-sphere complexes with amine groups, which can explain the high adsorption capacity values on biopolymer or carbon adsorbents that are modified with nitrogen groups. Meanwhile, the metals Ni(II) and Co(II) generally show lower adsorption capacities, which can be attributed to stronger hydration shells and the difficulty in forming stable surface complexes.

The differences in behavior among these adsorbates show that adsorption performance cannot be generally viewed solely based on the type of adsorbent. An adsorbent that has an advantage in adsorbing Pb(II) metal does not necessarily produce the same efficiency results with other adsorbates under the same environmental conditions. Therefore, the interpretation of adsorption data must consider the combination of the properties of the adsorbent and the specific characteristics of the adsorbate to avoid an oversimplified understanding of a material's performance.

Carbon-based adsorbents have a more varied maximum adsorption capacity (4.16 - 491 mg g^{-1}), indicating the occurrence of heterogeneity in adsorption. Adsorbents with large surface areas, such as activated carbon foam and modified graphene oxide, provide higher maximum adsorption capacities. This adsorption generally follows the Langmuir or Freundlich models, indicating that adsorption occurs in monolayer or multilayer form with moderate binding energy. This adsorption mechanism is quite effective in increasing the initial adsorption capacity but is susceptible to competition from metal ions and deionization during the regeneration process.

In biopolymer-based adsorbents, the maximum adsorption capacity varies more widely, ranging from 6.96 to over 214 mg g^{-1}. Alginate-chitosan adsorbents with specific ratios show a significant increase in maximum adsorption capacity, which can be attributed to the increased presence of amine and carboxyl groups available for metal ion chelation. This adsorption system generally follows the Langmuir and Sips models, indicating the formation of homogeneous adsorption sites with high energy consistent with the chelation mechanism. However, the strength of these bonds also suggests that some biopolymer-based adsorbents face difficulties in regeneration, even though their initial adsorption efficiency is quite high.

Magnetic-based adsorbents provide quite interesting results, where some adsorbents with relatively small surface areas can achieve very high maximum adsorption capacities. One example is engineered magnetic cobalt ferrite (CFO) microgranules, which reach a maximum adsorption capacity for the metal Pb(II) of up to 1951.98 mg g^{-1}. This indicates that the adsorption mechanism not only depends on physical characteristics but also on the strength of chemical interactions between the adsorbate and the surface of the adsorbent (metal oxides). In this material, the adsorption generally fits the Freundlich model, which indicates surface heterogeneity and a wide distribution of adsorption energies, allowing multilayer adsorption on sites with high energy.

The comparison between Tables 1 and 2 provides information that carbon-based adsorbents excel in providing a large surface area and adsorbate diffusion, biopolymer-based adsorbents excel in selectivity and binding strength through chelation, while magnetic-based adsorbents excel in the strength of chemical interactions and ease of separation. In composite adsorbents, the mechanisms work simultaneously, resulting in a significant increase in maximum adsorption capacity and improving operational convenience.

Biopolymer-based adsorbents exhibit a wider variation in adsorption capacities compared to carbon-based materials. For example, alganite–chitosan composites prepared with different ratios demonstrated adsorption capacities for Cd(II) and Pb(II) ranging from 155 to 214.28 mg g^{-1}, with the 3:1 ratio showing the best performance. Polylactic acid/hydroxyapatite (PLA/Hap-2.5) achieved exceptionally high removal efficiencies for Pb(II) and As(II), at 100% and 93%, respectively, highlighting its potential as a multifunctional adsorbent. In contrast, HNT-BC@Alg showed relatively low adsorption capacities for Cd(II) and Ni(II), despite achieving comparatively high removal efficiencies. The performance of biopolymer-based adsorbents can be further enhanced through hybrid composite modification, such as core–shell magnetic chitosan, which exhibited a qm of 111 mg g^{-1} for Pb(II), or biopolymer–clay nanocomposites, which reached a qm of 214.28 mg g^{-1} for Cu(II). These findings suggest that by incorporating inorganic or magnetic components, the limitations of surface area and active site distribution in biopolymers can be mitigated, thereby improving adsorption efficiency. Consequently, biopolymers not only retain their advantages of sustainability and biodegradability but can also achieve competitive performance. This comparison becomes even more compelling when contrasted with magnetic adsorbents, which display significant performance differences.

Magnetic adsorbents exhibit outstanding performance compared to carbon-based and biopolymer adsorbents, particularly in terms of maximum adsorption capacity (qm), which can reach the scale of hundreds to even thousands of mg g^{-1}. For instance, engineered

magnetic cobalt ferrite (CFO) nanoparticles and microgranules demonstrated exceptionally high qm values of 1382.74 mg g^{-1} and 1951.98 mg g^{-1}, respectively, for Pb(II), with CFO nanoparticles also achieving a high removal efficiency of 97.76%. These results significantly surpass the adsorption capacities typically reported for carbon-based or biopolymer adsorbents. Other ferrite-based materials, such as $CoFe_2O_4$-G, $NiFe_2O_4$, and $MnFe_2O_4$/GO nanocomposites, also showed considerable adsorption capacities ranging between 74.62 and 636.94 mg g^{-1} for Pb(II) and Cd(II). Generally, magnetic adsorbents follow the Langmuir isotherm model, indicating homogeneous surface adsorption and strong affinity toward target ions. Another notable advantage unique to magnetic adsorbents is their facile separation from the aqueous phase after adsorption through the application of an external magnetic field, making them highly promising for repeated use in industrial-scale wastewater treatment. Nonetheless, clear differences remain between carbon-based, biopolymer, and magnetic adsorbents in terms of surface area, adsorption capacity, and overall regeneration stability, highlighting the need for tailored material design depending on specific application requirements.

Carbon-based adsorbents generally exhibit relatively high maximum adsorption capacities (qm), which directly correlate with their large specific surface areas that provide abundant active sites for metal ion interactions. In contrast, magnetic adsorbents typically possess lower surface areas, resulting in comparatively smaller qm values. Nevertheless, they remain competitive due to strong electrostatic interactions between their surface charges and metal ions, as well as their practical advantage of easy separation after adsorption using an external magnetic field. Meanwhile, biopolymer-based adsorbents stand out in terms of sustainability and biodegradability, although their adsorption capacities are usually lower unless modified into composites. Beyond the intrinsic properties of the materials, the overall effectiveness of an adsorption process is also strongly influenced by operational conditions such as pH, contact time, temperature, and the presence of competing ions in solution. These factors can alter metal ion speciation while simultaneously affecting surface charge and active site distribution, thereby ultimately determining the adsorption performance.

One of the most crucial factors influencing adsorption effectiveness lies in the operational conditions applied during the process. Among these, pH plays the most significant role, as Pb(II) and Cd(II) generally exhibit their highest adsorption capacities under neutral to slightly basic conditions, while Cr(VI) tends to remain more stable in acidic media. Contact time is also an important parameter, with carbon-based adsorbents typically reaching equilibrium faster than biopolymer-based materials, whereas magnetic adsorbents often require intermediate contact times but eventually deliver higher final adsorption capacities. Temperature is usually maintained at room conditions (25–30 °C), yet several studies have reported improved adsorption performance at moderate temperatures due to enhanced diffusion of ions into the pores. This observation aligns with recent research trends highlighting a shift from single-material adsorbents toward composite materials, which are engineered to maximize performance by integrating complementary properties from different components.

In terms of research trends, there has been a clear shift from the use of single-material adsorbents toward the development of composite materials that integrate the advantages of different adsorbent groups. Biopolymers modified with carbon or magnetic nanoparticles have been shown to significantly enhance adsorption performance by combining sustainability with high adsorption capacity and ease of material recovery. Similarly, composites combining carbon-based materials with ferrite nanoparticles can unite the benefits of high surface area with magnetic properties. This analysis emphasizes that the strengths and weaknesses of individual adsorbents can be complemented through such combinations, resulting in hybrid materials with balanced performance. Carbon-based adsorbents excel in adsorption capacity and surface area, biopolymers contribute environmental friendliness and biodegradability, while magnetic materials stand out as strong candidates for industrial-scale applications due to their high efficiency and ease of separation after adsorption. Nonetheless, a key challenge for future development lies in applying these adsorbents under real wastewater conditions, which are often highly complex. In such environments, multiple metal ions coexist and compete for active sites, frequently leading to significant reductions in adsorption performance.

In **Table 2**, which already includes application, the adsorption behavior indicates that the performance of the adsorbent at the laboratory scale cannot always be directly applied in practical implementation. Generally, the adsorbent also depends on environmental factors, where a sufficiently high adsorption capacity occurs under controlled environmental conditions. However, its adsorption efficiency can decrease quite significantly when implemented in real wastewater systems that have pH fluctuations, varying ionic strength, as well as the presence of competing adsorbates and dissolved organic matter. These factors can influence metal speciation and reduce the number of active sites on the adsorbent surface for adsorbate attachment.

In addition to adsorption efficiency, the large-scale implementation of adsorbents requires careful consideration of regeneration performance, operational stability, and long-term economic feasibility. Factors such as desorption efficiency, retention of adsorption capacity over multiple regeneration cycles, structural integrity, magnetic stability, and overall adsorbent lifespan are critical determinants of industrial applicability. Magnetic-based adsorbents offer significant advantages in terms of rapid separation using external magnetic fields, which can reduce operational costs associated with solid–liquid separation. However, repeated regeneration may result in partial loss of

magnetic properties or active adsorption sites, depending on the composite structure. Carbon-based adsorbents generally exhibit high adsorption performance and relatively good chemical stability, although their regeneration efficiency and synthesis costs may limit practical large-scale application. Biopolymer-based adsorbents represent a sustainable and environmentally friendly alternative; nevertheless, challenges related to structural degradation, mechanical stability, and performance retention during repeated adsorption–desorption cycles remain important considerations. Therefore, adsorption capacity alone should not be regarded as the sole criterion for evaluating adsorbent suitability, and regeneration behavior as well as long-term stability should be considered when assessing their industrial potential.

The numerous considerations can provide an option for selecting an adsorbent that is quite optimal, not only based on the maximum adsorption capacity value. Furthermore, with a little understanding of the adsorption mechanism in this study, it can also offer more rational insights for designing and choosing an appropriate adsorbent according to operational conditions. This approach also serves as a foundation in bridging the gap between laboratory-scale results and the application of adsorbents in industrial-scale wastewater treatment systems.

Table 2. Adsorption for various adsorbents

Type of Adsorbents	Adsorbent	Adsorbate	Model Isoterm	Adsorption Capacity (mg g^{-1})	Removal Efficiency (%)	pH	Time (min)	Temp. (°C)	Ref
Carbon-based	Carbon-based from Sawdust	Pb(II)	Langmuir	58.25	-	7	60	25	[12]
	Carbon-based from Acrylic Fabric	Pb(II)	Langmuir	31.25	-	7	60	-	[12]
	Carbon-based from Tire Powder	Pb(II)	Langmuir	50.48	-	7	60	-	[12]
	Carbon-based from Rice Husk	Pb(II)	Langmuir	59.73	-	7	60	-	[12]
	Activated Carbon Foam	Pb(II)	Sips	491	19.83	-	1440	-	[13]
		Cu(II)	Sips	247	73.99	-	1440	-	[13]
		Zn(II)	Sips		34.35	-	1440	-	[13]
		Cd(II)	Sips		59.82	-	1440	-	[13]
	AC/Fe3O4@SiO2-NH (1:0.5)	Pb(II)	Langmuir	86.2	-	5.2	1440	30	[14]
	AC/Fe3O4@SiO2-NH (1:0.25)		Langmuir	104.2	-	5.2	1440	30	[14]
	AC/Fe3O4@SiO2-NH (1:0.15)		Langmuir	89.3	-	5.2	1440	30	[14]
	Biochar (peanut shell)	Pb(II)	Freundlich	10.98	81	-	200	30	[15]
			Freundlich	11.25	72	-	200	40	[15]
			Freundlich	12.82	66	-	200	50	[15]
	Carbon Gel	Pb(II)	Freundlich	16.95	-	3-7	3-1440	25	[16]
		Cu(II)	Langmuir	6.64	-	3-7	3-1440	25	[16]
		Co	Langmuir	5.46	-	3-7	3-1440	25	[16]
		Ni	Langmuir	4.16	-	3-7	3-1440	25	[16]
	Carbon Gel-0.5 Gaphite Intercalation Compound	Pb(II)	Freundlich	16.95	-	3-7	3-1440	25	[16]
		Cu(II)	Langmuir	7.91	-	3-7	3-1440	25	[16]
		Co	Langmuir	7.97	-	3-7	3-1440	25	[16]
		Ni	Langmuir	4.57	-	3-7	3-1440	25	[16]
	Carbon Gel-1.0 Gaphite Intercalation Compound	Pb(II)	Langmuir	17.01	85.43	3-7	3-1440	25	[16]
		Cu(II)	Langmuir	7.54	-	3-7	3-1440	25	[16]
		Co	Freundlich	7.68	-	3-7	3-1440	25	[16]
		Ni	Langmuir	4.84	-	3-7	3-1440	25	[16]
	Carbon Gel-2.0 Gaphite Intercalation Compound	Pb(II)	Langmuir	17.7	98.92	3-7	3-1440	25	[16]
		Cu(II)	Langmuir	8.64	-	3-7	3-1440	25	[16]
		Co	Langmuir	7.86	-	3-7	3-1440	25	[16]
		Ni	Langmuir	5.03	-	3-7	3-1440	25	[16]
	Mesoporous	Pb(II)	Langmuir	196.34	-	8	20	25	[17]

Type of Adsorbents	Adsorbent	Adsorbate	Model Isoterm	Adsorption Capacity (mg g^{-1})	Removal Efficiency (%)	pH	Time (min)	Temp. (°C)	Ref
	Carbon Nitride Functionalized with Melamine-based Dendrimer Amine (MDA-MCN-1)	Cu(II)	Langmuir	199.75	-	8	3-1440	25	[17]
	Activated Carbon Prepared from Olive Branches	Pb(II)	Freundlich	41.32	-	5	1440	30	[30]
		Zn(II)	Freundlich	34.97	-	3	1440	30	[30]
		Cu(II)	Langmuir	43.1	-	5	1440	30	[30]
		Cd(II)	Freundlich	38.17	-	5	1440	30	[30]
	P-CMK-3	Pb(II)	Langmuir	145	-	5	1440	20	[18]
		Cu(II)	Langmuir	32	-	5	1440	20	[18]
		Zn(II)	Langmuir	35	-	5	1440	20	[18]
		Cd(II)	Langmuir	76	-	5	1440	20	[18]
	O-CMK-3	Pb(II)	Freundlich	176	-	5	1440	20	[18]
		Cu(II)	Langmuir	32	-	5	1440	20	[18]
		Zn(II)	Freundlich	67	-	5	1440	20	[18]
		Cd(II)	Freundlich	55	-	5	1440	20	[18]
	A-CMK-3	Pb(II)	Langmuir	245	-	5	1440	20	[18]
		Cu(II)	Langmuir	43	-	5	1440	20	[18]
		Zn(II)	Freundlich	53	-	5	1440	20	[18]
		Cd(II)	Freundlich	80	-	5	1440	20	[18]
	Graphene Oxide Modified with 2,2-dipyridylamine	Pb(II)	Langmuir	369.749	-	5	4	-	[31]
		Cd(II)	Langmuir	257.201	-	5	4	-	[31]
		Ni(II)	Langmuir	180.893	-	5	4	-	[31]
		Cu(II)	Langmuir	358.824	-	5	4	-	[31]
Biopolymer	Alginate-Chitosan (2:1)	Cd(II)	Langmuir	159.04	-	5	50	25	[32]
		Pb(II)	Freundlich	155.25	-	5	50	25	[32]
	Alginate-Chitosan (3:1)	Cd(II)	Langmuir	211.68	-	5	-	25	[32]
		Pb(II)	Sips	217.35	-	5	-	25	[32]
	Alginate-Chitosan (4:1)	Cd(II)	Langmuir	180.992	-	5	-	25	[32]
		Pb(II)	Freundlich	180.09	-	5	-	25	[32]
	Polylactic Acid/Hydroxyapatite-2.5 (PLA/Hap-2.5)	Pb(II)	Langmuir		100	7	2880	25	[33]
		As(II)	Freundlich		93	7	-	25	[33]
	Halloysite Nanotubes and Ball-milled Biochar (HNT-BC@Alg)	Cd(II)	Langmuir	6.96 ± 0.31	92.5	6.25	720	25	[19]
		Cu(II)	Freundlich	16.87 ± 1.50	95.01	6.25	720	25	[19]
		Ni(II)	Langmuir	2.85 ± 0.08	80.85	6.25	720	25	[19]
		Pb(II)	Langmuir	26.49 ± 2.04	99.05	6.25	720	25	[19]
	Core-shell Magnetic Chitosan Biopolymer	Pb(II)	Freundlich	111	-	6	10	30	[34]
		Cu(II)	Freundlich	33.3	-	6	10	30	[34]
	Biopolymer-clay Nanocomposite	Cu(II)	Langmuir	214.28	-	3	1440	25	[35]
Ma gnetic	$Cu_{0.50}Mg_{0.50}Fe_2O_4$ @SiO_2	Pb(II)	Langmuir	56.689	97	7	60	-	[20]
		Zn(II)	Langmuir	51.84	92	-	-	-	[20]

Type of Adsorbents	Adsorbent	Adsorbate	Model Isoterm	Adsorption Capacity (mg g^{-1})	Removal Efficiency (%)	pH	Time (min)	Temp. (^oC)	Ref
	Polyvinyl Alcohol-Barium Ferrite Nanoparticle	Pb(II)	Langmuir	3.9635	-	-	30-150	25	[36]
		Cd(II)	Langmuir	2.505	91.2	-	-	25	[36]
		Cu(II)	Langmuir	4.0551	100	-	-	25	[36]
	Polyvinyl Alcohol-Nickel Ferrite Nanoparticle	Pb(II)	Freundlich	4.662	83.47	-	-	-	[36]
		Cd(II)	Freundlich	1.0691	-	-	-	-	[36]
		Cu(II)	Freundlich	4.1385	99.05	-	-	-	[36]
	Fe_3O_4 In situ	Pb(II)	Freundlich	145.5	100	9	5	50	[37]
		Cd(II)	Freundlich	106.3	100	9	5	-	[37]
	$MnFe_2O_4$/GO Nanocomposite	Pb(II)	Langmuir	636.94	98.8	6	30-480	-	[21]
		NR Dye	Langmuir	46.08	94	6	30-480	-	[21]
	$NiFe_2O_4$	Cr(VI)	Langmuir	12.7	65	5	120	25	[22]
		As(V)	Langmuir	29.7	77	5	120	-	[22]
	Engineering Magnetic Cobalt Ferrite (CFO) Nanoparticles	Pb(II)	Freundlich	1382.74	97.76	-	30	25	[23]
	Engineering Magnetic Cobalt Ferrite (CFO) Microganules	Pb(II)	Freundlich	1951.98	77.02	-	-	-	[23]
	Fe_3O_4@MnO_2@Al_2O_3	Crystal Violet Dye	Langmuir	40.9682	99.311	12	60	-	[38]
		Cd(II)	Freundlich	48.5052	99.7296	6	-	-	[38]
	$CoFe_2O_4$-G	Pb(II)	Langmuir	142.8	-	5	-	37	[28]
		Cd(II)	Langmuir	105.26	-	7	-	-	[28]
	$NiFe_2O_4$-G	Pb(II)	Langmuir	111.1	-	5	-	-	[28]
		Cd(II)	Langmuir	74.62	-	7	-	-	[28]

In addition to adsorption efficiency, the large-scale implementation of adsorbents requires careful consideration of regeneration performance, operational stability, and long-term economic feasibility. Factors such as desorption efficiency, retention of adsorption capacity over multiple regeneration cycles, structural integrity, magnetic stability, and overall adsorbent lifespan are critical determinants of industrial applicability. Magnetic-based adsorbents offer significant advantages in terms of rapid separation using external magnetic fields, which can reduce operational costs associated with solid–liquid separation. However, repeated regeneration may result in partial loss of magnetic properties or active adsorption sites, depending on the composite structure. Carbon-based adsorbents generally exhibit high adsorption performance and relatively good chemical stability, although their regeneration efficiency and synthesis costs may limit practical large-scale application. Biopolymer-based adsorbents represent a sustainable and environmentally friendly alternative; nevertheless, challenges related to structural degradation, mechanical stability, and performance retention during repeated adsorption–desorption cycles remain important considerations. Therefore, adsorption capacity alone should not be regarded as the sole criterion for evaluating adsorbent suitability, and regeneration behavior as well as long-term stability should be considered when assessing their industrial potential.

The numerous considerations can provide an option for selecting an adsorbent that is quite optimal, not only based on the maximum adsorption capacity value. Furthermore, with a little understanding of the adsorption mechanism in this study, it can also offer more rational insights for designing and choosing an appropriate adsorbent according to operational conditions. This approach also serves as a foundation in bridging the gap between laboratory-scale results and the application of adsorbents in industrial-scale wastewater treatment systems.

3.3. Adsorption for Magnetic, Carbon-Based, and Biopolymer Composites Adsorbent

The results of a bibliometric analysis conducted using VOSviewer, which visualizes the mapping of keyword co-occurrence relationships in publications related to heavy metal adsorption (**Figure 1**). This visualization provides an overview of how research themes are interconnected and how the field has evolved over time. Each node on the map represents a keyword that appears in the analyzed publications, where the node size indicates the frequency of occurrence of that keyword across the literature. The connecting lines represent the strength of association

between keywords, while different colors indicate distinct thematic clusters that are interconnected based on the similarity of their research contexts.

Figure 1a shows a strong interrelation between adsorption and several major research directions, including the development of new materials, structural characterization, and process modeling. The green-colored nodes represent research themes focused on the removal of heavy metal ions through sorption processes using metal oxide-based materials such as ferrites. This theme emphasizes improving adsorption efficiency and the regeneration ability of the sorbent materials. The red-colored nodes correspond to studies related to nanoparticles, highlighting the importance of particle size, surface area, and porosity in determining adsorption capacity. Meanwhile, the blue-colored nodes focus more on adsorption kinetics and isotherm models, with keywords such as *Pb²⁺*, *Freundlich model*, and *adsorption kinetics* representing studies on the interaction mechanisms between metal ions and adsorbent surfaces. In addition, several nodes show keywords such as *Langmuir isotherm* and *carbon gel*, indicating more theoretical studies emphasizing adsorption equilibrium modeling and the development of high-porosity carbon-based materials. Other nodes, including *chitosan*, *biopolymer*, and *adsorptive membrane*, indicate research trends oriented toward the use of natural and environmentally friendly materials to enhance the simultaneous removal efficiency of heavy metal ions.

Figure 1b presents the temporal analysis of keywords based on publication years, illustrating research trends over the period from 2016 to 2024. Blue-colored nodes represent keywords that dominated earlier years, while yellow-colored nodes indicate more recent research topics. Early topics such as *Pb²⁺*, *adsorption process*, and *Freundlich model* dominated the initial period, reflecting a research focus primarily on the fundamental understanding of adsorption mechanisms. Over time, the trend shifted toward the development of new materials and technologies, as indicated by the appearance of keywords such as *nanoparticle*, *carbon gel*, and *adsorptive membrane* in the later period. This shift represents the evolution of research from fundamental approaches toward the application of advanced technologies based on nanoparticles and biopolymers to improve the performance and sustainability of the adsorption process.

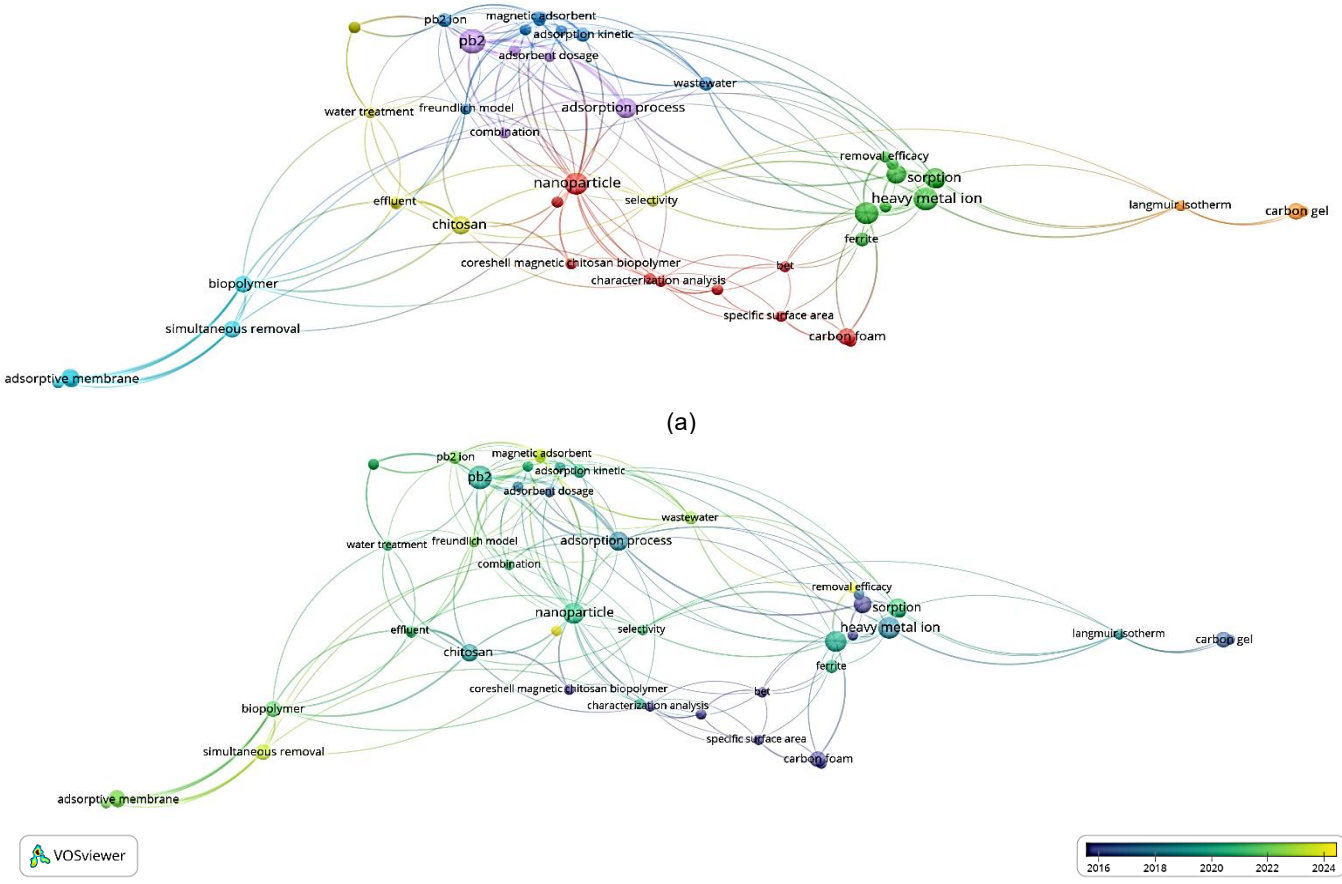

Figure 1. Keyword mapping of heavy metal adsorption research through bibliometric analysis (vosviewer)

Overall, the results of the VOSviewer analysis indicate that research on heavy metal adsorption has developed significantly and become increasingly complex. The focus of research has expanded beyond basic mechanistic studies toward the innovation of multifunctional materials with tunable structural and

chemical properties for specific adsorbate targets. Furthermore, the integration of experimental studies, advanced characterization, and adsorption modeling (both isotherm and kinetic) demonstrates a growing synergy between theoretical and practical aspects in optimizing the efficiency and sustainability of heavy metal adsorption processes.

Despite the substantial growth of research on heavy metal adsorption, the bibliometric mapping indicates that studies are predominantly focused on the development and optimization of individual adsorbent materials. The identified keyword clusters reveal strong research activity in magnetic nanoparticles, carbon-based materials, adsorption kinetics, and biopolymer-derived adsorbents; however, these topics are generally investigated as separate research domains. Consequently, comprehensive comparative assessments that systematically evaluate the relative strengths, limitations, and performance characteristics of different adsorbent classes remain limited in the existing literature.

The temporal evolution of keywords also suggests an increasing emphasis on multifunctional and sustainable adsorbent materials. Nevertheless, research trends remain largely centered on adsorption capacity enhancement and material synthesis, whereas aspects such as regeneration performance, operational stability, long-term reusability, and industrial-scale applicability receive comparatively less attention. These observations highlight important knowledge gaps and provide further justification for the present review, which critically compares magnetic, carbon-based, and biopolymer composite adsorbents not only in terms of adsorption performance but also with respect to their physicochemical properties, regeneration potential, and practical applicability for heavy metal remediation.

4. CONCLUSION

This systematic review shows that magnetic, carbon-based, and biopolymer adsorbents each offer specific strengths and limitations in heavy metal removal. Carbon-based adsorbents generally achieve high capacities due to their large surface areas, biopolymers provide sustainable alternatives but require modification to improve performance, and magnetic materials offer efficient separation with regeneration challenges that remain. The increasing development of hybrid composites that integrate these material classes reflects a clear research trend toward multifunctional adsorbents with enhanced effectiveness. Future work should focus on scalable and sustainable synthesis, improved long-term stability, and comprehensive evaluation under real wastewater conditions to support their practical implementation in industrial treatment systems.

This study highlights the importance of adsorption mechanisme alongside maximum adsorption capacity when evaluating adsorbent performance. The analysis shows that adsorbents with a large surface area do not always provide the best adsorption performance if not supported by suitable active sites. Conversely, adsorbents with a relatively low surface area can exhibit a higher maximum adsorption capacity when accompanied by stronger interactions between the adsorbate and the adsorbent.

The combination of carbon material, biopolymer, and magnetic material in the form of composites can synergistically combine the advantages of each. Carbon plays a role in providing a large surface area and good diffusion pathways, biopolymers offer active sites used for interacting with adsorbates, while magnetic materials facilitate separation and regeneration. These composite materials become one of the strategies with the potential to produce highly effective, environmentally friendly, and operationally applicable adsorbents.

However, this study was still conducted at a laboratory scale using synthetic solutions, so the reported adsorbent performance has not yet fully reflected real environmental wastewater conditions. The presence of competing ions, dissolved organic matter, and pH fluctuations can significantly affect adsorption efficiency. In additon, adsorbent fouling caused by suspended organic compounds may decrease the accessibility from active sites and reduce long-term adsorption stability. Therefore, future research should focus on evaluating under real environmental conditions, including metal competition systems, fouling resistance, long-term operational stability and regeneration tests.

This study not only compares the performance of different adsorbents with quantitative data but also presents a conceptual framework for future adsorbent development. It aims to bridge the gap between laboratory research and industrial applications, especially in effective wastewater treatment.

5. AUTHOR'S DECLARATION

5.1. Supporting Information

There is no supporting information in this paper. The data supporting this research's findings are available on request from the corresponding author (R.Basuki).

5.2. Acknowledgements

The authors sincerely acknowledge the financial support provided by the Department of Chemistry, Republic of Indonesia Defense University. The authors also extend their gratitude for the facilities and laboratory resources made available by the Defense University.

5.3. Conflict of Interest

The author declare no conflict of interest in this publication.

5.4. Author Contributions

SN performed the conceptualization, investigation, methodology, writing original draft, review & editing. RB supervises the experiment, data calculation, and revise the manuscript. MFPK collaborated on writing and revising the manuscript. All authors approved the final version of the manuscript.

5.5. AI Statement

Trinka AI was utilize to enhance the clarity, grammar, and overall readability of this manuscript. All technical content, data interpretation, and conclusion were solely developed and verified by the authors. The final version of the manuscript was thoroughly reviewed to ensure accuracy, coherence, and aligment with the study's findings.

6. REFERENCES

[1] Sekarwati, N. and Murachman, B. 2014. Dampak logam berat Cu (Tembaga) dan Ag (Perak) pada limbah cair industri perak terhadap kualitas air sumur dan kesehatan masyarakat serta upaya pengendaliannya di Kota Gede Yogyakarta. *Ekosains*. 7(1). Doi: https://doi.org/10.47317/JKM.V9I1.242

[2] Rasmito, A. 2018. Penurunan kadar logam berat limbah cair industri emas dengan kaustik soda. *JTIK*. 1(2). 16–29. Doi: https://doi.org/10.54980/jtik.v1i2.27

[3] Kusumawati, E., Jayanti, R.D., Putri, L.H., Annisa, N. and Paramitha, T. 2024. Evaluasi dan modifikasi alat penukar ion dengan penambahan kolom adsorpsi karbon aktif untuk menurunkan kesadahan. *Kovalen*. 10(1). 1–10. Doi: https://doi.org/10.22487/kovalen.2024.v10.i1.16556

[4] Susanty, S. and Bachmid, F. 2016. Perbandingan Metode Ekstraksi Maserasi dan Refluks terhadap Kadar fenolik dari ekstrak tongkol jagung (*Zea mays* L.). *J. Konversi*. 5(2). 87–92. Doi: https://doi.org/10.24853/konversi.5.2.87-92

[5] Takarani, P., Novita, S.F. and Fathoni, R.A. 2019. Pengaruh massa dan waktu adsorben selulosa dari kulit jagung terhadap konsentrasi penyerapan. *Semin. Nas. Rekayasa Trop.* 2(1). 117–121.

[6] Samadi, A., Wang, Z., Wang, S., Nataraj, S.K., Kong, L. and Zhao, S. 2023. Polyaniline-Based adsorbents for water treatment: roles of low-cost materials and 2D materials. *Chem. Eng. J.* 478. 147506. Doi: https://doi.org/10.1016/j.cej.2023.147506

[7] Bao, S., Yang, W., Wang, Y., Yu, Y. and Sun, Y. 2020. One-Pot synthesis of magnetic graphene oxide composites as an efficient and recoverable adsorbent for cd(ii) and pb(ii) removal from aqueous solution. *J. Hazard. Mater.* 381. 120914. Doi: https://doi.org/10.1016/j.jhazmat.2019.120914

[8] Luo, X., Lei, X., Cai, N., Xie, X., Xue, Y. and Yu, F. 2016. Removal of heavy metal ions from water by magnetic cellulose-based beads with embedded chemically modified magnetite nanoparticles and activated carbon. *ACS Sustain. Chem. Eng.* 4(7). 3960–3969. Doi: https://doi.org/10.1021/acssuschemeng.6b00790

[9] Zheng, X., Zheng, H., Xiong, Z., Zhao, R., Liu, Y., Zhao, C. and Zheng, C. 2020. Novel anionic polyacrylamide-modify-chitosan magnetic composite nanoparticles with excellent adsorption capacity for cationic dyes and pH-independent adsorption capability for metal Ions. *Chem. Eng. J.* 392. 123706. Doi: https://doi.org/10.1016/j.cej.2019.123706

[10] Awad, A.M., Jalab, R., Benamor, A., Nasser, M.S., Ba-Abbad, M.M., El-Naas, M. and Mohammad, A.W. 2020. Adsorption of organic pollutants by nanomaterial-based adsorbents: an overview. *J. Mol. Liq.* 301. 112335. Doi: https://doi.org/10.1016/j.molliq.2019.112335

[11] Zhai, L., Zheng, X., Liu, M., Wang, X., Li, W., Zhu, X., Yuan, A., Xu, Y. and Song, P. 2023. Tuning surface functionalizations of uio-66 towards high adsorption capacity and selectivity eliminations for heavy metal ions. *Chem. Eng. J. 154*. 110937. Doi: https://doi.org/10.1016/j.inoche.2023.110937

[12] Song, M., Wei, Y., Cai, S., Yu, L., Zhong, Z. and Jin, B. 2018. Study on adsorption properties and mechanism of Pb^{2+} with different carbon-based adsorbents. *Sci. Total Environ*. 618. 1416–1422. Doi: https://doi.org/10.1016/j.scitotenv.2017.09.268

[13] Lee, C.G., Jeon, J.W., Hwang, M.J., Ahn, K.H., Park, C., Choi, J.W. and Lee, S.H. 2015. Lead and copper removal from aqueous solutions using carbon foam derived from phenol resin. *Chemosphere*. 130. 59–65. Doi: https://doi.org/10.1016/j.chemosphere.2015.02.055

[14] Fu, R., Liu, Y., Lou, Z., Wang, Z., Baig, S.A. and Xu, X. 2016. Adsorptive removal of Pb(II) by magnetic activated carbon incorporated with amino groups from aqueous solutions. *J. Taiwan Inst. Chem. Eng*. 62. 247–258. Doi: https://doi.org/10.1016/j.jtice.2016.02.012

[15] Natrayan, L., Kaliappan, S., Dheeraj Kumar Reddy, C.N., Karthick, M., Sivakumar, N.S., Patil, P.P., Sekar, S. and Thanappan, S. 2022. Development and characterization of carbon-based adsorbents derived from agricultural wastes and their effectiveness in adsorption of heavy metals in waste water. *Bioinorg. Chem. Appl.* 2022. Doi: https://doi.org/10.1155/2022/1659855

[16] Osińska, M. 2017. Removal of Lead(II), Copper(II), Cobalt(II) and Nickel(II) ions from aqueous solutions using carbon gels. *J. Sol-Gel Sci. Technol.* 81(3). 678–692. Doi: https://doi.org/10.1007/s10971-016-4256-0

[17] Anbia, M. and Haqshenas, M. 2015. Adsorption studies of Pb(II) and Cu(II) ions on mesoporous carbon nitride functionalized with melamine-based dendrimer amine. *Int. J. Environ. Sci. Technol.* 12(8). 2649–2664. Doi: https://doi.org/10.1007/s13762-015-0776-3

[18] Barczak, M., Michalak-Zwierz, K., Gdula, K., Tyszczuk-Rotko, K., Dobrowolski, R. and Dąbrowski, A. 2015. Ordered mesoporous carbons as effective sorbents for removal of heavy metal ions. *Microporous Mesoporous Mater.* 211. 162–173. Doi: https://doi.org/10.1016/j.micromeso.2015.03.010

[19] Hassan, M., Liu, Y., Naidu, R., Du, J., Qi, F., Donne, S.W. and Islam, M.M. 2021. Mesoporous biopolymer architecture enhanced the adsorption and selectivity of aqueous heavy-metal ions. *ACS Omega.* 6(23). 15316–15331. Doi: https://doi.org/10.1021/acsomega.1c01642

[20] Irfan, M., Arif, A., Munir, M.A., Naz, M.Y., Shukrullah, S., Rahman, S., Jalalah, M. and Almawgani, A.H.M. 2023. Statistically analyzed heavy metal removal efficiency of silica-coated $Cu_{0.5}Mg_{0.5}Fe_2O_4$ magnetic adsorbent for wastewater treatment. *ACS Omega.* 8(50). 47623–47634. Doi: https://doi.org/10.1021/acsomega.3c05764

[21] Katubi, K.M.M., Alsaiari, N.S., Alzahrani, F.M., Siddeeg, S.M. and Tahoon, M.A. 2021. Synthesis of manganese ferrite/graphene oxide magnetic nanocomposite for pollutants removal from water. *Processes*. 9(4). Doi: https://doi.org/10.3390/pr9040589

[22] Hassan, A.A., Fahim, Y.A. and Ali, M.E.M. 2025. Efficient removal of Cr(VI) and As(V) from aqueous solution using magnetically separable nickel ferrite nanoparticles. *J. Cluster Sci.* 36(4). Doi: https://doi.org/10.1007/s10876-024-02736-4

[23] Ansari, S.M., Kashid, V., Sinha, B.B., Sen, D., Kolekar, Y.D. and Ramana, C.V. 2023. Synthesis, characterization and performance evaluation of magnetic nanostructured $CoFe_2O_4$ for adsorption removal of Contaminant Heavy Metal Ions. *Appl. Ferrites.* Doi: https://doi.org/10.5772/intechopen.1002349

[24] Busroni, Anwar, C. and Santosa, S.J. 2023. Penjerapan Kation Fe^{3+} dan Pb^{2+} Menggunakan TBKA dan TBMTKA sebagai bahan penjerap: kajian variasi pH, kapasitas adsorpsi, dan waktu kontak. *Indones. J. Chem.* 24(1). 50–57. Doi: https://doi.org/10.55981/jtl.2023.242

[25] Perdana, A., Zarkasi, A., Hamdani, D., Inu Natalisanto, A., Munir, R., Barong Tongkok, J., Kelua, G., Samarinda Ulu, K. and Timur, K. 2023. Karakteristik adsorben ampas teh dalam menyerap ion logam timbal menggunakan model isoterm langmuir. *J. Ilmu Inov. Fis.* 7(1). Doi: https://doi.org/10.24198/jiif.v7i1.42746

[26] Ramadhan, M.D., Iriany, Misran, E. and Turmuzi, M. 2021. Studi model isoterm adsorpsi kristal violet oleh biosorben kulit ubi kayu (*Manihot esculenta*). *J. Tek. Kim. USU*. 10(1). 38–44. Doi: https://doi.org/10.32734/jtk.v10i1.5485

[27] Nurhidayati, I., Enriyani, R. and Maimulyanti, A. 2020. Pengaruh pH, waktu kontak, dan kecepatan pengadukan pada adsorpsi fosfat oleh sedimen. *J. Ris. Kim.* 44(1). 16–19.

[28] Santhosh, C., Kollu, P., Felix, S., Velmurugan, V., Jeong, S.K. and Grace, A.N. 2015. $CoFe_2O_4$ and $NiFe_2O_4$@graphene adsorbents for heavy metal ions: kinetic and thermodynamic analysis. *RSC Adv.* 5(37). 28965–28972. Doi: https://doi.org/10.1039/c5ra02905h

[29] Saraswati, N.L.P.A. 2022. Pengaruh suhu aktivasi arang terhadap kondisi equilibrium dan parameter termodinamika

adsorpsi senyawa remazol red. *J. Kim.* 16(3). 40–47. Doi: https://doi.org/10.23887/wms.v16i3.54629

[30] Alkherraz, A.M., Ali, A.K. and Elsherif, K.M. 2020. Removal of Pb(II), Zn(II), Cu(II) and Cd(II) from aqueous solutions by adsorption onto olive branches activated carbon: equilibrium and thermodynamic studies. *Sci. Rev. Chem. Commun.* 1. 11–20. Doi: https://doi.org/10.5281/zenodo.2579465

[31] Zare-Dorabei, R., Ferdowsi, S.M., Barzin, A. and Tadjarodi, A. 2016. Highly efficient simultaneous ultrasonic-assisted adsorption of Pb(II), Cd(II), Ni(II) and Cu(II) ions from aqueous solutions by graphene oxide modified with 2,2′-Dipyridylamine: central composite design optimization. *Ultrason. Sonochem.* 32. 265–276. Doi: https://doi.org/10.1016/j.ultsonch.2016.03.020

[32] Hamza, M.F., Hamad, N.A., Hamad, D.M., Khalafalla, M.S., Abdel-Rahman, A.A.H., Zeid, I.F., Wei, Y., Hessien, M.M., Fouda, A. and Salem, W.M. 2021. Synthesis of eco-friendly biopolymer alginate-chitosan composite to adsorb the heavy metals Cd(II) and Pb(II) from contaminated effluents. *Materials.* 14(9). Doi: https://doi.org/10.3390/ma14092189

[33] Shokri, E., Khanghahi, B., Esmizadeh, E. and Etemadi, H. 2022. Biopolymer-based adsorptive membrane for simultaneous removal of cationic and anionic heavy metals from water. Int. *J. Environ. Sci. Technol.* 19(5). 4167–4180. Doi: https://doi.org/10.1007/s13762-021-03592-9

[34] Beyki, M.H., Miri, S., Shemirani, F., Bayat, M. and Ranjbar, P.R. 2016. A New derivative of core-shell magnetic chitosan biopolymer: synthesis, characterization and application for adsorption of lead and copper ions. *Clean Soil Air Water.* 44(6). 710–719. Doi: https://doi.org/10.1002/clen.201400244

[35] Güney, B.C. and Arslan, Y. 2023. Removal of Cu(II) by biopolymer-clay nanocomposite adsorbent. *React. Kinet. Mech. Catal.* 136(1). 433–448. Doi: https://doi.org/10.1007/s11144-022-02340-5

[36] Manimozhi, V., Saravanathamizhan, R., Sivakumar, E.K.T. and Jaisankar, V. 2020. Adsorption study of heavy metals removal from wastewater using PVA-nano ferrite composites. *Int. J. Nanosci. Nanotechnol.* 16(3). 189–200.

[37] Vicente-Martínez, Y., Arroniz-Lázaro, A., Hernández-Córdoba, M. and López-García, I. 2024. Use of in-situ synthesized magnetic ferrite to remove heavy metals from waters. *Green Anal. Chem.* 8. Doi: https://doi.org/10.1016/j.greeac.2023.100089

[38] Mokif, L.A., Obaid, Z.H. and Juda, S.A. 2024. Synthesis of new composite adsorbents for removing heavy metals and dyes from aqueous solution. *J. Ecol. Eng.* 25(6). 164–179. Doi: https://doi.org/10.12911/22998993/187148