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Removal of heavy metals in industrial wastewater using adsorption technology: Efficiency and influencing factors

Fernando García Ávila [a,b], Janneth Cabrera-Sumba [a], Sandra Valdez-Pilataxi [a], Jessica Villalta-Chungata [a], Lorgio Valdiviezo-Gonzales [c,*], Cecilia Alegria-Arnedo [d]

[a] Universidad de Cuenca, Chemical Sciences Faculty, Cuenca, Ecuador

[b] Environmental Risk Assessment Group in Production and Services Systems (RISKEN), Universidad de Cuenca, Ecuador

[c] Universidad Tecnológica del Perú, Facultad de Ingeniería Industrial, Lima, Peru

[d] Departamento Académico de Química, Universidad Nacional Agraria La Molina, Peru

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ABSTRACT

Most industries are responsible for environmental pollution because their wastewater contains heavy metals that are hazardous. These metals tend to persist indefinitely in the environment, compromising not only human health but also the well-being of ecosystems. The objective of this study was to analyze the adsorption technology for removing heavy metals in industrial wastewater, evaluating influencing factors, adsorbent materials, applied isotherms and their advantages, through a systematic review of the scientific literature of the last 10 years. To conduct this research, the Scopus digital database was consulted. The search was conducted using a systematic review methodology and the PICO framework to identify, analyze, and interpret data on adsorption technology, factors influencing adsorption, the efficiency of different materials used as adsorbents, and the advantages and disadvantages of adsorption isotherms. To filter the information, the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement were followed, which allowed the articles to be selected to answer the research questions posed in this study. Based on the results, it was found that the factors influencing the adsorption of heavy metals include pH (range of 3–9), contact time (range of 10–14,400 min), adsorbent dosage (0.011–20 g/L), temperature (25–30 °C), particle size, and agitation speed (100–800 ppm). Among the most efficient adsorbents are acacia cellulose lignin with 99.8% Cr, bentonite clay with 99% Cu, 96% Cd, and 99% Pb, modified sugarcane bagasse with 96.9% Cu, and activated carbon with 82.8% Cr at pH 3. The least efficient adsorbents are natural moss (54.5% Cr) and biochar from corn husks (20% Cr). The Freundlich isotherm model is the most used, and it can vary depending on the type of adsorbent, the correlation coefficient fit, and the type of heavy metal being treated. Finally, the advantages and limitations of some adsorbents are presented, primarily highlighting their low costs, reusability, and the sustainability they can offer in reducing environmental pollution.

1. Introduction

Currently, the pollution of both surface and groundwater is one of the most alarming issues due to the degradation of this natural resource caused by population growth, making it a global problem (Vera et al., 2016; García-Ávila et al., 2021). Most of the heavy metal contamination is due to anthropogenic activities, primarily industrial ones, as they constantly use metals that are highly toxic pollutants, which increase their concentration in water (Subramaniyam et al., 2022; Ni'mah et al., 2024). Among the wastes that pose the greatest risk to both human health and ecosystem balance are heavy metals (García-Céspedes et al., 2016), due to their toxicity, which depends on their mobility in the environment, persistence, chemical variation, and tendency to bioaccumulate in the environment (Rubio et al., 2015).

The United States Environmental Protection Agency considers several metals, such as beryllium and mercury, as hazardous due to their use in industrial sectors. This also includes cadmium, lead, chromium, copper, manganese, nickel, cobalt, zinc, and tin (Younas et al., 2021;

* Corresponding author.
E-mail addresses: garcia10f@hotmail.com (F.G. Ávila), janneth.cabrera@ucuenca.edu.ec (J. Cabrera-Sumba), sandra.valdez@ucuenca.edu.ec (S. Valdez-Pilataxi), jessicaa.villalta@ucuenca.edu.ec (J. Villalta-Chungata), lvaldiviez@utp.edu.pe (L. Valdiviezo-Gonzales), calegria@lamolina.edu.pe (C. Alegria-Arnedo).

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Mariana et al., 2021). The World Health Organization (WHO) established that metal ion concentrations should range between 0.01 and 1 ppm in water; however, current concentrations of heavy metal ions can reach up to 450 ppm in effluents (Tejada-Tovar et al., 2015).

Among the various effects that heavy metals can have on humans at high concentrations are conditions ranging from damage to vital organs to the development of cancer (Reyes et al., 2016). However, in the environment, they can subtly accumulate to toxic concentrations for plant and animals, and in soils, they can persist for hundreds or thousands of years (Juárez, 2006). Different traditional treatment methods have been proposed, such as coagulation, membrane separation, chemical precipitation, ion exchange, electrochemical methods, enhanced oxidation, and biological treatment (Bayuo et al., 2023; Venäläinen, 2023), as well as coagulation and reverse osmosis (Khoshraftar et al., 2023). However, these methods are very expensive, complex, and time-consuming for metal removal (Carolin et al., 2017). On the other hand, the adsorption method is simpler in operational conditions, has a wide pH range, and a high capacity for binding metals (Sarria-Villa et al., 2020). Comparatively, the adsorption process is preferred for wastewater treatment due to its convenience, simplicity of operation, and low cost (Kainth et al., 2024; Arbabi et al., 2015).

Heavy metals are one of the contaminants that exhibit the greatest resistance to treatment in wastewater treatment plants (WWTPs) (Sánchez Peña, 2019). Adsorption is a method used for the removal of heavy metals present in either drinking water or industrial and municipal wastewater discharges (Mzinyane, 2022; Sharifian et al., 2023). Adsorption is a phenomenon that involves the migration of certain substances from the gaseous or liquid phase to the surface of a solid substrate (Sarria-Villa et al., 2020). The efficiency of adsorption processes depends on several factors, such as the type, quantity, surface composition, and physicochemical characteristics of the adsorbent, as well as the chemical nature and concentration of the adsorbate (Bedova-Betancur et al., 2023; Dey et al., 2022).

The most important step in the adsorption process is selecting an adsorbent with high adsorption capacity, abundance, and low cost (Ozeken et al., 2023; Aktar et al., 2023), which does not produce secondary pollution and is environmentally friendly (Khosravi et al., 2020). Additionally, there are various types of sorbents with large surface areas, microporous characteristics, and specific surface chemical properties (e.g., minerals, organic, or biological), such as zeolites, industrial by-products, agricultural waste, biomass, and polymeric materials (AlJaberi and Mohammed, 2018; Cheng et al., 2021).

The industries that contribute most to heavy metal pollution include mining, electroplating, metallurgy, pigment production, and ceramics, all of which use metals such as Pb(II), Ni(II), and Arsenic (Ahmad and Mirza, 2018; Zhi et al., 2023). The plastics, paint, and textile industries use Cr in their processes (Hussain et al., 2022; Putra et al., 2024). The nickel-cadmium battery manufacturing, anti-corrosive agents, and pigment industries use Cd extensively in their processes (Huda et al., 2023). Industries have the primary obligation to minimize or prevent negative impacts on the environment through the treatment of wastewater before discharging it (Niño et al., 2013).

Additionally, treating contaminated water allows industries to recover part of their water for use in other processes within their facilities (Murali et al., 2021). The objective of this work is to analyze, through an exhaustive review of various scientific articles from the Scopus digital database, the adsorption technology for the treatment of wastewater containing heavy metals produced by industries over the last 10 years.

Table 1
Description of the PICO system components.

Population	Industries that work with heavy metals for the manufacturing of products and by-products.
Intervention	Implementation of conventional technology "Adsorption" to remove heavy metals from industrial wastewater.
Comparison	Different types of materials used as adsorbents for the removal of heavy metals in industrial wastewater.
Results	Effectiveness and feasibility of conventional technology "Adsorption" in the removal of heavy metals from industrial wastewater.

This analysis allowed to investigate the application of adsorption technology for the removal of heavy metals in industrial wastewater, evaluating the key factors influencing its effectiveness, the most used adsorbent materials and their respective removal capacities. To this end, the efficiency of different adsorbent materials was analyzed, the most used adsorption isotherms were identified, and the advantages and limitations of their application in various industrial contexts were examined. These issues were addressed through a systematic review of recent scientific literature.

This review is crucial for the field of heavy metal removal in industrial wastewater, as it provides a systematic analysis of adsorption technologies and the factors influencing their efficiency. By following the PRISMA methodology, it is ensured that the information collected is of high quality and relevant, which can guide future research and practice in pollutant management. Unlike other studies that may focus on a single type of adsorbent or a specific context, this article covers a variety of adsorbent materials, including biomass, and evaluates their efficiency under a wide range of experimental conditions. Furthermore, it focuses on the sustainability and reusability of adsorbents, aspects that are not always considered in previous research, making it more relevant in the current context of environmental concerns.

2. Methodology

To carry out the review process, the methodology of systematic review of scientific literature was employed. This rigorous approach begins with the collection of information generated by various researchers on a specific topic or question. The selection of studies is carried out with the aim of minimizing biases considering aspects such as: delimitation of the topic, selection and specification of keywords, the range of publication years, and the databases to consult. This process ensures the acquisition of reliable and quality information.

To ensure an accurate systematic review, the guidelines established in the PRISMA statement (Preferred Reporting Items for Systematic reviews and Meta-Analyses), published in 2009, were followed. The main purpose of this guide is to assist different authors in improving the quality of their publications and transparently document the information that is essential for conducting a systematic review.

The systematic review was carried out following a specific strategy in which the main topic to be investigated was defined (industrial wastewater); the intervention (removal of heavy metals) and the expected outcome (adsorption technology). This strategy allowed for formulating key questions that guided the research in a precise and effective manner.

2.1. Protocol and focus questions

When defining the research questions for this systematic review, the PICO framework developed by Tobi et al. (2019) was adopted, and the PRISMA model proposed by García-Peñalvo (2022) was followed. The PICO method has become established as an effective strategy for formulating research questions in order to achieve greater specificity and conceptual clarity when conducting the systematic review (García-Ávila et al., 2023). In other words, this methodology facilitates the search and selection of relevant and high-quality information based on solid evidence.

The method structures the research questions in the systematic review through four important components: Population (Problem), Intervention, Comparison, and Results. Population/Problem: Defines the population or the problem of interest for the study, considered as the dependent variable, representing what is affected by the intervention. In other words, it refers to: What is the problem or the study population? Intervention: This is the independent variable that describes the action

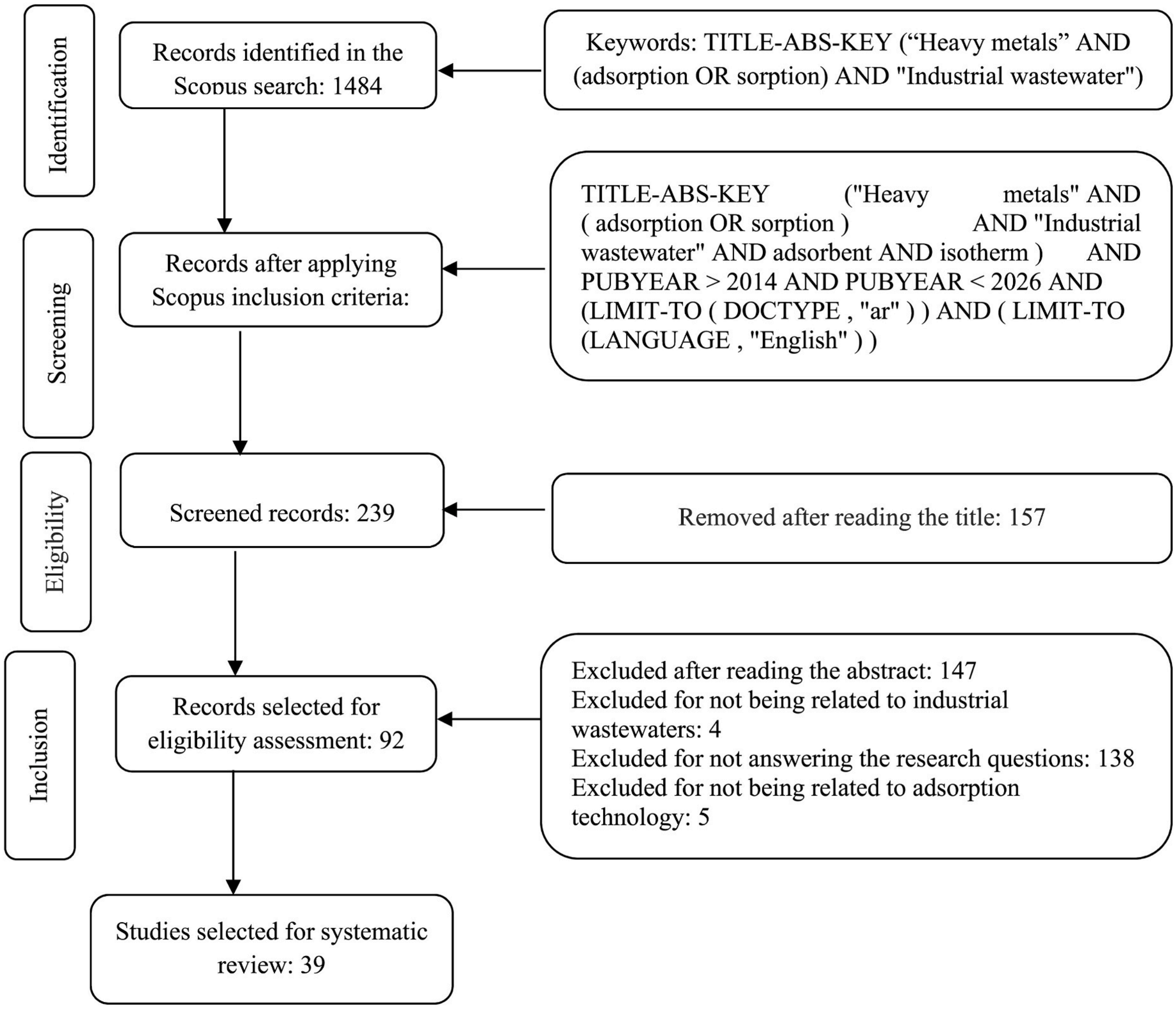

Fig. 1. Diagram of the process for searching information articles.

or change being evaluated in relation to the population or problem in question. In other words, it refers to: What action or change is being evaluated in relation to the population/problem? Comparison: This variable focuses on identifying whether there is an alternative to the intervention to the study. In other words, it refers to: Is there an alternative to the evaluated intervention? Results: This variable refers to the measures used to determine the impact or effectiveness of the intervention in relation to the problem. In other words, it refers to: What are the relevant outcomes being evaluated? The application of the PICO strategy was carried out, and the results are presented in Table 1, which details each component of the research question and its relation to the study conducted.

2.1.1. *Research questions*

Based on the PICO strategy, the following questions were formulated:

1. What are the factors influencing the adsorption of heavy metals from industrial wastewater?
2. What is the effectiveness of different materials used as adsorbents in the removal of heavy metals from industrial wastewater?
3. What is the most commonly used adsorption isotherm for the removal of heavy metals in industrial wastewater, and what are its advantages and limitations when applied in different industrial contexts?

2.2. *Research process*

To carry out this research, a series of defined steps were followed to ensure its rigor and quality, including: (1). Define the topic for the systematic review, clearly establishing the scope and boundaries of the research. (2). Establish and determine the keywords directly related to the study topic; these keywords were essential for the subsequent information search. (3). Screen the publication year of the found articles to investigate information using the databases. This stage allowed limiting the search to the most current and relevant information for the research. This step ensured that only relevant and pertinent information was included for the objectives of this systematic review. (4). Filter the information to ensure a high-quality and reliable review that meets the standards required for this research.

After conducting the aforementioned process, the obtained results were analyzed to draw meaningful conclusions and meet the quality standards required for this research.

2.3. *Initial search*

To begin the search in the Scopus digital database, the following keywords were used: "Removal of heavy metals" AND (adsorption OR sorption) AND "Industrial wastewater", which provided a total of 1484 articles related to the topic. To obtain better results, filters were applied to identify articles that address the research questions proposed in this work. Below, the search guidelines based on the PRISMA methodology,

Table 2
Adsorbent or bioadsorbent materials used for the Adsorption of heavy metals from industrial wastewater.

Type of Adsorbent	Precursor Material
Living Organisms	- Natural moss (Ozeken et al., 2023). - *Escherichia coli* (*E. coli*) (Khosravi et al., 2020). - Methylobacterium hispanicum (Jeong et al., 2019). - Microalga Spirulina platensis (Malakootian et al., 2016). - Green algae (Birungi and Chirwa, 2015). -Filamentous green algae Spirogyra porticalis (Sayyaf et al., 2016).
Biomasses	- Coffee pulp (Gomez-Aguilar et al., 2020). - Mulberry leaf (Mangood et al., 2023). - Pistachio shell (Beidokh ti et al., 2019). - Rice husk (Sanka et al., 2020). - Corn husk (Sanka et al., 2020). - Watermelon rind (Li et al., 2019a). - Porous carbon derived from biospecies (Li et al., 2019b). - Platanus orientalis bark (Akar et al., 2019). - Sugarcane bagasse (Gupta et al., 2018). - Pine sawdust (Elboughdiri et al., 2021). - Banana peel (Mohd Salim et al., 2016). - Mangifera seed shell (Kose et al., 2015). - Corn cobs (Jin et al., 2019).
Biopolymers	- Gum arabic (Shalikh and Majeed, 2022). - Palm cellulose copolymer (Rahman et al., 2020). - Chelating ligand of poly (hydroxamic acid) - poly (amidoxime) from acacia cellulose grafted with poly (methyl acrylate-co-acrylonitrile) (Rahman et al., 2016). - Polyethyleneimine (PEI) modified nanocellulose cross-linked with magnetic bentonite (Sun et al., 2022).
Activated Carbons	- Activated carbon extracted from pineapples (Saleh Ibrahim et al., 2022). - Activated carbon extracted from sugarcane bagasse (Gupta et al., 2018). - Activated carbon (Sajjad et al., 2017). - Activated carbon from mixed waste (ALOthman et al., 2016).
Chemical Modification	- Kaolin modified by calcination with NaOH NaOH (Yang et al., 2018). - Nanocellulose modified with polyethyleneimine (PEI) cross-linked with magnetic bentonite (Sun et al., 2022).
Other materials	- Magnetic biochar (MBN3) (Noor et al., 2023). - Porous flocculant particles from coal fly ash residues (MFCA) (Hussain et al., 2022). - Bentonite clay (Maleki et al., 2019). - Iranian sepiolite (Hojati and Landi, 2015). - Copper oxide (CuO) (Kondabey et al., 2019) - Plant ashes and dielectrophoresis (Jin et al., 2019). - Mixture of solid waste (RS) with Clinoptilolite (CL) modified in a 10:1 ratio (Aljerf, 2018). - Vermiculite mixed with chitosan (Prakash et al., 2017). - Ethylene and polyurethane sorbent (PES) (Iqbal et al., 2017). - Vinyl acetate sorbent (VAS) (Iqbal et al., 2017) - Magnetite nanoparticles (Sosun et al., 2022). - Humic acid on a chitosan-crosslinked silica gel surface (SiChiHA) (Prasetyo and Toyoda, 2023). - Macroporous terpolymer of glycidyl methacrylate (GMA), methyl methacrylate (MMA), and divinylbenzene (DVB) (Yayayürük and Erdem Yayayürük, 2016). - Wax debris with magnetite nanoparticles (Arbabi et al., 2018). - Modified clinoptilolite (CL) (Aljerf, 2018).

as well as the exclusion criteria for some documents, are detailed.

2.4. Systematic search based on the PRISMA statement

The search was conducted in the Scopus database. The combination of keywords that yielded the best results was: (TITLE-ABS-KEY ("Removal of heavy metals" AND (adsorption OR sorption) AND "Industrial wastewater")). This combination resulted in 1484 articles in the Scopus digital database. Initially, this number of articles was obtained because inclusion criteria were not applied in the search. Scopus: It is a bibliographic database of abstracts and citations from scientific journal articles with quality web content, created by Elsevier and launched in 2004 (Guz and Rushchitsky, 2009).

Prior to the selection of articles, certain inclusion and exclusion criteria were established.

2.5. Inclusion criteria

In the present research, inclusion criteria were established to define the boundaries of the review, aiming to focus on specific studies and research, thereby ensuring that this systematic review is reliable. The inclusion criteria pertinent to the research questions are as follows:

- The keywords used in the search must appear in the title and abstract of the article.
- The studies must be directly related to the removal of heavy metals through adsorption technology.
- The studies must be related to the treatment of industrial wastewater.
- The studies must address the efficiency of different adsorbent materials, adsorption isotherms, and factors influencing the removal of heavy metals in an industrial context.
- The articles must be published between 2014 and 2024.
- The language of the articles to be reviewed must be limited to English.
- The studies were analyzed across a broad geographical scope.

2.6. Exclusion criteria

The following exclusion criteria were established for the research

Table 3
Factors influencing the adsorption of heavy metals in industrial wastewaters. Where: T: Contact Time, D: Adsorbent or bioadsorbent dose, temp: Temperature, Tp: Particle Size, Va: Stirring speed.

Heavy metals removed	Type of adsorbent	Factors influencing adsorption						Authors
		pH	t	D	T	Tp	Va	
Cu (II)	-Natural moss	5	360 min	5 g/L	25 °C	180 μm	350 rpm	(Ozeken et al., 2023; Mangood et al., 2023; Hussain et al., 2022; Maleki et al., 2019; Gupta et al., 2018; Sun et al., 2022; Yayayürük and Erdem Yayayürük, 2016; ALOthman et al., 2016)
	-Powdered mulberry leaf	7	60 min	0.8 g/L	25 °C	–	300 rpm	
	-Flocculating porous particles from coal fly ash residues (MFCA)	5	60 min	1 g/L	30 °C	50 nm	180 rpm	
	-Bentonite clay	7	120 min	0.05 g/L	25 °C	200 nm	150 rpm	
	-Sugarcane bagasse (SG), sugarcane bagasse modified with acid (ASG), sugarcane bagasse modified with base (BSG), and activated carbon (AC)	5	60 min	5 g/L	25 °C	150–300 μm	150–160 rpm	
	-Nanocellulose modified with polyethyleneimine (PEI) crosslinked with magnetic bentonite	6	10 min	2 g/L	28 °C	–	200 rpm	
	-Macroporous terpolymer of glycidyl methacrylate (GMA), methyl methacrylate (MMA), and divinylbenzene (DVB)	7	30 min	1.5 g/L	26 °C	–	150 rpm	
	-Activated carbon prepared from mixed waste	6	180 min	0.3 g/L	25 °C	5 mm	200 rpm	
Cu	-Palm cellulose copolymer	6	60 min	1 g/L	28 °C	150 μm	300 rpm	(Rahman et al., 2020; Khosravi et al., 2020; Rahman et al., 2016; Arbabi et al., 2018; Mohd Salim et al., 2016)
	-Biofilm of *Escherichia coli* (*E. coli*) placed on zeolite.	6	14400 min	1 g/L	28 °C	324.70 nm	150 rpm	
	-Chelating ligands of poly (hydroxamic acid)-poly (amidoxime) derived from acacia cellulose grafted with poly (methyl acrylate-co-acrylonitrile)	6	60 min	1.5 g/L	25 °C	0.45 μm	200 rpm	
	-Activated carbon from bean wax waste activated by magnetite nanoparticles	7	40 min	1 g/L	27 °C	1180 μm	100 rpm	
	-Banana peel	9	120 min	0.9 g/L	28 °C	400 μm	300 rpm	
Pb	-Carbonized gum Arabic	6.5	30 min	0.05 g/L	25 °C	12 nm	–	(Shalikh and Majeed, 2022; Rahman et al., 2020; Sanka et al., 2020; Rahman et al., 2016; Sajjad et al., 2017; Malakootian et al., 2016; Mohd Salim et al., 2016)
	-Palm cellulose copolymer	6	60 min	1 g/L	28 °C	150 μm	300 rpm	
	-Rice husk biochar	6.5	20–30 min	1 g/L	30 °C	<0.125 mm	160 rpm	
	-Corn husk biochar	6	20–30 min	1 g/L	30 °C	<2 nm	160 rpm	
	-Chelating ligands of poly (hydroxamic acid)-poly (amidoxime) from acacia cellulose grafted with poly (methyl acrylate-co-acrylonitrile)	6	60 min	1.5 g/L	25 °C	0.45 μm	200 rpm	
	-Activated carbon (AC)	3	60 min	2 g/L	30 °C	–	150 rpm	
	-Microalgae Spirulina platensis	7	60 min	2 g/L	25 °C	–	180 rpm	
	-Banana peel	9	120 min	0.9 g/L	28 °C	400 μm	300 rpm	
Pb (II)	-Powdered mulberry leaf	7	60 min	0.8 g/L	25 °C	–	300 rpm	Mangood et al., 2023; Hussain et al., 2022; Maleki et al., 2019; Yang et al., 2018; Jeong et al., 2019; ALOthman et al., 2016)
	-Flocculant porous particles from coal fly ash waste (MFCA)	5	60 min	1 g/L	30 °C	50 nm	180 rpm	
	-Bentonite clay	7	120 min	0.05 g/L	25 °C	200 nm	–	
	-Modified kaolin combined	5.5	60 min	1 g/L	25 °C	–	200 rpm	
	-Strain (EM2) of Methylobacterium hispanicum producing bacterial films	7	60 min	1 g/L	30 °C	600 nm	150 rpm	
	-Activated carbon prepared from mixed waste	6	180 min	0.3 g/L	25 °C	5 mm	200 rpm	
Cd (II)	-Magnetic biocarbon (MBN3)	6	60 min	0.3 g/L	25 °C	150 μm	125 rpm	(Noor et al., 2023; Maleki et al., 2019; Yang et al., 2018; Prakash et al., 2017; Iqbal et al., 2017)
	-Bentonite clay	7	120 min	0.05 g/L	25 °C	200 nm	–	
	-Kaolin modified by calcination with NaOH	5.5	60 min	1 g/L	25 °C	–	–	
	-Vermiculite mixed with chitosan	5.5	300 min	2 g/L	30 °C	228,8 nm	160 rpm	
	-Shoe waste (ethylene polyurethane - type I shoe material)	4.9	932 min	1.3 g/L	25 °C	300 μm	180 rpm	
	-Shoe waste (vinyl acetate - type II shoe material)	5	881 min	1.2 g/L	25 °C	300 μm	180 rpm	
	-Carbonized gum Arabic	5	157 min	0.05 g/L	14 °C	12 nm	–	Shalikh and Majeed (2022);

(continued on next page)

Table 3 (*continued*)

Heavy metals removed	Type of adsorbent	Factors influencing adsorption						Authors
		pH	t	D	T	Tp	Va	
	-Chelating ligands of poly (hydroxamic acid)-poly (amidoxime) from acacia cellulose grafted with poly (methyl acrylate-co-acrylonitrile)	6	60 min	1.5 g/L	25 °C	0.45 µm	200 rpm	
	-Activated carbon (AC)	3	60 min	2 g/L	30 °C	–	150 rpm	
Ni (II)	-Powdered mulberry leaf	7	60 min	0.8 g/L	25 °C	–	300 rpm	(Mangood et al., 2023; Hussain et al., 2022; Beidokhti et al., 2019; Iqbal et al., 2017)
	-Flocculant porous particles from coal fly ash residues (MFCA)	5	60 min	1 g/L	30 °C	50 nm	180 rpm	(Rahman et al., 2020; Rahman et al., 2016; Akar et al., 2019)
	-Pistachio shell powder (PSP)	4–6	60 min	5 g/L	28 °C	150 µm	250 rpm	
	-Bentonite clay	7	120 min	0.05 g/L	25 °C	200 nm	–	
	-Ethylene and polyurethane sorbent (PES)	4.5	934 min	1.3 g/L	28 °C	–	150 rom	
	-Vinyl acetate sorbent (VAS)	4.6	881 min	1.2 g/L	28 °C	–	150 rpm	
	-Palm cellulose copolymer	6	60 min	1 g/L	28 °C	150 µm	300 rpm	
	-Chelating ligands of poly(hydroxamic acid)-poly(amidoxime) from acacia cellulose grafted with poly(methyl acrylate-co-acrylonitrile)	6	60 min	1.5 g/L	25 °C	0.45 µm	200 rpm	(Rahman et al., 2016, 2020; Akar et al., 2019)
	-Powder from modified Platanus orientalis bark	3	90 min	2 g/L	28 °C	–	–	
Cr (VI)	-Natural moss	2	360 min	5 g/L	25 °C	180 µm	350 rpm	(Ozeken et al., 2023; Akar et al., 2019; Prakash et al., 2017; Sayyaf et al., 2016)
	-Powder from modified Platanus orientalis bark	5	300 min	2 g/L	28 °C	–	–	
	-Vermiculite mixed with chitosan	5	300 min	2 g/L	30 °C	357.9 nm	160 rpm	
	-Powdered filamentous green alga Spirogyra porticalis	3	360 min	1 g/L	30 °C	–	–	
Cr (III)	-Copper Oxide (CuO)	8	120 min	0,1 g/l	25 °C	150–500 nm	200 rpm	Kondabey et al. (2019)
Cr	-Rice husk biochar	6.5	20–30 min	1 g/L	30 °C	<0,125 mm	160 rpm	(Sanka et al., 2020; Rahman et al., 2016; Sajjad et al., 2017)
	-Corn husk biochar	6	20–30 min	1 g/L	30 °C	<2 nm	160 rpm	
	-Chelating ligands of poly(hydroxamic acid)-poly(amidoxime) from acacia cellulose grafted with poly(methyl acrylate-co-acrylonitrile)	6	30 min	1,5 g/L	25 °C	0.45 µm	200 rpm	
	-Activated carbon (AC)	3	60 min	2 g/L	30 °C	–	150 rpm	
(tCr) total chromium	-Mixture of solid waste (RS) with Clinoptilolite (CL) modified in a 10:1 ratio	6.5	60 min	0.011 g/L	30 °C	10 µm	150 rpm	Aljerf (2018)
Fe	-Activated carbon extracted from pineapples	6	180 min	3 g/L	25 °C	0.54–2.95 nm	250 rpm	(Saleh Ibrahim et al., 2022; Kose et al., 2015)
	-Mangifera seed shell substrate	4.5	30 min	5 g/L	30 °C	425 µm	100 rpm	
Fe	-Palm cellulose copolymer	5	60 min	1 g/L	28 °C	150 µm	300 rpm	(Rahman et al., 2016, 2020; Sanka et al., 2020)
	-Rice husk biocarbon	6.5	20–30 min	1 g/L	30 °C	<0.125 mm	160 rpm	
	-Chelating ligands of poly (hydroxamic acid)-poly(amidoxime) from acacia cellulose grafted with poly(methyl acrylate-co-acrylonitrile)	5	60 min	1 g/L	25 °C	0.45 µm	200 rpm	
Co (II)	-Carbonized gum Arabic	5.4	198 min	0.05 g/L	25 °C	12 nm	–	(Shalikh,2022; Rahman et al., 2016, 2020)
	-Palm cellulose copolymer	6.5	60 min	1 g/L	28 °C	150 µm	300 rpm	
	-Chelating ligands of poly (hydroxamic acid)-poly(amidoxime) from acacia cellulose grafted with poly(methyl acrylate-co-acrylonitrile)	6.5	30 min	1 g/L	25 °C	0.45 µm	200 rpm	
	-Mulberry leaf powder	7	60 min	0.8 g/L	25 °C		300 rpm	Mangood et al. (2023)
Mn (II)	-Coffee pulp	4	90 min	20 g/L	20 °C	180 µm	100 rpm	(Gómez Aguilar et al., 2020; Hussain et al., 2022; Kose et al., 2015)
	-Flocculant porous particles from coal fly ash residues (MFCA)	5	60 min	1 g/L	30 °C	50 nm	–	
	-Mangifera seed shell substrate	4.5	30 min	5 g/L	30 °C	425 µm	100 rpm	
	-Chelating ligands of poly (hydroxamic acid)-poly (amidoxime) derived from acacia cellulose grafted with poly (methyl acrylate-co-acrylonitrile)	6	30 min	1.5 g/L	25 °C	–	200 rpm	Rahman et al. (2016)
Zn (II)	-Biofilm of *Escherichia coli* (*E. coli*) placed on zeolite.	6	14400 min	1 g/L	28 °C	213.90 nm	150 rpm	(Khosravi et al., 2020; Rahman et al., 2016)

(*continued on next page*)

Table 3 (*continued*)

Heavy metals removed	Type of adsorbent	Factors influencing adsorption						Authors
		pH	t	D	T	Tp	Va	
	-Chelating ligands of poly (hydroxamic acid)-poly (amidoxime) derived from acacia cellulose grafted with poly (methyl acrylate-co-acrylonitrile).	6	60 min	1.5 g/L	25 °C	0.45 µm	200 rpm	
	-Iranian sepiolite	5–9	120 min	2–16 g/L	20–40 °C	20–50 µm	200 rpm	(Hojati and Landi, 2015)
Hg (II)	-Bentonite clay	7	120 min	0.05 g/L	25 °C	200 nm	–	(Maleki et al., 2019; Li et al., 2019)
	-Porous carbon derived from bio-species	6	150 min	0.08 g/L	25 °C	–	800 rpm	
Ti	-Porous biocarbon from watermelon rinds	6.5	30 min	0,5 g/L	25 °C	3.419 nm	200 rpm	(Li et al., 2019)
	-Green algae from eutrophic water sources	5–6	60 min	1,11 g/L	23 °C	–	350 rpm	(Birungi and Chirwa, 2015)
As (V)	-Adsorption technique (ADS) with plant ashes	9	180 min	5 g/L	28 °C	0.053 mm	180 rpm	Jin et al. (2019)
	-Adsorption technique (ADS) with plant ashes and dielectrophoresis (DEP) (ADS/DEP)	9	180 min	5 g/L	28 °C	0.053 mm	180 rpm	
Th (IV)	-Humic acid on a silica gel surface coated with cross-linked chitosan (SiChiHA)	3.5	120 min	2,5 g/L	30 °C	400 nm	100 rpm	Prasetyo and Toyoda (2023)
U (VI)	-Humic acid on a silica gel surface coated with cross-linked chitosan (SiChiHA)	5	120 min	3 g/L	30 °C	400 nm	100 rpm	Prasetyo and Toyoda (2023)

process to ensure the quality of the review of the articles selected for this study, thereby discarding those that do not meet the established standards: Articles that are not related to industrial wastewater should be excluded. Articles that do not address the research questions should be excluded. Articles that are not related to adsorption technology should be excluded.

By applying the above criteria, the combination of search terms was refined as follows: (TITLE-ABS-KEY (“Removal of heavy metals” AND (adsorption OR sorption) AND “Industrial wastewater”)) AND (LIMIT-TO (KEYWORD, “Adsorption”, “Heavy metals”, “Industrial wastewaters”, “pH”, “Adsorption isotherms”, “Contact time”, “Adsorbents”, “Temperature”, “Sorption”, “Concentration (parameter)”) AND (LIMIT-TO (LANGUAGE, “English”) AND (LIMIT-TO (DOCTYPE, “Article”) AND (LIMIT-TO (SUBJECT AREA, “Environmental Science”) AND PUBYEAR >2015 AND PUBYEAR <2024.

This refinement reduced the number of documents in Scopus to 396 articles. After reviewing the titles of the selected articles, 92 documents remained. Subsequently, by reading the abstracts, the selection was further narrowed down to 39 articles.

2.7. Selection of articles

To carry out the systematic review on the removal of heavy metals from industrial wastewater using adsorption technology, the search was initiated in the Scopus digital database. The search strategy was structured using keywords and Boolean operators such as AND and OR, with the combination "heavy metals" AND (adsorption OR sorption) AND "Industrial wastewater," resulting in a total of 1484 articles. Subsequently, inclusion and exclusion criteria were applied to refine the results. Keywords were set to "Heavy metals" AND (adsorption OR sorption) AND "Industrial wastewater" AND adsorbent AND isotherm. Additionally, the search was restricted to articles in "English," classified as "Article" and with publication dates between "2015 and 2024." This filtering resulted in a total of 239 articles for analysis.

After reviewing the articles, 157 were discarded for not meeting the established criteria, leaving 239 articles for the next stage. The abstracts of the remaining 239 articles were then analyzed, excluding 147 because they were not related to industrial wastewater, did not address the research questions, and were not connected to adsorption technology. This resulted in the selection of 92 articles for a more detailed evaluation. Finally, a thorough review of the 92 articles was conducted, and 39 articles were selected for the systematic review.

In Fig. 1, a diagram of the article search process for this systematic review is presented, showing those that were selected after undergoing a process of searching, identifying, and filtering, using the PRISMA statement. The application of studies conducted in different countries was considered with the aim of expanding knowledge on various adsorption technologies for the removal of heavy metals from industrial wastewater.

3. Results and discussion

3.1. P1. What are the factors that influence the adsorption of heavy metals in industrial wastewater?

Table 2 lists the main materials used in various studies for the removal of heavy metals from industrial wastewater. Tejada-Tovar et al. (2015) mention that microbial biomasses (fungi, bacteria, and algae) and agro-industrial wastes (coconut shells, orange peels, lemon peels, cassava peels, apple peels, tamarind peels, among others) have been the materials used for adsorption and are the most studied set to date, according to the publication of their article.

Table 2 highlights a variety of materials that can be used as adsorbents and bioadsorbents for the removal of heavy metals from wastewater. The materials are divided into six categories: (1). Living organisms: This category includes bacteria, algae, and other microorganisms that can absorb metals due to their cellular properties. However, they may require specific conditions to maintain their viability and effectiveness. (2). Biomasses: This category includes plant derivatives and agricultural waste, which are currently sustainable and low-cost options. Their efficiency depends on the structure and composition of the material. (3). Biopolymers: Materials that can be natural or chemically modified to improve their adsorption capacity, thereby showing affinity for heavy metals, are included. (4). Activated Carbon: This category includes materials with high specific surface area and porosity, which have been widely used in adsorption processes due to their high porosity and adsorption capacity. (5). Chemical Modification: This category includes materials that have been nano-modified to enhance their adsorption capacity, thereby facilitating the separation of the adsorbent from the aqueous medium. This category can be expensive. (6). Other Materials: This category includes a wide range of synthetic and natural adsorbents with diverse properties.

Table 4
Efficiency of Different Materials Used as Adsorbents in the Removal of Heavy Metals from Industrial Wastewater. Where; Ce: Initial concentration of the adsorbate, R: Percentage of heavy metal removal, qe: Maximum adsorption capacity.

Heavy metals	Adsorbents	Ce	R	qe	Authors
Cr (VI)	- Natural moss	1000 mg/L	54.5 %	41.2 mg/g	(Ozeken et al., 2023; Akar et al., 2019; Prakash et al., 2017; Sayyaf et al., 2016)
	- Powder from modified bark of Platanus orientalis	86.39 mg/L	90.7 %	19.920 mg/g	
	- Powder from unmodified bark of Platanus orientalis	86.39 mg/L	89.6 %	13.423 mg/g	
	- Modified clinoptilolite (a type of zeolite)	81.4 mg/L	75.4 %	37 mg/g	
	- Powdered filamentous green algae Spirogyra porticalis	39.26 mg/L	70 %	27.48 mg/g	
	- Vermiculite mixed with chitosan	670 mg/L	59.2 %	1071.86 mg/g	
Cr	- Rice husk biochar	1.82 mg/L	65 %	0.06 mg/g	(Sanka et al., 2020; Rahman et al., 2016; Sajjad et al., 2017)
	- Corn leaf biochar	1.82 mg/L	20 %	0.03 mg/g	
	- Chelating ligands of poly(hydroxamic acid)-poly (amidoxime) from acacia cellulose grafted with poly(methyl acrylate-co-acrylonitrile)	24.53 mg/L	99.8 %	102.96 mg/g	
	- Activated carbon (AC)	5 mg/L	70 %	0.17 mg/g	
Cr (III)	- Copper oxide (CuO)	50 mg/L, 225 mg/L, 450 mg/L	57.24 %, 89.14 % y 99.99 %	105.68 mg/g, 147.49 mg/g, 197.56 mg/g	Kondabey et al. (2019)
(tCr) in the ammoniacal phase	- Solid waste (SW) mixture with modified Clinoptilolite (CL) in a 10:1 ratio	100 mg/L	90 %	37 mg/g	Aljerf (2018)
Cu (II)	- Natural moss	50 mg/L	70 %	22.7 mg/g	(Ozeken et al., 2023; Mangood et al., 2023; Hussain et al., 2022; Maleki et al., 2019; Gupta et al., 2018; Sun et al., 2022)
	- Mulberry leaf powder	1000 mg/L	85 %	2.88 mg/g	
	- Flocculant porous particles from coal fly ash residues (MCFA)	100 mg/L	95.88 %	0.4341 mg/g	
	- Bentonite clay	3000 mg/L	99 %	1000 mg/g	
	- Sugarcane bagasse (SG)	52.4 mg/L	88.9 %	4.84 mg/g	
	- Sugarcane bagasse modified with acid (ASG)	52.4 mg/L	96.9 %	5.35 mg/g	
	- Sugarcane bagasse modified with base (BSG)	52.4 mg/L	94.8 %	2.06 mg/g	
	- Activated carbon (AC)	52.4 mg/L	98.5 %	5.62 mg/g	
	- Nanocellulose modified with polyethyleneimine (PEI) crosslinked with magnetic bentonite	100 mg/L	86.79 %	757.45 mg/g	
Cu	- Palm cellulose copolymer	4000 mg/L	95 %	260 mg/g	(Rahman et al., 2020; Khosravi et al., 2020; Rahman et al., 2016; Arbabi et al., 2018; Mohd Salim et al., 2016)
	- *Escherichia coli* (*E. coli*) biofilm placed on zeolite	40 mg/L	54.61 %	3.29 mg/g	
	- Chelating ligands of poly (hydroxamic acid)-poly (amidoxime) from acacia cellulose grafted with poly (methyl acrylate-co-acrylonitrile)	5.19 mg/L	99.8 %	184.29 mg/g	
	- Wax residues with magnetite nanoparticles	100 mg/L	99.73 %	49.75 mg/g	
	- Banana peel	2 mg/L	66 %	5.720 mg/g	
Cd (II)	- Magnetic biocarbon (MBN3)	140 mg/L	87.6 %	47.9 mg/g	(Noor et al., 2023; Maleki et al., 2019; Yang et al., 2018; Prakash et al., 2017; Iqbal et al., 2017)
	- Bentonite clay				
	- Kaolin modified by calcination with NaOH				
	- Shoe waste (polyurethane ethylene - Type I footwear material)	305 mg/L	66.66 %	180.222 mg/g	
	- Shoe waste (vinyl acetate - Type II footwear material)	402 mg/L	94.66 %	396.312 mg/g	
	- Vermiculite mixed with chitosan	670 mg/L	71.5 %	563.09 mg/g	
Cd	- Carbonized gum Arabic	50 mg/L	90.7 %	41.88 mg/g	(Shalikh and Majeed, 2022; Rahman et al., 2016; Sajjad et al., 2017)
	- Chelating ligands of poly (hydroxamic acid)-poly (amidoxime) from acacia cellulose grafted with poly (methyl acrylate-co-acrylonitrile)	0.084 mg/L	94.7 %	149.51 mg/g	
	- Activated carbon (AC)	5 mg/L	79.8 %	0.11 mg/g	
Co	- Carbonized gum Arabic	50 mg/L	68.75 %	31.3 mg/g	(Shalikh and Majeed, 2022; Rahman et al., 2016, 2020)
	- Palm cellulose copolymer	4000 mg/L	95 %	168 mg/g	
	- Chelating ligands of poly (hydroxamic acid)-poly (amidoxime) from acacia cellulose grafted with poly (methyl acrylate-co-acrylonitrile)	0.290 mg/L	99.9 %	113.14 mg/g	
	- Powdered mulberry leaves	1000 mg/L	100 %	1.15 mg/g	(Mangood et al., 2023)
Pb	- Carbonized gum Arabic	50 mg/L	80 %	36.4 mg/g	(Shalikh and Majeed, 2022; Rahman et al., 2020; Sanka et al., 2020; Rahman et al., 2016; Sajjad et al., 2017; Malakootian et al., 2016; Mohd Salim et al., 2016)
	- Palm cellulose copolymer	4000 mg/L	95 %	272 mg/g	
	- Rice husk biochar	1.59 mg/L	>90 %	0.11 mg/g	
	- Corn leaf biochar	1.59 mg/L	>35 %	0.03 mg/g	
	- Chelating ligands of poly (hydroxamic acid)-poly (amidoxime) from acacia cellulose grafted with poly (methyl acrylate-co-acrylonitrile)	1.188 mg/g	99.2 %	103.6 mg/g	
	- Activated carbon (AC)	5 mg/L	>78%	0.19 mg/g	
	- Biosorption with Spirulina platensis	150 mg/L	84.32 %	40 mg/g	
	- Banana peel	4 mg/L	80 %	89.286 mg/g	
Pb (II)	- Powdered mulberry leaves	1000 mg/l	69 %	0.50 mg/g	(Mangood et al., 2023; Hussain et al., 2022; Maleki et al., 2019; Yang et al., 2018; Jeong et al., 2019)
	- Flocculant porous particles from coal fly ash residues (MCFA)	100 mg/l	99.91 %	12.1957 mg/g	
	- Bentonite clay	3000 mg/L	99 %	900 mg/g	
	- Kaolin modified by calcination with NaOH	200 mg/L	80.59 %	161.84 mg/g	

(*continued on next page*)

Table 4 (*continued*)

Heavy metals	Adsorbents	Ce	R	qe	Authors
	- Floating biofilm of Methylobacterium hispanicum strain (EM2)	800 mg/L	96 %	79,84 mg/g	
Mn	Coffee pulp	46.6 mg/L	53.40 %	8.01 mg/g	(Gómez Aguilar et al., 2020; Hussain et al., 2022; Kose et al., 2015)
	- Flocculant porous particles from coal fly ash residues (MCFA)	100 mg/L	94.26 %	558,9219 mg/g	
	- Mangifera indica seed hull substrate	40 mg/L	82 %	5.2 mg/g	
	- Chelating ligands of poly (hydroxamic acid)-poly (amidoxime) from acacia cellulose grafted with poly (methyl acrylate-co-acrylonitrile)	9.8 mg/L	99.9 %	538.91 mg/g	Rahman et al. (2016)
Ni (II)	- Mulberry leaf powder	1000 mg/L	80 %	1.14 mg/g	(Mangood et al., 2023; Hussain et al., 2022; Beidokhti et al., 2019; Maleki et al., 2019; Iqbal et al., 2017)
	- Flocculating porous particles from coal fly ash residues (MCFA)	100 mg/L	71.04 %	210,9737 mg/g	
	- Pistachio shell powder (PHP)	1000 mg/L	75 %	14 mg/g	
	- Bentonite clay	2600 mg/L	92 %	900 mg/g	
	- Ethylene and polyurethane (PES)	299 mg/L	64.7 %	171.99 mg/g	
	- Vinyl acetate (VAS)	402 mg/L	92.7 %	388.08 mg/g	
Ni	- Palm cellulose copolymer	4000 mg/L	95 %	172 mg/g	(Rahman et al., 2016, 2020; Akar et al., 2019)
	- Chelating ligands of poly(hydroxamic acid)-poly (amidoxime) derived from acacia cellulose grafted with poly(methyl acrylate-co-acrylonitrile)	35.56 mg/L	99.8 %	124.41 mg/g	
	- Modified bark powder of Platanus orientalis	556.4 mg/L	56.5 %	126.58 mg/g	
	- Unmodified bark powder of Platanus orientalis	556.4 mg/L	74.5 %	285.714 mg/g	
Fe (II)	- Activated carbon extracted from pineapples (ACPC)	60 mg/L	99.55 %	39.72 mg/g	(Saleh Ibrahim et al., 2022; Kose et al., 2015)
	- ango seed shell substrate (Mangifera indica)	6.55 mg/L	81 %	1.1 mg/g	
Fe	- Palm cellulose copolymer	4000 mg/L	95 %	210 mg/g	(Rahman et al., 2016, 2020; Sanka et al., 2020)
	- Rice husk biochar	9.28 mg/L	90 %	0.76 mg/g	
	- Chelating ligands of poly(hydroxamic acid)-poly (amidoxime) derived from acacia cellulose grafted with poly(methyl acrylate-co-acrylonitrile)	6.722 mg/L	99.8 %	164.97 mg/g	
Zn	- *Escherichia coli* biofilm placed on zeolite	40 mg/L	57.35 %	3.43 mg/g	(Khosravi et al., 2020; Rahman et al., 2016)
	- Chelating ligands of poly(hydroxamic acid)-poly (amidoxime) derived from acacia cellulose grafted with poly(methyl acrylate-co-acrylonitrile)	75.86 mg/L	99.8 %	130.47 mg/g	
Zn (II)	- Sepiolite	285.5 mg/L	95 %	13.1 mg/g	(Hojati and Landi, 2015)
Hg (II)	- Bentonite clay	2600 mg/L	92 %	875 mg/g	(Maleki et al., 2019; Li et al., 2019b),
	- Porous carbon derived from bio-species	5 mg/L	96.8 %	9.8 mg/g	
As (V)	- Adsorption technique (ADS) with plant ash	15 mg/L	91.4 %	2.5 mg/g	Jin et al. (2019)
	- Adsorption technique (ADS) with plant ash and dielectrophoresis (DEP) (ADS/DEP)	15 mg/L	94.7 %	3.1 mg/g	
Tl	- Green algae Chlorella vulgaris	250–500 mg/L	100 %	1000 mg/g	(Birungi and Chirwa, 2015)
Th (IV)	- Humic acid on a chitosan-crosslinked silica gel surface (SiChiHA)	12.34 mg/L	47.1 %	30.6 mg/g	Prasetyo and Toyoda (2023)
U (VI)	- Humic acid on a chitosan-crosslinked silica gel surface (SiChiHA)	33.45 mg/L	56.13 %	75.4 mg/g	Prasetyo and Toyoda (2023)

In Table 3, the factors influencing the adsorption of heavy metals from wastewater are detailed, including pH, contact time, adsorbent dose, temperature, particle size, and stirring speed. In this systematic review, "Removal of Heavy Metals from Industrial Wastewater Through Adsorption Technology," the main heavy metals recorded are Cu (II), Cu, Pb (II), Pb, Cd (II), Cd, Ni (II), Ni, Cr (VI), Cr (III), Cr (total Cr), Fe (II), Fe, Co (II), Co, Mn (II), Mn, Zn (II), Zn, Hg (II), Ti (I), Ti, As (V), Th (IV), and U (VI), with Cu (II) being the most studied metal.

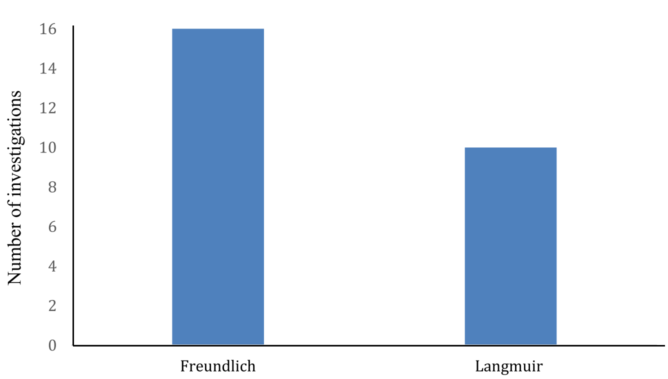

Fig. 2. Type of Isotherm used in each study.

The results obtained in Table 3 indicate that 72% of the studies (28 out of 39) achieved a pH in the range of 3–6.9. This suggests that adsorption reaches equilibrium at an acidic pH. On the other hand, only 28% of the studies (11 out of 39) reported a pH range of 7–9, implying that in these cases, adsorption reaches equilibrium at a basic pH. According to Tejada-Tovar et al. (2015), pH is an important parameter that controls metal adsorption processes on different adsorbents, as hydrogen ions act as a strongly competitive adsorbate. In other words, the adsorption of metal ions depends on the nature of the adsorbent surface as well as the distribution of the metal's chemical species in the aqueous solution. The authors who report basic pH levels between 7 and 9 include (Mangood et al., 2023; Maleki et al., 2019; Hojati and Landi, 2015; Jeong et al., 2019; Kondabey et al., 2019; Jin et al., 2019; Arbabi et al., 2018; Sosun et al., 2022; Yayayürük and Erdem Yayayürük, 2016; Malakootian et al., 2016; Mohd Salim et al., 2016).

Contact time determines how long the adsorbent is in contact with the heavy metal to reach adsorption equilibrium. In the studies cited in Table 4, contact time varies significantly depending on the type of adsorbent and the heavy metal being removed. The times range from 10 min to 14,400 min. Generally, this is because the adsorption rate in the initial stage is rapid and there is a high availability of active sites on the

Table 5
Most commonly used adsorption isotherm for the removal of heavy metals from industrial wastewater.

Heavy metal	Adsorbent	I_{so}	Cin. R	R^2	Authors
Cr(VI)	- Natural moss	Langmuir	Pseudo-second order	0.990	Ozeken et al. (2023)
Cr	- Rice and corn husk biochar	Freundlich	Pseudo-second order	0.99	(Sanka et al., 2020; Sajjad et al., 2017; Elboughdiri et al., 2021)
	- Activated carbon (AC)	Langmuir	–	0.97	
	- Steam-activated sawdust	Freundlich	Pseudo-second order	0.99	
tCr	- Solid waste (SW) mixed with modified Clinoptilolite (CL) in a 10:1 ratio	Freundlich	Pseudo-second order	0.905	Aljerf (2018)
Cr VI	- Modified Platanus orientalis bark powder	Freundlich	–	0.998	(Akar et al., 2019; Prakash et al., 2017)
	- Vermiculite mixed with chitosan	Freundlich	Pseudo-second order	0.99	
Cu	- Activated carbon (AC)	Langmuir	–	0.97	(Sajjad et al., 2017; Khosravi et al., 2020; Mohd et al., 2016; Rahman et al., 2020)
	- Banana peel	Langmuir	–	0.99	
	- Palm cellulose copolymer	Freundlich	Pseudo-first order	0.99	
	- *Escherichia coli* biofilm placed on zeolite	Langmuir	Pseudo-second order	0.968	
Cu(II)	- Natural moss	Langmuir	Pseudo-second order	0.994	(Ozeken et al., 2023; Mangood et al., 2023; Hussain et al., 2022; Sun et al., 2022; Yayayürük and Erdem Yayayürük, 2016)
	- Mulberry leaf powder	Freundlich	Pseudo-second order	0.98	
	- Porous flocculating particles from ash residues	Freundlich	Pseudo-second order	0.99	
	- Nanocellulose modified with polyethyleneimine (PEI) cross-linked with magnetic bentonite	Freundlich	Pseudo-second order	0.983	
	- Macroporous terpolymer of glycidyl methacrylate (GMA), methyl methacrylate (MMA), and divinylbenzene (DVB)	Langmuir	Pseudo-second order	0.99	
Cd	- Activated carbon (AC)	Langmuir	–	0.97	Sajjad et al. (2017)
Cd(II)	- Magnetic biochar (MBN3)	Langmuir	Pseudo-second order	0.985	(Noor et al., 2023; Prakash et al., 2017; Sosun et al., 2022; Iqbal et al., 2017)
	- Vermiculite mixed with chitosan	Freundlich	Pseudo-second order	0.99	
	- Magnetite nanoparticles	Freundlich	Pseudo-first order	0.998	
	- Shoe waste (vinyl acetate - type I shoe material)	Freundlich	Pseudo-second order	0.99	
Co	- Palm cellulose copolymer	Freundlich	Pseudo-first order	0.99	Rahman et al. (2020)
Co(II)	- Powdered mulberry leaves	Langmuir	Pseudo-second order	0.99	Mangood et al. (2023)
Hg	- Porous carbon derived from biospecies	Freundlich	Pseudo-second order	0.98	(Li et al., 2019)
Mn (II)	- Coffee pulp	Langmuir	Ho and McKay's pseudo-second order	0.994	(Gómez Aguilar et al., 2020; Hussain et al., 2022; Kose et al., 2015)
	- Porous flocculating particles from ash residues	Freundlich	Pseudo-second order	0.99	
	- Mangifera indica seed shell substrate	Freundlich	Pseudo-first order	0.99	
Pb	- Palm cellulose copolymer	Freundlich	Pseudo-first order	0.99	(Rahman et al., 2020; Sanka et al., 2020; Sajjad et al., 2017; Malakootian et al., 2016; Mohd et al., 2016)
	- Rice and corn husk biochar	Freundlich	Pseudo-second order	0.99	
	- Activated carbon (AC)	Langmuir	–	0.97	
	- Microalgae Spirulina platensis	Langmuir	Pseudo-second order	0.99	
	- Banana peel	Langmuir	–	0.99	
Pb (II)	- Powdered mulberry leaves	Langmuir	Pseudo-second order	0.99	(Mangood et al., 2023; Hussain et al., 2022; Jeong et al., 2019)
	- Flocculating porous particles from fly ash waste	Freundlich	Pseudo-second order	0.99	
	- Floating biofilm of Methylobacterium hispanicum (EM2) strain	Freundlich	Pseudo-second order	0.98	
Ni (II)	- Powdered mulberry leaves	Langmuir	Pseudo-second order	0.99	(Mangood et al., 2023; Hussain et al., 2022; Beidokhti et al., 2019; Rahman et al., 2020; Sosun et al., 2022)
	- Flocculating porous particles from ash waste	Freundlich	Pseudo-second order	0.99	
	- Pistachio shell powder (PHP)	Freundlich	Pseudo-second order	0.98	
	- Palm cellulose copolymer	Freundlich	Pseudo-first order	0.99	
	- Magnetite nanoparticles	Freundlich	Pseudo-first order	0.998	
Fe	- Palm cellulose copolymer	Freundlich	Pseudo-first order	0.99	(Rahman et al., 2020; Sanka et al., 2020)
	- Rice and corn cob biochar	Freundlich		0.99	
Fe (II)	- Activated carbon extracted from pineapples (ACPC)	Freundlich	–	0.97	(Saleh Ibrahim et al., 2022; Kose et al., 2015)
	- Mangifera indica seed shell substrate	Freundlich	Pseudo-first order	0.99	

(*continued on next page*)

Table 5 (*continued*)

Heavy metal	Adsorbent	I_{so}	Cin. R	R^2	Authors
Tl	- Green algae	Langmuir	Pseudo-second order	0.99	(Birungi and Chirwa, 2015)
Th(IV)	- Humic acid bound on silica gel modified with chitosan	Langmuir	Pseudo-second order	–	Prasetyo and Toyoda (2023)
U(VI)	- Binding of humic acid on silica gel modified with chitosan	Langmuir	Pseudo-second order	–	Prasetyo and Toyoda (2023)
Zn (II)	- Biofilm of *Escherichia coli* placed on zeolite	Langmuir	Pseudo-second order	0.97	Khosravi et al. (2020)

Where; Iso = Adsorption isotherm, Cin. R = Reaction kinetics, and R^2 = Model fit.

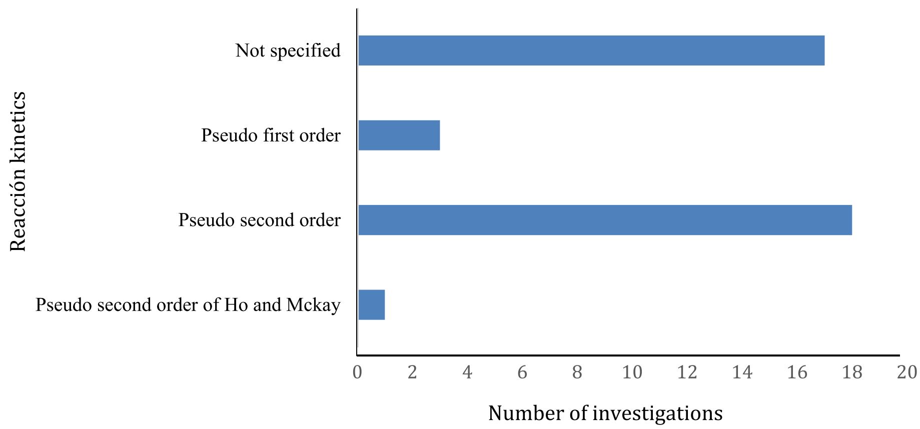

Fig. 3. Reaction kinetics used in each of the investigations for their respective fitting.

adsorbent surface. As time progresses, the adsorption rate decreases because the active sites become saturated until equilibrium is reached. In the study conducted by Yayayürük and Erdem Yayayürük (2016) using nanocellulose modified with polyethyleneimine (PEI) crosslinked with magnetic bentonite, the contact time for removing Cu (II) is 10 min. This indicates the time required to reach adsorption equilibrium for Cu (II) and a rapid saturation of active sites. While Khosravi et al. (2020) report that the contact time to remove Cu and Zn using *Escherichia coli* (*E. coli*) biofilm placed on zeolite is 14,400 min, due to the adsorbent requiring a relatively long time to reach equilibrium, whether due to its structure or surface characteristics. For the removal of Pb, Pb (II), Cd, Cd (II), Ni (II), Ni, (tCr), Fe, Co (II), and Ti, the most commonly used contact time among various adsorbents is 60 min. For Cr (III), Cr (VI), Co (II), Zn (II), Hg (II), As (V), Th (IV), and U (VI), the contact time ranges from 120 to 360 min. Finally, for the metals Fe (II), Mn (II), and Ti (I), the most commonly used contact time is 30 min.

The dosage of adsorbent or bioadsorbent used in a solution ensures that there are sufficient active sites to absorb heavy metals. This factor is essential as it determines the availability of active sites for metal adsorption. In the studies presented in Table 4, the adsorbent dosage varies depending on the type of adsorbent and the heavy metal being removed, ranging from a dosage as low as 0.011–20 g/L. However, it is important to note that a low dosage may result in a lower total adsorption capacity, as there are fewer active sites available to capture metal ions, though it may be sufficient if the metal concentration is relatively low. Conversely, a high adsorbent dosage increases the adsorption capacity but may reach a saturation point where adding more adsorbent does not lead to significantly higher adsorption (Kumar et al., 2019).

According to Tejada-Tovar et al. (2015), temperature is one of the factors that most influences adsorption, as it affects the adsorption rate and the maximum adsorption capacity. A temperature around 25–30 °C is considered optimal for the adsorption of heavy metals, since an increase in temperature can cause changes in the texture of the sorbent and deterioration of the material, leading to a loss of sorption capacity. In this systematic review, the studies examined align with the findings of Tejada-Tovar et al. (2015), with the exception of the study by Gómez Aguilar et al. (2020), which mentions that for the removal of Mn (II) using coffee pulp as an adsorbent, the optimal temperature is 20 °C. At this temperature, the adsorption process is efficient as there is a balance between the mobility of the molecules and kinetic energy. Additionally, the study by Birungi and Chirwa (2015) indicates that for the removal of Ti using green algae from eutrophic water sources as a sorbent, the optimal temperature is 23 °C. For the removal of Cu (II), Pb (II), Cd (II), Cd, Ni (II), Cr (III), Fe (II), Fe, Co, Co (II), Mn, Zn, Hg (I), and Ti (I), the optimal temperature is 25 °C. For the metals Cu, Ni (II), Ni, Fe, Zn, and As (V), the optimal temperature is 28 °C. For the metals Cr (VI), Cr, (tCr), Fe (II), Fe, Mn (II), Th (IV), and U (IV), the optimal temperature is 30 °C. On the contrary, the results obtained in Table 4 demonstrate the importance of particle size, as it is essential for achieving good results that show the adsorption capacity or the removal percentage of heavy metals. Among the reviewed studies, the particle size varies according to the type of adsorbent used by each author, ranging from nanometers (nm) to micrometers (μm). The small particle size provides active sites for adsorption; however, it can cause greater internal diffusion resistance, especially in adsorbents with very small pores. In contrast, larger particle sizes offer a lower specific surface area, resulting in a lower adsorption capacity but facilitating better diffusion of metal ions within, due to lower diffusion resistance. Therefore, it is essential to find a balance between the specific surface area and the diffusion resistance, which involves selecting a particle size that maximizes adsorption efficiency without introducing significant limitations in adsorption kinetics. It is worth mentioning that some reviewed studies do not report the particle size used in their research.

Finally, agitation speed is another factor that influences adsorption. From the review of the articles, the results obtained for agitation speed

Tabla 6
Adsorption mechanisms of different materials for the removal of heavy metals from industrial wastewater.

Type of Adsorbent	Precursor Material	Adsorption mechanism
Living Organisms	Natural moss (Ozeken et al., 2023).	The adsorption mechanism of natural moss involves processes such as complexation, adsorption, diffusion, chelation and precipitation, depending on the specific characteristics of the biomass used. These processes allow moss to act as an effective adsorbent for the removal of heavy metal ions from water.
	Escherichia coli (*E. coli*) (Khosravi et al., 2020).	The adsorption mechanism of *Escherichia coli* (*E. coli*) is based on electrostatic interactions due to its negatively charged surface, complex formation with metals through functional groups, physical adsorption, production of extracellular polymeric substances (EPS) that increase the adsorption surface, and ion exchange where metal cations replace other cations on the surface.
	Methylobacterium hispanicum (Jeong et al., 2019).	The adsorption mechanism of Methylobacterium hispanicum EM2 for the removal of Pb(II) is based on the electrostatic attraction between the negative charge of its surface and the positive Pb(II) ions, as well as on chemical interactions through functional groups on the surface of the microorganism.
	Microalgae Spirulina platensis (Malakootian et al., 2016).	The adsorption mechanism of the microalga Spirulina platensis for lead removal is based on electrostatic and chemical interactions, where lead ions are attracted to the surface of the algae. Adsorption follows the Langmuir model and second-order kinetics, indicating that it occurs at specific sites. The structure and functional groups of the biomass also contribute to its adsorption capacity, although efficiency decreases when the available sites become saturated.
	Green micro-algae (Birungi and Chirwa, 2015)	The adsorption mechanism of green microalgae for thallium removal involves the interaction of functional groups such as carboxyls and phenols on their surface with metal ions, through ionic and coordination bonds.
	Filamentous green algae Spirogyra porticalis (Sayyaf et al., 2016).	The adsorption mechanism of Spirogyra porticalis involves biosorption, where metal ions form complexes with biomaterials using their ligands or functional groups. These functional groups, such as amino, hydroxyl, carboxyl and sulfate, act as binding sites for metal ions on the surface of the algal cell wall. This process is based on physicochemical reactions such as electrostatic attraction.
Biomasses	Coffee pulp (Gómez Aguilar et al., 2020).	The adsorption mechanism consists of a combination of electrostatic interactions and chemical bonds between the functional groups of the coffee pulp and the manganese cations, which allows for effective removal of this contaminant from water.
	Mulberry leaf (Mangood et al., 2023).	The adsorption mechanism of berry leaves involves chemical interactions, physical characteristics of the surface, and environmental conditions such as pH, which together facilitate the capture of metal ions from contaminated water.
	Pistachio hull (Beidokh ti et al., 2019).	The adsorption mechanism of Pistachio Hull Waste for the removal of nickel ions involves complex interactions that depend on the pH, the nature of the functional groups on the adsorbent surface and the kinetics of the adsorption process.
	Rice and corn husk (Sanka et al., 2020).	The adsorption mechanism of rice and corn biochars involves a combination of physical and chemical interactions that allow the effective capture of metal ions in wastewater.
	Watermelon rind (Li et al., 2019a).	The adsorption mechanism of watermelon peel-derived biochar for Tl(I) removal involves the formation of complexes on the adsorbent surface, especially under alkaline conditions, where hydroxyl groups interact with Tl(I) ions. Although electrostatic interactions were also present.
	Porous carbon derived from biospecies (Li et al., 2019b).	The hierarchically porous adsorbent uses a combination of physical and chemical adsorption to achieve a high removal capacity of mercury ions from aqueous media.
	Platanus orientalis bark (Akar et al., 2019).	The adsorption mechanisms of Platanus orientalis include chemical interactions with functional groups, a porous surface that increases binding sites, the influence of pH, and observable changes in the surface of the material upon adsorption of heavy metals.
	Sugarcane bagasse (Gupta et al., 2018).	The adsorption mechanism of sugarcane bagasse involves the chemical interaction between the functional groups of the material and the Cu(II) ions, influenced by the modification of the adsorbent and the pH of the solution.
	Pine sawdust (Elboughdiri et al., 2021).	The adsorption mechanism prevailing in the pine sawdust adsorbent is chemisorption, evidenced by the fitting of the kinetic data to the pseudo-second order model.
	Banana peel (Mohd et al., 2016).	The adsorption mechanism prevailing on banana peel is the electrostatic interaction between carboxylic functional groups, which are deprotonated and become negative at pH above 4, and positively charged metal ions, such as lead (Pb) and copper (Cu). This interaction increases the availability of binding sites for the adsorption of toxic metals in solution.
	Mangifera seed shell (Kose et al., 2015).	According to the study, the adsorption occurred through physical and chemical interactions, where the seed shell acts as an adsorbent due to its surface rich in functional groups that can interact with metal ions. These interactions may include ionic bonds, Van der Waals forces and hydrogen bonds.
	Corn cobs (Jin et al., 2019).	The adsorption mechanism prevailing in corncob is mainly based on physical adsorption, which includes interactions such as Van der Waals forces and hydrogen bonding. The porous structure and high specific surface area of corncob facilitate the capture of As(V) through these mechanisms. Furthermore, heat treatment of corncob to carbonize it can increase its adsorption capacity by creating more available sites for contaminant binding.
Biopolymers	Gum arabic (Shalikh and Majeed, 2022).	The adsorption mechanism of carbonized gum arabic includes three stages: first, the transport of the adsorbate to the surface by film diffusion; then, diffusion within the

(*continued on next page*)

Tabla 6 (*continued*)

Type of Adsorbent	Precursor Material	Adsorption mechanism
		pores; and finally, adsorption on the internal surfaces. This process is affected by pH and contact time, which influences the interaction with heavy metals.
	Palm cellulose copolymer (Rahman et al., 2020).	The adsorption mechanism of the palm cellulose copolymer adsorbent is based on the formation of chemical bonds between the amidoxime functional groups of the polymer and metal ions. This process involves the transfer or exchange of electrons between the polymer and metals, resulting in a strong chemical interaction.
	Chelating ligand of poly (hydroxamic acid) - poly (amidoxime) from acacia cellulose grafted with poly (methyl acrylate-co-acrylonitrile) (Rahman et al., 2016).	The adsorption mechanism of poly(hydroxamic acid)-poly(amidoxime) chelating ligands is based on the formation of stable complexes between the functional groups of the ligands and the metal ions, facilitated by the dissociation of the proton from the hydroxyl group. This coordination is more efficient at a pH of around 6, where the adsorption capacity increases, especially towards metal ions such as copper.
	Polyethyleneimine (PEI) modified nanocellulose cross-linked with magnetic bentonite (Sun et al., 2022).	The adsorption mechanism of nanocellulose-modified Polyethyleneimine (PEI) and magnetic bentonite for Ag(I) removal is based on chemical interactions between the amino groups of PEI and metal ions, as well as electrostatic attractions.
Activated Carbons	Activated carbon extracted from pineapples (Saleh Ibrahim et al., 2022).	Physisorption was used for the removal of contaminants such as heavy metals and dyes, where physical interactions allowed the molecules to adsorb onto the surface of the activated carbon. Chemisorption also played a role, especially in the removal of metal ions, where stronger chemical bonds were formed between the contaminants and the activated carbon, increasing the adsorption efficiency.
	Activated carbon (Sajjad et al., 2017).	The adsorption mechanism of activated carbon involves physical interaction through Van der Waals forces and hydrogen bonding, where contaminants adhere to the carbon surface.
	Activated carbon from mixed waste (ALOthman et al., 2016).	The adsorption mechanism that prevailed in the activated carbon adsorbent is physical adsorption, which is based on electrostatic interactions between metal ions (Cu(II) and Pb(II)) and adsorption sites on the carbon surface.
Chemical Modification	Kaolin modified by calcination with NaOH NaOH (Yang et al., 2018).	The adsorption mechanism that prevailed in the modified kaolin adsorbent was chemical adsorption, evidenced by the best fit of the data to the pseudo-second-order kinetic equation. This indicates that the interaction between metal ions and modified kaolin is predominantly chemical. Furthermore, the adsorption process was observed to be heterogeneous, suggesting the involvement of multiple adsorption sites on the surface of the material.
	Sugarcane bagasse modified with acid (ASG) Gupta et al. (2018).	The adsorption mechanism of acid-modified bagasse sugar (ASG) involves the interaction of metal ions, such as Cu(II), with acidic functional groups present on the surface of the adsorbent. These groups, such as carboxyls and hydroxyls, facilitate the formation of bonds between the metal and the adsorbent, thus increasing the adsorption capacity.
	Sugarcane bagasse modified with base (BSG) Gupta et al. (2018).	The adsorption mechanism of base-modified bagasse sugar (BSG) is based on the interaction of metal ions with functional groups generated by the alkaline modification. This treatment increases the number of active sites on the surface of the adsorbent, improving its capacity to attract and retain metal ions such as Cu(II).
	Nanocellulose modified with polyethyleneimine (PEI) cross-linked with magnetic bentonite (Sun et al., 2022).	The adsorption mechanism of the polyethyleneimine-magnetic bentonite modified nanocellulose composite (PNMBC) is based on chemisorption, where the main interaction comes from the chelation of functional groups and electrostatic forces.
Other materials	Magnetic biochar (MBN3) (Noor et al., 2023).	The adsorption mechanism of Magnetic biochar adsorbent includes internal sphere complexation, surface precipitation, electrostatic attraction and physical adsorption. Cd^{2+} ions attach directly to the surface of magnetic biochar or to the active functional groups present on its surface.
	Porous flocculant particles from coal fly ash residues (MFCA) (Hussain et al., 2022).	The adsorption mechanism of porous materials obtained from modified coal ash (MCFA) involves both physical and chemical adsorption. The modification increases the surface area and the amount of oxygen-containing groups, thus improving the chelation capacity of heavy metals (HMs). This allows the HMs to adhere to the active sites on the surface of the adsorbent, facilitating their removal from contaminated water.
	Bentonite clay (Maleki et al., 2019).	The adsorption mechanism of bentonite clay is based on its high specific surface area and cation exchange capacity, which allows it to attract and retain metal ions and contaminants in its structure. The interaction occurs mainly through electrostatic forces, chemical bonds and the formation of complexes between metal ions and functional groups present on the surface of the clay.
	Iranian sepiolite (Hojati and Landi, 2015).	The adsorption mechanism of Iranian sepiolite for Zn^{2+} ions is physical adsorption on sepiolite particles, complemented by chemical precipitation of Zn^{2+} ions from solution.
	Copper oxide (CuO) (Kondabey et al., 2019)	The adsorption mechanism is physical adsorption, where chromium ions (Cr(III)) bind to the active sites on the CuO surface. This process is influenced by the availability of active sites and competition with hydroxide ions (OH) in the solution, which affects the adsorption efficiency. Saturation of the active sites leads to an equilibrium state after a specific time, in this case, 24 h.
	Plant ashes (Jin et al., 2019).	The adsorption mechanism of plant ash adsorbent is mainly based on the physical and chemical interaction between As(V) and the material surface. The porous structure and spherical shape of plant ash particles facilitate a larger surface area, which increases the adsorption capacity.
	Mixture of solid waste (RS) with Clinoptilolite (CL) modified in a 10:1 ratio (Aljerf, 2018).	The adsorption mechanism that prevailed in the modified zeolite (clinoptilolite) is mainly ion exchange. In this case, the cations present in the solution are exchanged by cations on the surface of the modified clinoptilolite, facilitating the adsorption of contaminants such as bromocresol purple (BCP) dye and heavy metals. In addition, this process is complemented by chemisorption.

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Tabla 6 (*continued*)

Type of Adsorbent	Precursor Material	Adsorption mechanism
	Vermiculite mixed with chitosan (Prakash et al., 2017).	The adsorption mechanism of the chitosan-mixed vermiculite adsorbent involves three steps: (1) diffusion of ions to the external surface of the adsorbent; (2) diffusion of ions into the pores of the adsorbent; and (3) adsorption of ions on the internal surface of the adsorbent. This process is favored by the structure of the material and the presence of intramolecular hydrogen bonds.
	Ethylene and polyurethane sorbent (PES) (Iqbal et al., 2017).	The adsorption mechanism of ethylene and polyurethane adsorbent (PES and VAS) is controlled by several factors, including the interaction between heavy metal ions (such as Ni(II)) and functional groups available on the surface of the adsorbent.
	Magnetite nanoparticles (Sosun et al., 2022).	The adsorption mechanism of the adsorbent is based on the interaction between metal ions and the surface of iron oxide nanoparticles, functionalized with trioctyl phosphine oxide (TOPO).
	Humic acid on a chitosan-crosslinked silica gel surface (SiChiHA) (Prasetyo and Toyoda, 2023).	The adsorption mechanism of the humic acid adsorbent on the chitosan-crosslinked silica gel surface (SiChiHA) is based on the formation of peptide bonds between the amino groups of chitosan and the carboxylate groups of humic acid. This process allows an effective modification of the surface, increasing the adsorption capacity of the material. In addition, the presence of basic functional groups in chitosan favors the attraction of negatively charged species.
	Macroporous terpolymer of glycidyl methacrylate (GMA), methyl methacrylate (MMA), and divinylbenzene (DVB) (Yayayürük and Erdem Yayayürük, 2016).	The adsorption mechanism of the macroporous terpolymer of glycidyl methacrylate (GMA), methyl methacrylate (MMA) and divinylbenzene (DVB) is based on the formation of complexes between the functional groups of diethylenetriamine tetraacetic acid (DTTA) and metal ions, such as Cu(II). This process includes electrostatic interactions and coordinate bonds that allow the capture of the ions on the polymer surface.
	Sand and Jacobi activated carbon (Arbabi et al., 2018).	The adsorption mechanism of the sand-activated carbon adsorbent involves two main steps: first, solids are adsorbed by Van der Waals forces and dipole moments on the external surfaces of the activated carbon; second, solids are allowed to move into the cavities of the carbon. This process enables the decomposition of organic materials in the wastewater.

range from 100 rpm to 800 rpm. Agitation speed is crucial in the adsorption process as it affects the diffusion of heavy metals towards the surface of the adsorbent, thereby improving the efficiency of the process. In general, a higher agitation speed can increase the adsorption rate by reducing the resistance to mass transfer in the liquid film surrounding the adsorbent particles. However, it must be optimized along with other factors such as pH, contact time, adsorbent dose, temperature, and particle size to achieve the best results in the removal of heavy metals from industrial wastewater.

3.2. P2. What is the efficiency of different materials and used as adsorbents in the removal of heavy metals from industrial wastewater?

The main materials used as adsorbents are classified into organic and inorganic types that remove various heavy metals from different industrial effluents. Table 4 shows the removal efficiency, initial concentration of the contaminant, and the maximum adsorption capacity of the adsorbent. Therefore, the study by Córdova Llacsahuache and Torres Odar, 2020 mentions that organic wastes contain structures such as proteins, polysaccharides, carboxyl groups, hydroxyls, and amine or amide groups, which offer better removal efficiency because the dissolved ions bond through electrostatic attraction.

Ozeken et al. (2023), Akar et al. (2019), Prakash et al. (2017), and Sayyaf et al. (2016) used different adsorbents such as: natural moss, powdered *Platanus orientalis* bark, modified Clinoptilolite, powdered filamentous green algae *Spirogyra porticalis*, and vermiculite mixed with chitosan for the removal of Cr (VI). Therefore, powdered modified *Platanus orientalis* bark demonstrated a removal efficiency of 90.7%, with a maximum adsorption capacity of 19.920 mg/g and an initial adsorbate concentration of 86.39 mg/L. In contrast, natural moss is identified as the adsorbent that removes the least Cr (VI), with an efficiency of 54.5%. However, Ozeken et al. (2023) mention in their study that REB is an abundant, cost-effective, and efficient adsorbent for the removal of heavy metals from aqueous solutions.

In the study conducted by Rahman et al. (2016), it was demonstrated that chelating ligands derived from grafted acacia cellulose have the ability to remove 99.8% of chromium when the initial contaminant concentration is 24.53 mg/LAdditionally, the same author conducted studies for metals such as Zn, Ni, Pb, Cd, Mn, and Cu with removal percentages of 99.8%, 99.8%, 99.2%, 94.7%, 99.9%, and 99.8%, respectively. However, Sajjad et al. (2017) mention in their study that activated carbon (AC) achieved a maximum chromium removal of 70% at pH = 6. However, when the pH was reduced to 3, the removal increased to 82.8%. Therefore, they emphasize that the removal of potentially toxic elements from aqueous solutions largely depends on the pH. However, AC can be used for the removal of metals such as Cd and Pb, with removal percentages of 79.8% and 78%, respectively. On the other hand, Sanka et al. (2020) found in their study that rice husk biochar exhibited a higher chromium removal capacity compared to corn husk biochar, with 65% and 20%, respectively.

Industrial effluents from tanneries, rich in heavy metals and basic dyes like bromocresol purple (BCP), pose an economic problem and a serious environmental hazard. Therefore, in the research conducted by Aljerf (2018), the importance of the adsorption properties of a modified clinoptilolite (CL) (a type of zeolite) for the removal of total chromium (tCr) in the ammoniacal phase was evaluated. This study achieved a removal of 90%, with a maximum adsorption capacity of 37 mg/g. The adsorption was spontaneous and endothermic, with an increase in entropy.

Gupta et al. (2018) investigated the adsorption potential of sugarcane bagasse (SG), acid-modified sugarcane bagasse (ASG), base-modified sugarcane bagasse (BSG), and activated carbon (AC) as adsorbents for the removal of Cu (II) from synthetic effluents and industrial wastewater in a batch process. Thus, the following removal efficiencies were obtained: SG = 88.9%, ASG = 96.9%, BSG = 94.8%, and AC = 98.5%, respectively. The morphology and functionality of the adsorbents' surfaces were identified using scanning electron microscopy (SEM) and Fourier-transform infrared spectroscopy (FTIR), respectively. Additionally, bentonite clay demonstrated high performance, removing 99% of Cu (II) with an initial concentration of 3000 mg/L and a maximum adsorption capacity of 1000 mg/g. For the removal of Cd (II), a removal percentage of 96% was achieved, with an initial concentration of 2600 mg/L and a maximum adsorption capacity of 850 mg/g. For Pb (II), the removal percentage was 99%, with an initial concentration of

3000 mg/L and a maximum adsorption capacity of 900 mg/g. For Hg (II), the removal percentage was 92%, with the initial concentration being the same as for Cd (II). This was demonstrated by Maleki et al. (2019) in their study.

According to the study conducted by Jin et al. (2019), adsorption (ADS) and dielectrophoresis (DEP) techniques were combined (ADS/-DEP) to efficiently remove As(V) from industrial wastewater. The maximum removal efficiency of As(V) was 91.4%. To achieve this removal, fly ash, activated carbon, corn cobs, and plant ash were tested to determine the best adsorbent based on its adsorption capacity.

Plant ashes showed the highest adsorption capacity compared to the others. On the other hand, Birungi and Chirwa (2015) focused on the use of green algae Chlorella vulgaris to determine the sorption potential and recovery of Tl. It was found that removal efficiency reached 100% for lower concentrations of $\geq$150 mg/L of Tl. At higher concentrations, in the range of 250–500 mg/L, the algae performance was even better, with a sorption capacity (q_{max}) between 830 and 1000 mg/g. Prasetyo and Toyoda (2023) in their research prepared a low-cost adsorbent by immobilizing humic acid on a surface of silica gel coated with cross-linked chitosan (SiChiHA). The adsorbent was developed to selectively remove Th (IV) and U (VI) from an aqueous solution. Consequently, the removal was 47.1% and 56.13%, respectively, with an initial concentration of 12.34 mg/L and a maximum adsorption capacity of 30.6 mg/g for Th (IV), and an initial concentration of 33.45 mg/L and a maximum adsorption capacity of 75.4 mg/g for U (VI).

3.3. *P3. What is the most used adsorption isotherm for the removal of heavy metals in industrial wastewater, and what are the advantages and limitations of its application in different industrial contexts?*

The results regarding the most used isotherm for the adsorption of heavy metals from industrial wastewater show that the Freundlich isotherm is the most employed. Out of a total of 26 reviewed articles, 16 studies used the Freundlich isotherm, while the remaining 10 studies used the Langmuir isotherm, as shown in Fig. 2 through a bar chart.

Regarding Table 5, the studies conducted by Saleh Ibrahim et al. (2022), Beidokhti et al. (2019), Rahman et al. (2020), Sanka et al. (2020), Jeong et al. (2019), Li et al. (2019), Aljerf (2018), Sun et al. (2022), Sosun et al. (2022), Elboughdiri et al. (2021), Iqbal et al. (2017), Kose et al. (2015), and Akar et al. (2019) use the Freundlich isotherm model because it has demonstrated greater reliability in the results for the adsorption of heavy metals. Additionally, it has the ability to explain adsorption behavior on a heterogeneous (multilayer) surface of the adsorbent and presents adsorption sites with different energies.

The Langmuir isotherm is the second most used model for adsorption studies (Sosun et al., 2022; Khosravi et al., 2020). This model assumes that adsorption is homogeneous across all sites on the adsorbent surface and that its maximum adsorption corresponds to a saturated monolayer, further preventing interactions between the adsorbed species (Ozeken et al., 2023; Yayayürük and Erdem Yayayürük, 2016; Mohd et al., 2016; Noor et al., 2023).

On the other hand, it can be observed that in reaction kinetics, the pseudo-second-order model is the most used for fitting within the models according to the studies conducted (Fig. 3).

The results show that the isotherm model can vary according to the type of adsorbent, the correlation coefficient fit, and the type of heavy metal being treated. For example, studies such as (Ozeken et al., 2023; Mangood et al., 2023; Hussain et al., 2022; Sun et al., 2022; Yayayürük and Erdem Yayayürük, 2016) address Cu (II) using different adsorbents like mulberry leaves powder, porous particles, nanocellulose modified with polyethyleneimine (PEI) crosslinked with magnetic bentonite, and macroporous terpolymer of glycidyl methacrylate (GMA), methyl methacrylate (MMA), and divinylbenzene (DVB). Additionally, in terms of correlation coefficient fits, the Freundlich isotherm predominates in

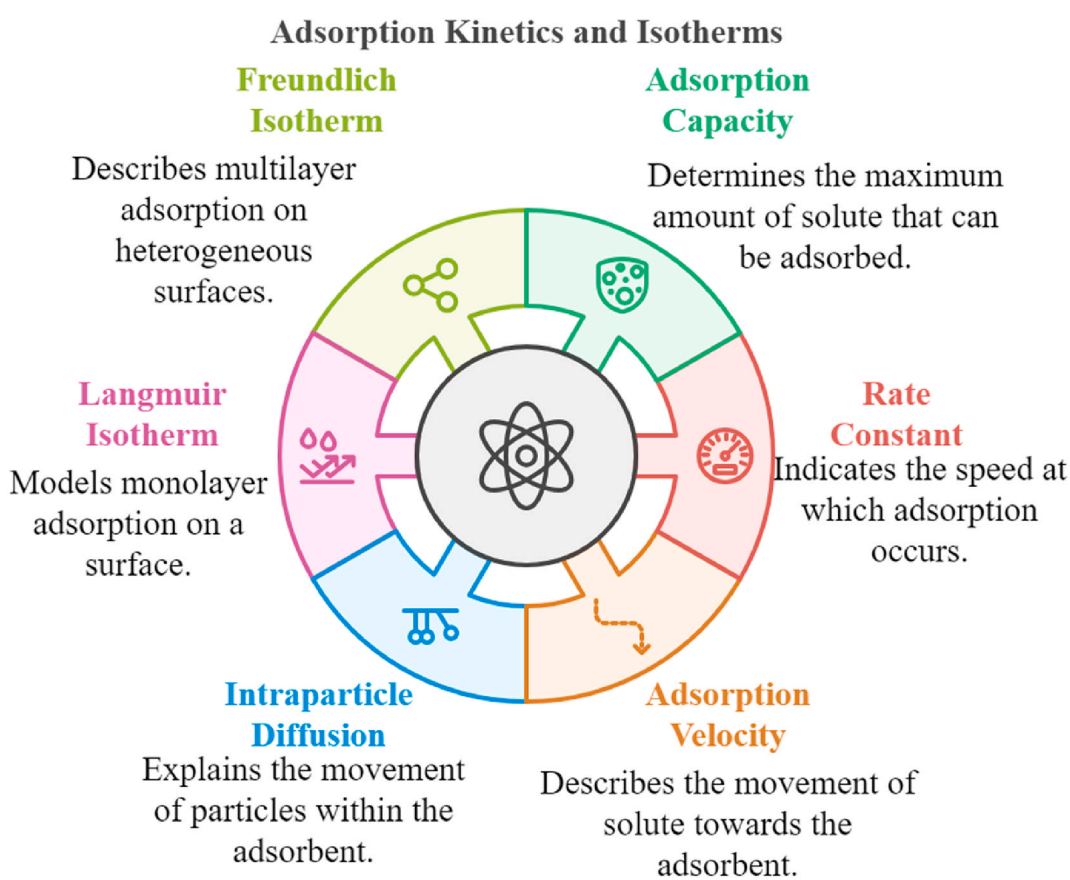
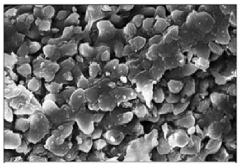
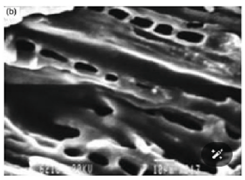
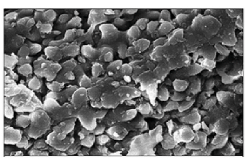
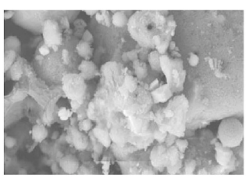
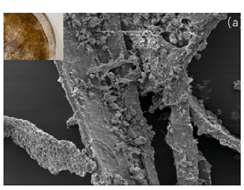
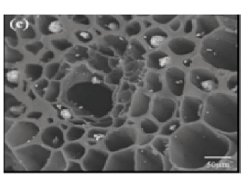
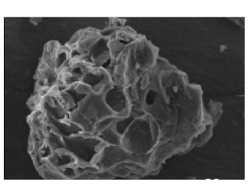
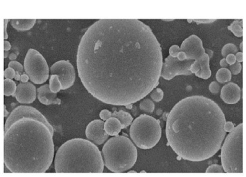


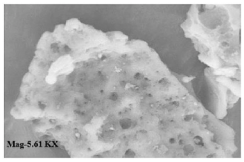
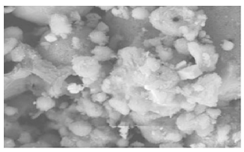
Fig. 4. Kinetics and isotherms in the adsorption process.

Table 7
Adsorbent used in the removal of heavy metals from industrial wastewater concerning the total surface area. Where As = Total surface area of the adsorbent.

Heavy metal	Surface morphology of the adsorbent	Adsorbent	A_s	Authors
Cr(VI)		- Natural moss	5.15 m^2/g	Ozeken et al. (2023)
Cr		- Steam-activated sawdust	795.68 m^2/g	Elboughdiri et al. (2021)
Cu(II)		- Natural moss	5.15 m^2/g	(Ozeken et al., 2023; Hussain et al., 2022; Sun et al., 2022)
		- Flocculant porous particles from ash residues	32.011 m^2/g	
		- Nanocellulose modified with polyethyleneimine (PEI) cross-linked with magnetic bentonite	14.24 m^2/g	
Cd(II)		- Magnetic biochar (MBN3)	63.5 m^2/g	Noor et al. (2023)
Hg		- Porous carbon derived from biospecies	350.8 m^2/g	Li et al. (2019a)
Mn (II)		- Flocculating porous particles from ash residues	32.011 m^2/g	Hussain et al. (2022)

(*continued on next page*)

Table 7 (*continued*)

Heavy metal	Surface morphology of the adsorbent	Adsorbent	A_s	Authors
Pb (II)		- Flocculating porous particles from ash residues	32.011 m^2/g	Hussain et al. (2022)
Ni (II)		- Flocculating porous particles from ash residues	32.011 m^2/g	Hussain et al. (2022)

most studies, demonstrating a good fit with pseudo-second-order reaction kinetics ($R^2 > 0.9$). It also highlights that the adsorption occurs on a heterogeneous, multilayer surface. In contrast, natural moss shows a better fit with the Langmuir isotherm, which indicates that the adsorption occurs on a homogeneous, monolayer surface (Ozeken et al., 2023).

In some of the reviewed studies, both the Freundlich and Langmuir models were applied and analyzed using determination coefficients (R^2), according to which model provided a better fit. For example, the study by Mangood et al. (2023) evaluated the adsorption capacities of various heavy metals using the same adsorbent. In this case, the reaction kinetics model used was the Pseudo-second-order model, which showed a better fit for the Langmuir model ($R^2 = 0.99$) for the metals Ni II, Pb II, and Co II. However, for Cu II, the Freundlich isotherm matched the fit of the Langmuir isotherm ($R^2 = 0.98$), indicating that adsorption occurs on a homogeneous and monolayer surface, while for Cu II, it highlights the complex mechanism of the chemical or physical adsorption taking place.

Ozeken et al. (2023), Noor et al. (2023), and Hussain et al. (2022) in their studies used both Freundlich and Langmuir isotherms, where the correlation coefficients were greater than 0.9. These were acceptable for expressing the adsorption mechanisms of each heavy metal they studied, revealing an external surface with some active sites distributed homogeneously and others distributed heterogeneously on the adsorbent.

Table 6 presents a variety of adsorbents and the associated adsorption mechanisms, allowing for an in-depth understanding of how different substances can be used for the removal of contaminants, especially heavy metals, from water. This table discusses various adsorbents, such as living organisms, biomass and activated carbon, highlighting their adsorption mechanisms, which include electrochemical interactions, chemical complexation and physical adsorption. Environmental conditions, such as pH and contact time, influence their effectiveness. The use of natural materials and waste offers sustainable solutions for the removal of contaminants from water.

The authors of the reviewed studies indicate that adsorption kinetics describes the rate at which a solute is adsorbed on the surface of an adsorbent, as well as the time that adsorbates remain at the solid-liquid interface. This phenomenon is crucial to understanding how the adsorption process takes place under different conditions. Adsorption isotherms play a fundamental role in characterizing the interaction between adsorbate and adsorbent, as well as in determining the optimal adsorption capacity of the adsorbent. The most common models, such as Langmuir and Freundlich, provide information on the nature of the adsorbent surface and the behavior of the system.

The adsorption kinetics equation can be represented graphically, where the shape of the straight line allows determining key parameters, such as the adsorption capacity of the adsorbent, the rate constant, the adsorption rate, and the intraparticle diffusion. The correlation coefficient obtained from these graphs is essential to identify the adsorption kinetics model that best describes the process under study. The Langmuir and Freundlich adsorption isotherms, by analyzing their slopes and intercepts, offer valuable information about the adsorption affinity, the mean free energy and the nature of the process (whether it is physisorption or chemisorption, as well as whether it is a monolayer or multilayer process).

Therefore, both the adsorption kinetics and the revised isotherms are essential tools to understand in depth the adsorption process, allowing to optimize applications in water treatment and in various industries where the removal of contaminants is critical; this relationship can be represented by Fig. 4.

In Table 7, it is shown that adsorbents such as porous carbon derived from bio-species and steam-activated sawdust have larger surface areas, with 350.8 m^2/g and 795.68 m^2/g, respectively. Following these, magnetic biochar (MBN3) has a surface area of 63.5 m^2/g, porous flocculating particles from ash residues have a surface area of 32.01 m^2/g, PEI-modified nanocellulose crosslinked with magnetic bentonite has 14.24 m^2/g, and natural moss has a much smaller surface area compared to the other adsorbents, with 5.15 m^2/g. These findings align with the research conducted by Córdova Llacsahuache and Torres Odar, 2020, which states that the surface area of the adsorbent increases the adsorption capacity. Therefore, a larger surface area means more available sites for the adsorbate molecules to adhere to. Additionally, a larger surface area of the adsorbent speeds up the adsorption process. And an adsorbent with a large surface area can be more efficient, reducing the amount of material needed and, therefore, the operational costs.

In Table 8, the advantages, regeneration cycles, and limitations of some adsorbents that are very useful for adsorption processes are presented. Although the studies do not provide solid information regarding regeneration cycles and costs, further research is needed.

3.4. Technical-economic analysis and a feasibility study of the adsorbent

Table 9 presents a variety of natural and recyclable adsorbents that show high efficiency in removing heavy metals, such as Copper Oxide and Banana Peel. These materials are effective in wastewater treatment, contributing to the improvement of water quality.

The reusability of many adsorbents, such as *Escherichia coli* and Spirulina platensis, reduces operating costs and promotes sustainability. The use of natural adsorbents and agricultural waste, such as Mango Seed Peel and Coffee Pulp, promotes sustainable practices and the circular economy.

Furthermore, the implementation of these adsorbents improves water quality and offers significant environmental benefits. The technical and economic feasibility of many of them is supported by studies that demonstrate their effectiveness, making them promising options for

Table 8
Comparison of the different adsorbents regarding their advantages, regeneration cycles, and limitations.

Adsorbent	Advantages	Regeneration cycles	Limitations	Authors
Natural moss (REB)	- Economical and sustainable for reducing environmental pollution. - Greater adsorption capacity for Cr (VI) and Cu (II).	- Up to 5 cycles can be used. No regeneration (Cr (VI) and Cu (II) ions could not be desorbed from REB).	- The presence or increase in salt concentration causes a decrease in the number of ions adsorbed, possibly due to the increased ionic strength in the presence of foreign ions. These ions can competitively saturate the active sites of REB, leading to reduced adsorption efficiencies. - Low adsorption capacity of natural REB.	Ozeken et al. (2023)
Magnetic Biocarbon (MBN3)	- The slow heating process of pyrolysis helps the volatile matter to break down, forming more surface pores, thus having a higher efficiency capacity to absorb or retain metals.		- The surface of the magnetic biocarbon is heterogeneous, which means that only certain sites are active, restricting its adsorption capacity for different types of metal ions. - The results obtained are from a laboratory under controlled conditions, whereas further research is needed at an industrial level. - At temperatures above 500 °C, the metal adsorption efficiency decreases. Specifically, an overdose would occur at 700 °C, reducing porosity and surface area.	Noor et al. (2023)
Coffee pulp	- The use of coffee pulp as an adsorbent can help contribute to Sustainable Development Goal No. 3 (Good Health and Well-being) and Goal No. 6 (Clean Water and Sanitation) of the 2030 Agenda for Sustainable Development. - It can be effective in the removal of the heavy metal Mn(II).		- Coffee pulp may have limitations. - Further research is needed regarding the use of coffee pulp as an adsorbent, with or without chemical modification, to verify its effectiveness and applicability.	(Gómez Aguilar et al., 2020)
Mulberry leaf powder	- They are cheap and easy to obtain. - It can be effective in the adsorption of heavy metals such as Pb^{2+}, Ni^{2+}, Co^{2+}, and Cu^{2+}, which indicates that it may also be used to adsorb other heavy metals present in wastewater.		- pH can be a very important factor to consider, as it needs to be adjusted for each metal that needs to be removed. - The maximum adsorption capacity for metals might not be sufficient for high concentrations of heavy metals in wastewater, leading to a decrease in adsorption effectiveness. - Competition for adsorption sites among ions when there are more heavy metals present. - The study does not mention whether the adsorbent is regenerable, which can be crucial and potentially expensive.	Mangood et al. (2023)
Activated carbon extracted from pineapples	- Ozone pumping is a good activating factor to increase efficiency in the adsorption process.		- The efficiency of heavy metal removal at high concentrations can decrease adsorption efficiency because active sites become saturated and adsorption starts occurring in less active or lower-energy areas.	(Saleh Ibrahim et al., 2022)
Palm cellulose copolymer	- The synthesized polymeric ligand absorbs heavy metals from electroplating wastewater with up to 95% efficiency.	- The ligand can be recycled for at least 10 cycles with no significant loss in its initial adsorption capacity.		Rahman et al. (2020)
***Escherichia coli* biofilm placed on zeolite**	- Rapid removal in the initial hours. - They are low-cost and abundant, as well as being very eco-friendly and sustainable for the environment.		- At high pH, the adsorption capacity for heavy metals may decrease. - High concentrations of the contaminant significantly reduce the efficiency of metal adsorption.	Khosravi et al. (2020)
Magnetite nanoparticles	- Non-toxic. - Abundant presence on Earth makes its use feasible and cost-effective. - Targeting specific contaminated areas through magnetic support. - The adsorption process occurs on the external surface of the iron oxide, ensuring shorter adsorption times (higher kinetic rates). - Iron oxide nanoparticles are reusable.		- Increasing the contact time, the number of available active sites on the adsorbents becomes occupied by heavy metal ions, resulting in surface saturation of the sorbent and reducing the diffusion of ions into the pores.	Sosun et al. (2022)
Humic acid on a surface of silica gel coated with cross-linked chitosan (SiChiHA)	- Low-cost adsorbent. Increasing the concentration of NaCl does not affect the efficiency of heavy metal removal.	At least five cycles without a significant loss of capacity.	- Efficiency can be affected by the pH parameter.	Prasetyo and Toyoda (2023)

wastewater treatment. Overall, these adsorbents are viable and environmentally friendly options for water treatment, aligning with current sustainability needs.

3.5. Applicability of the findings from the review

Industrial wastewater contains a variety of contaminants such as heavy metals, organic compounds, chemicals, and nutrients that can be

Table 9
Comparative analysis of adsorbents for heavy metal removal in industrial wastewater: Efficiency, sustainability, and economic feasibility.

Type of Adsorbent	Technical Aspects			Economic Aspects			Feasibility Study			Justification	
	Adsorption efficiency	Reusability	Sustainability	Material Cost	Operating Cost	Environmental Benefit	Technical feasibility	Economic Viability	Environmental Impact	Efficiency and Sustainability	Cost Reduction
Natural moss (Ozeken et al., 2023)	High in Cr(VI) and Cu(II).	Can be used multiple times without regeneration.	Natural material, reduces waste.	Low and abundant	Decreased by reusability	Improving public health and reducing pollutants.	High efficiency in the removal of Cr(VI) and Cu (II).	Low material and operation cost, high reusability.	It contributes to waste reduction and improves public health.	High in Cr(VI) and Cu(II). Natural material, reusable several times. Contributes to waste reduction.	Low material and operating costs due to its reusability. Improves public health by reducing pollution.
Escherichia coli (Khosravi et al., 2020)	Effective in Cu^{2+} and Zn^{2+}.	It can be reused.	Abundant microorganisms, sustainable processes.	Low (easy cultivation)	Maintenance and condition control	Generating income from metal recovery.	Validated in studies for the removal of heavy metals.	Low cultivation costs and potential for income from metal recovery.	Sustainable processes and improvement of water quality.	Effective in removing Cu^{2+} and Zn^{2+}. Abundant and sustainable microorganism.	Low cultivation costs, potential income from metal recovery.
Methylobacterium hispanicum EM2 (Jeong et al., 2019)	96% in Pb(II).	Reusable under controlled conditions.	Sustainable, contributes to waste reduction.	Cultivation and maintenance costs	Infrastructure for treatment	Improve water quality, avoid penalties.	High Pb(II) adsorption capacity, resistant to high concentrations.	Competitive production costs, economic benefits from metal reduction.	Eco-friendly solution that contributes to sustainability.	High adsorption capacity of Pb(II) (96%). Sustainable and environmentally friendly.	Competitive production costs, improved water quality avoids penalties.
Spirulina platensis (Malakootian et al., 2016)	Up to 36.01% in heavy metals.	Reusable.	Sustainable production, low resource consumption.	Relatively low	Nutrients and labor	Generation of additional income.	Proven in studies with high adsorption capacity.	Low production cost and potential for additional income.	Promotes sustainable practices and improves water quality.	High adsorption capacity for heavy metals. Sustainable production.	Low cultivation costs, possibility of additional income from marketing.
Coffee Pulp (Gómez Aguilar et al., 2020)	Up to 53.40% Mn(II).	Can be used as agricultural waste.	Contributes to the circular economy.	Low (agricultural by-product)	Transport and processing	Savings in treatment, reduction of waste.	Effective in removing contaminants, easy to prepare.	Low collection costs, savings on chemical treatments.	It uses agricultural waste, contributing to the circular economy.	Efficiency of up to 53.40% in Mn(II). Recyclable and sustainable material.	Savings in wastewater treatment by using a recyclable material.
Mango Seed Husk (Kose et al., 2015)	81–82% in Fe (II) and Mn (II).	Reusable.	Abundant, low cost.	Low (industry residue)	Minimal processing	Improvement in waste management.	Good adsorption capacity for heavy metals.	Low harvesting and processing costs.	Contributes to the reduction of agricultural waste.	High efficiency in adsorption of heavy metals. Abundant and low cost.	Low collection costs, reduced effluent treatment costs.
Filamentous green algae Spirogyra porticalis (Sayyaf et al., 2016)	27.48 mg/g for Cr(VI).	Reusable after treatment.	Natural material, contributes to sustainability.	Low (abundant in aquatic environments)	Maintenance and collection	Sustainability and waste reduction.	High adsorption capacity for Cr (VI) under controlled conditions.	Relatively low procurement and preparation costs.	Improves water quality and uses a natural resource.	Adsorption capacity of 27.48 mg/g for Cr(VI). Sustainable and easy to obtain.	Low production and preparation costs, improved water quality.

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Table 9 (*continued*)

Type of Adsorbent	Technical Aspects			Economic Aspects			Feasibility Study			Justification	
	Adsorption efficiency	Reusability	Sustainability	Material Cost	Operating Cost	Environmental Benefit	Technical feasibility	Economic Viability	Environmental Impact	Efficiency and Sustainability	Cost Reduction
Coffee pulp (Gómez Aguilar et al., 2020)	Up to 53.40% Mn(II).	Can be used as agricultural waste.	Sustainable and recyclable.	Low (agricultural by-product)	Processing and storage	Reduction of pollutants and improvement of water quality.	Efficient in removing heavy metals.	Savings in wastewater treatment.	It uses an agricultural by-product, contributing to sustainability.	Efficiency of up to 53.40% in Mn(II). Sustainable and recyclable.	Reduction of treatment costs by using waste material.
Pistachio hull (Beidokh ti et al., 2019)	14 mg/g for Ni.	Reusable.	Reduces agricultural waste.	Low (waste material)	Prosecution	Reduces agricultural waste.	Effective in removing heavy metals.	Minimum acquisition costs, high availability.	Contribute to the circular economy by reducing waste.	Adsorption capacity of 14 mg/g for Ni. Waste material, contributing to sustainability.	Low acquisition cost, reduced wastewater treatment costs.
Rice and corn husk (Sanka et al., 2020)	High metal removal capacity.	Reusable.	Sustainable and recyclable material.	Low (agricultural residues)	Processing and storage	Improves water quality, contributes to sustainability.	High adsorption capacity and easy preparation.	Low and competitive production costs.	It uses agricultural waste, contributing to sustainability.	High efficiency in metal removal. Abundant and sustainable material.	Low acquisition costs, reduced treatment costs.
Watermelon rind (Li et al., 2019a)	High in Tl(I).	Regenerable.	Agricultural waste, contributes to sustainability.	Low (agricultural by-product)	Production costs	Contributes to sustainability and soil improvement.	High efficiency in the removal of heavy metals.	Relatively low production costs.	Reduces agricultural waste and improves water quality.	High efficiency in removing contaminants. Sustainable and recyclable.	Savings in wastewater treatment and improvement in water quality.
Modified Kaolin (Yang et al., 2018)	High for Pb(II) and Cd(II).	It can be reused.	Sustainable, accessible.	Competitive	Low operating costs	Savings in treatments and improved water quality.	High adsorption capacity for heavy metals.	Competitive costs and savings on long-term treatments.	Contributes to sustainability and improves water quality.	High adsorption capacity for heavy metals. Sustainable and accessible.	Competitive production costs, lower long-term operating costs.
Copper Oxide (CuO) (Kondabey et al., 2019)	99.99% in Cr (III).	Reusable.	Recyclable material.	Dependent on synthesis methods	Maintenance and waste management	Improve water quality, avoid penalties.	High efficiency in Cr(III) removal.	Competitive production and operating costs.	Improves water quality and reduces pollution.	High efficiency in Cr(III) removal. Sustainable if production costs are optimized.	Possibility of reducing costs in wastewater treatment.
Modified Zeolite (Aljerf, 2018)	High in contaminants.	Reusable.	Sustainable and regenerable.	Low (accessible for implementation)	Competitive operating costs	Improvement in waste management.	High efficiency in removing contaminants.	Profitable due to its low cost and high effectiveness.	Promotes sustainable practices and improves water quality.	High efficiency in removing contaminants. Sustainable and regenerable.	Competitive operating costs, long-term cost reduction.
Bentonite Clay (Maleki et al., 2019)	High metal removal.	Reusable.	Low cost, natural resource.	Low (natural resource)	Low operating costs	Significant savings in treatment.	High adsorption capacity for heavy metals.	Low cost of raw materials and operation.	Contributes to sustainability and improves water quality.	High porosity and cation exchange capacity. Sustainable and abundant.	Low raw material costs, significant savings in wastewater treatment.
Iranian Sepiolite (Hojati and Landi, 2015)	More than 95% Zn2+.	Reusable.	Local mineral, contributes to sustainability.	Generally low	Waste management	Meets water quality standards.	High efficiency in Zn2+ removal.	Generally low material cost.	Reduce your carbon footprint	High efficiency in Zn^{2+} removal.	Reduced operating costs, high

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Table 9 (*continued*)

Type of Adsorbent	Technical Aspects			Economic Aspects			Feasibility Study			Justification	
	Adsorption efficiency	Reusability	Sustainability	Material Cost	Operating Cost	Environmental Benefit	Technical feasibility	Economic Viability	Environmental Impact	Efficiency and Sustainability	Cost Reduction
									by using a local mineral.	Sustainable and low cost.	efficiency reduces the need for additional treatments.
Magnetic Biochar (Noor et al., 2023)	47.9 mg/g for Cd2+.	Regenerable.	Agricultural waste, sustainable.	Relatively low	Optimized production costs	Contributes to sustainability.	Efficient in removing heavy metals.	Low production costs due to the use of agricultural waste.	Contributes to sustainability and improves water quality.	High efficiency in Cd^{2+} removal. Sustainable and recyclable.	Low production costs, reduction of operating costs in water treatment.
MCFA (Modified Coal Fly Ash) (Hussain et al., 2022)	99.91% for Pb^{2+} and 95.88% for Cu^{2+}.	Reusable.	Reduces industrial waste.	Relatively simple	Low operating costs	Contributes to sustainability.	High efficiency in the removal of heavy metals.	Low production costs and reduced operating costs.	Reduces industrial waste and improves water quality.	High efficiency in removing heavy metals. Sustainable by using waste.	Savings in operating and treatment costs, possibility of income from metal recovery.
Pine Sawdust (SAS) (Elboughdiri et al., 2021)	Effective in removing heavy metals.	Reusable.	Agricultural waste promotes sustainability.	$52/kg (low cost)	Favorable comparison	Improves water quality, reduces pollutants.	Effective in removing heavy metals.	Lower production costs than commercial adsorbents.	Promotes sustainable practices and improves water quality.	Effective in removing heavy metals. Sustainable and low cost.	Low production costs compared to commercial adsorbents.
Banana peel (Mohd et al., 2016)	Up to 89,286 mg/g of lead.	Reusable.	Reduce waste, sustainable.	Low or null	Economical due to the use of NaOH	Reduces waste and improves water quality.	High adsorption capacity for lead.	Low acquisition costs, uses a by-product.	Reduce waste and contribute to sustainability.	High efficiency in lead removal. Sustainable and low cost.	Low acquisition costs, reduced wastewater treatment costs.
Corncob (Jin et al., 2019)	High capacity after carbonization.	Reusable.	Agricultural waste, contributes to sustainability.	Low (agricultural by-product)	Processing costs	Reduces agricultural waste.	High efficiency in removing contaminants.	Low and sustainable production costs.	Reduces agricultural waste and improves water quality.	High efficiency in removing contaminants. Sustainable and low cost.	Low production costs, reduced operating costs.
Gum Arabic (Shalikh and Majeed, 2022)	Up to 90.7% for Cd.	Reusable.	Natural material, improved sustainability.	Low (available in large quantities)	Processing costs	Improves sustainability in treatment.	High efficiency in the removal of heavy metals.	Low acquisition costs, potential for revenue from secondary products.	Improves sustainability in wastewater treatment.	High efficiency in the removal of heavy metals. Sustainable and low cost.	Competitive production costs, improved water quality reduces treatment costs.
Palm Cellulose Copolymer (Rahman et al., 2020)	Up to 95% in heavy metals.	Recyclable at least 10 times.	Agricultural waste, biodegradable.	Low (abundant)	Lower operating costs	It contributes to the mitigation of environmental problems.	High efficiency in the removal of heavy metals.	Low production cost and high reusability.	It contributes to waste reduction and improves water quality.	High efficiency in removing heavy metals. Sustainable and recyclable.	Low raw material cost and high reusability reduce operating costs.
Poly (hydroxamic acid)-poly (amidoxime) (	Up to 99.9% of toxic metal ions.	Reusable.	Formation of stable,	Relatively economical	pH adjustment and maintenance	Generating income from metal recovery.	High adsorption capacity of metal ions.	Competitive production costs,	Contributes to sustainability	High adsorption capacity, up to 99.9% of metal	Operating costs justified by high efficiency

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Table 9 (*continued*)

Type of Adsorbent	Technical Aspects			Economic Aspects			Feasibility Study			Justification	
	Adsorption efficiency	Reusability	Sustainability	Material Cost	Operating Cost	Environmental Benefit	Technical feasibility	Economic Viability	Environmental Impact	Efficiency and Sustainability	Cost Reduction
Rahman et al., 2016)			sustainable complexes.					economic benefits from metal recovery.	and improves water quality.	ions. Sustainable in use.	in metal removal.
Activated Carbon (Saleh Ibrahim et al., 2022)	Greater than 90% in heavy metals.	It can be reactivated and reused.	Well-established, sustainable process.	$1000 - $3000 per ton	High operating costs	Improve sustainability, avoid fines.	High efficiency in the removal of heavy metals.	Relatively high production and operating costs.	It improves water quality, but can have a greater environmental impact if not managed properly.	High efficiency in removing heavy metals. Can be reactivated and reused.	High production and operating costs, but justified by effectiveness.
Modified Kaolin (Yang et al., 2018)	High adsorption capacity.	It can be reused.	Sustainable, accessible.	Competitive	Potentially low operating costs	Savings in treatments and improved water quality.	High adsorption capacity for heavy metals.	Competitive costs and savings on long-term treatments.	Contributes to sustainability and improves water quality.	High adsorption capacity. Sustainable and accessible.	Competitive costs, lower long-term operating costs.

toxic or harmful to human health and aquatic ecosystems. Therefore, the implementation of adsorption technology for treating industrial wastewater in various industrial contexts is promising as it offers a sustainable and cost-effective solution by utilizing an agro-industrial waste (Jeong et al., 2019).

Adsorption has been applied in industries such as manufacturing, chemicals, as well as in mining, metallurgy, chemical production, and the paper and pulp industry (for the removal of chemicals and dyes). This wastewater treatment technology is found in countries like the United States, Europe, China, India, and Brazil (Li et al., 2019b). However, it has limitations such as the proper selection of the adsorbent, operational conditions, the safe disposal of adsorbents saturated with contaminants, the requirement for conventional treatment prior to adsorption, and the challenges in scaling up from laboratory tests to large-scale industrial applications due to differences in conditions and the systems' capacity to handle large volumes of wastewater.

3.6. Knowledge gaps regarding the removal of heavy metals from industrial wastewater using adsorption technology

The present systematic review titled "Removal of Heavy Metals from Industrial Wastewater through Adsorption Technology" shows that the main heavy metals found in industrial effluents are: copper, lead, cadmium, nickel, chromium, iron, cobalt, manganese, zinc, mercury, titanium, arsenic, thorium, and uranium, these metal ions being considered potentially devastating to human health and the environment.

It is important to note that prolonged exposure to these heavy metals can cause serious health problems, such as damage to the nervous, respiratory, circulatory, and reproductive systems, as well as the development of chronic diseases like cancer. Therefore, the need to reduce their concentration in bodies of water, soil, and air has led to the implementation of techniques like adsorption, which have proven effective in removing these contaminants.

Among adsorption techniques, the use of biomass has proven efficient for the removal of heavy metals due to its easy availability, low cost, and high adsorption capacity, as seen in the use of rice husks, corn husks, sugarcane bagasse, pistachio shells, banana peels, and others. However, a deeper understanding is still needed regarding how to modify their physicochemical properties to increase active sorption sites efficiently. Specifically, further study is required on the adsorption mechanisms and how the functional groups present in biomass interact with different metal ions, in order to design and optimize adsorption processes more effectively.

Regarding high concentrations of contaminants, the impact or effect on the efficiency of adsorbents can be identified, such as variability in adsorption capacity. Despite various studies on the application of different adsorbents, there is a lack of research that provides a comparison to evaluate how high contaminant concentrations affect the adsorption capacity of each metal ion.

Regarding low-concentration pollutants, which are also very common and important in industry, recently, new adsorbent materials, such as nanomaterials and bioadsorbents, have been developed, which show a higher capture capacity even at low concentrations (Satyam and Patra, 2024). Furthermore, emerging technologies, such as adsorption in combination with electrochemical and photocatalytic processes, are being explored, which promise to improve the removal efficiency of pollutants in industrial wastewater (Abebe et al., 2018; Twizerimana and Wu, 2024). For the future, a more integrated approach combining different treatment technologies is envisaged, as well as the implementation of real-time monitoring systems to detect and manage low-concentration pollutants, thus ensuring a more effective and sustainable treatment of industrial wastewater.

Regarding pH conditions, it has been reviewed that pH can significantly influence the adsorption capacity for heavy metals, where elevated pH or high concentrations of contaminants can decrease the efficiency of heavy metal adsorption. Additionally, it has been noted that there are innovative adsorbent materials and natural and industrial sorbents with large surface areas and microporous characteristics, such as the use of agricultural residues, zeolite, biomass, industrial by-products, and polymeric materials.

Despite advances in adsorption technology for heavy metal removal from industrial wastewater, there are significant gaps in knowledge regarding the costs associated with its implementation. Many studies focus on the effectiveness of adsorbent materials but lack a comprehensive analysis of the capital and operating costs required for large-scale adsorption systems, including material procurement, equipment maintenance, and waste treatment. Furthermore, there is a lack of comparative studies evaluating the costs of adsorption versus other treatment technologies, such as coagulation-flocculation or filtration, which is crucial for industries to make informed decisions. Finally, operating costs can vary significantly depending on factors such as metal concentration, adsorbent type, and operating conditions, but there is a paucity of research analyzing how these factors influence the total costs of the adsorption process. Addressing these gaps is essential to promote the adoption of adsorption technologies in industrial wastewater treatment, ensuring their economic viability and long-term sustainability.

4. Conclusions

This study has shown that adsorption is an effective technique for the removal of heavy metals in wastewater, highlighting the importance of properly selecting adsorbents based on the specific characteristics of the pollutants and the conditions of the medium. Adsorption is presented as an effective solution for the removal of heavy metals due to the low implementation and maintenance costs, in relation to conventional heavy metal recovery treatments. One of the most significant findings is that the adsorption capacity is strongly related to the characteristics of the adsorbent, including its specific surface area, porosity and chemical nature. Materials such as agro-industrial waste, zeolites and biochars have proven to be highly effective in capturing heavy metals, offering a sustainable and economic alternative to conventional adsorbents, such as activated carbon. These materials are not only effective, but also contribute to waste reduction, aligning with the principles of circular economy. It will be found that the pH of the medium considerably influences the efficiency of adsorption. In general, high pH favors the removal of heavy metals, although at very high concentrations of contaminants, efficiency can be compromised. This finding underlines the importance of optimizing operating conditions to maximize metal removal, which implies rigorous control of pH and concentration of contaminants in the effluent.

Despite advances in the development of new adsorbent materials, there is an urgent need for further comparative research evaluating the impact of high concentrations of contaminants on the adsorption capacity of different metal ions. Furthermore, the use of materials of biological origin and agro-industrial waste is presented as a promising and sustainable alternative, contributing not only to the removal of heavy metals, but also to waste management. The implementation of innovative and sustainable adsorption technologies is essential to address heavy metal pollution and protect public health and the environment.

CRediT authorship contribution statement

Fernando García Ávila: Writing – original draft, Methodology, Conceptualization. **Janneth Cabrera-Sumba:** Methodology, Investigation, Formal analysis. **Sandra Valdez-Pilataxi:** Visualization, Resources, Data curation. **Jessica Villalta-Chungata:** Visualization, Resources, Investigation. **Lorgio Valdiviezo-Gonzales:** Writing – original draft, Validation. **Cecilia Alegria-Arnedo:** Resources, Formal analysis.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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