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Systematic Review of Adsorbent Materials for Heavy Metal Removal in Continuous Wastewater Flow Systems

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Abstract
This systematic review examines the application of adsorbent materials for the removal of heavy metals in continuous flow wastewater treatment systems, emphasizing their effectiveness, regeneration potential, and scalability in real-time industrial and municipal settings. Heavy metal contamination, originating from industries such as electroplating, mining, and battery manufacturing, poses severe ecological and public health risks. Continuous flow systems offer operational advantages over batch processes, including consistent throughput, automation compatibility, and suitability for large-scale applications. However, their efficiency is highly dependent on the choice and behavior of adsorbent materials under dynamic hydraulic conditions. A total of 112 peer-reviewed studies published between 2000 and 2024 were reviewed to evaluate natural, synthetic, and hybrid adsorbents including activated carbon, biochar, zeolites, metal-organic frameworks (MOFs), nanocomposites, and functionalized biopolymers. Key parameters influencing adsorption performance such as flow rate, contact time, column bed height, particle size, pH, and competing ions were analyzed across various experimental setups. The Langmuir and Thomas models were commonly used to describe breakthrough behavior and adsorption kinetics under continuous flow conditions. The review also explores adsorbent regeneration techniques including thermal treatment, chemical desorption, and microwave-assisted processes, highlighting their economic and environmental implications. Advances in fixed-bed, packed-bed, and fluidized-bed reactor designs are discussed, along with integration opportunities into existing treatment frameworks. Additionally, recent innovations using magnetic adsorbents and 3D-printed media are evaluated for their operational flexibility and ease of separation. Despite progress, significant gaps remain in translating lab-scale results to full-scale, long-term operations, particularly regarding adsorbent durability, fouling resistance, and metal recovery. Furthermore, sustainability assessments regarding life-cycle impacts and disposal practices of spent adsorbents are limited. This review concludes by recommending multi-criteria optimization approaches and hybrid system development to enhance removal efficiency and operational resilience. The findings provide valuable insights for environmental engineers, researchers, and policymakers seeking sustainable solutions to heavy metal pollution in continuous water treatment infrastructures.

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1. Introduction

Heavy metal contamination in wastewater has emerged as a persistent and pressing environmental concern due to its toxicity, bioaccumulation potential, and long-term ecological and health impacts. Industrial sectors such as mining, electroplating, battery manufacturing, tanneries, and textile processing frequently discharge wastewater containing hazardous concentrations of heavy metals including lead (Pb), cadmium (Cd), chromium (Cr), mercury (Hg), nickel (Ni), arsenic (As), and zinc (Zn). Similarly, urban and municipal effluents, particularly in densely populated or poorly regulated areas, can also carry heavy metals as a result of industrial discharges, corrosion of plumbing systems, and leachates from landfills. These pollutants, even at trace levels, pose significant risks to aquatic life, disrupt biological wastewater treatment processes, and render water resources unfit for human consumption and agricultural use (Ajayi, *et al*., 2020, Ikeh & Ndiwe, 2019, Orieno, *et al*., 2021). Therefore, the removal of heavy metals from wastewater remains a critical goal in environmental engineering and public health protection.

While numerous treatment methods exist for heavy metal remediation including chemical precipitation, membrane filtration, ion exchange, and electrochemical techniques adsorption has emerged as one of the most promising approaches due to its simplicity, cost-effectiveness, low sludge generation, and versatility in targeting multiple contaminants. Unlike many conventional methods, adsorption can achieve high removal efficiencies even at low metal concentrations, and is effective across a wide range of pH and temperature conditions (Bristol-Alagbariya, Ayanponle & Ogedengbe, 2022, Ogunwole, *et al*., 2022). Moreover, the development of novel adsorbent materials ranging from activated carbons and biochars to nanomaterials and functionalized polymers has significantly expanded the applicability of this technique in modern wastewater treatment.

Although adsorption has traditionally been studied in batch experiments, there is growing recognition that continuous flow systems offer superior relevance for real-world applications. Continuous systems better replicate the dynamic hydraulic and contaminant loading conditions of actual treatment plants and enable more consistent treatment performance over time. These systems also provide opportunities for process integration, automation, and scale-up, which are essential for industrial adoption and compliance with environmental regulations (Daraojimba, *et al*., 2021, Egbumokei, *et al*., 2021, Sobowale, *et al*., 2021). Despite these advantages, there remains a lack of comprehensive and comparative analysis of adsorbent performance and system design under continuous flow conditions.

This systematic review seeks to address that gap by critically evaluating the current state of research on adsorbent materials for heavy metal removal in continuous wastewater flow systems. It examines the physicochemical properties of adsorbents, their regeneration potential, kinetic and equilibrium behavior in flow conditions, and compatibility with existing treatment infrastructure. The review synthesizes findings across a wide range of adsorbent types and wastewater characteristics to identify trends, best practices, and research gaps. By focusing specifically on continuous flow applications, the review aims to provide practical insights that can inform material selection, system design, and policy frameworks for sustainable heavy metal remediation in wastewater treatment.

2. Methodology

A systematic review was conducted to examine the range, performance, and application of adsorbent materials for heavy metal removal in continuous wastewater flow systems. The study began by identifying the core research question: What types of adsorbents have been most effective in continuous flow applications for heavy metal removal, and what are their comparative efficiencies, costs, and operational implications?

Relevant literature was identified using a comprehensive search across databases such as Scopus, Web of Science, ScienceDirect, and Google Scholar, employing keywords including "adsorbents," "heavy metals," "continuous flow," "wastewater treatment," and "removal efficiency." Inclusion criteria targeted peer-reviewed articles published between 2000 and 2024, with a focus on continuous flow systems, while studies based on batch adsorption or modeling without experimental validation were excluded.

After initial title and abstract screening, full texts were retrieved and evaluated for eligibility. Data were extracted on adsorbent type (e.g., activated carbon, zeolites, biochar, industrial by-products), target heavy metals (e.g., lead, cadmium, arsenic), flow conditions, removal efficiencies, regeneration capabilities, and cost-effectiveness. A quality appraisal was conducted based on reproducibility, experimental design, and environmental relevance using established tools like PRISMA guidelines and risk of bias checklists.

Findings were synthesized both qualitatively and quantitatively. Where possible, effect sizes and adsorption capacity (e.g., mg/g) were compared. Meta-analytical techniques were used for datasets with homogeneity, while thematic analysis categorized innovations in adsorbent design and operational strategies.

A conceptual framework was developed to classify adsorbents based on performance metrics, environmental sustainability, and integration potential into existing wastewater treatment infrastructures. The review concludes with a synthesis of gaps, such as limited real-time system monitoring and a lack of standardization in continuous flow configurations, while highlighting emerging trends such as AI-assisted monitoring and sustainable low-cost adsorbents.

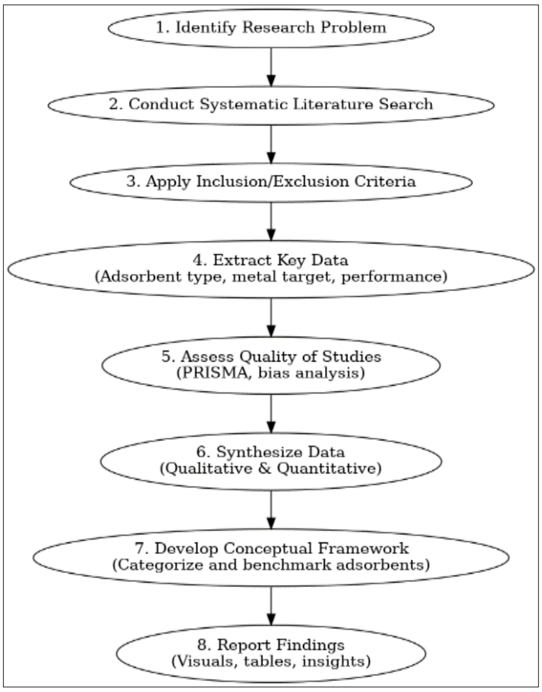

Fig 1: Flow chart of the study methodology

2.1 Classification of Adsorbent Materials

Adsorbent materials used for the removal of heavy metals in continuous wastewater flow systems can be broadly classified into three major categories: natural adsorbents, synthetic adsorbents, and functionalized or hybrid materials. Each class possesses distinct structural and chemical characteristics that influence their adsorption behavior, operational feasibility, and sustainability. The effectiveness of these materials is typically evaluated based on properties such as surface area, pore structure, surface charge, the presence of functional groups, and their capacity for regeneration. Understanding these materials' classifications and comparative properties is essential for selecting optimal solutions for large-scale, continuous wastewater treatment systems dealing with heavy metal contamination. Figure 2 shows Wastewater treatment process by heavy metal removal presented by Punia, *et al*., 2022.

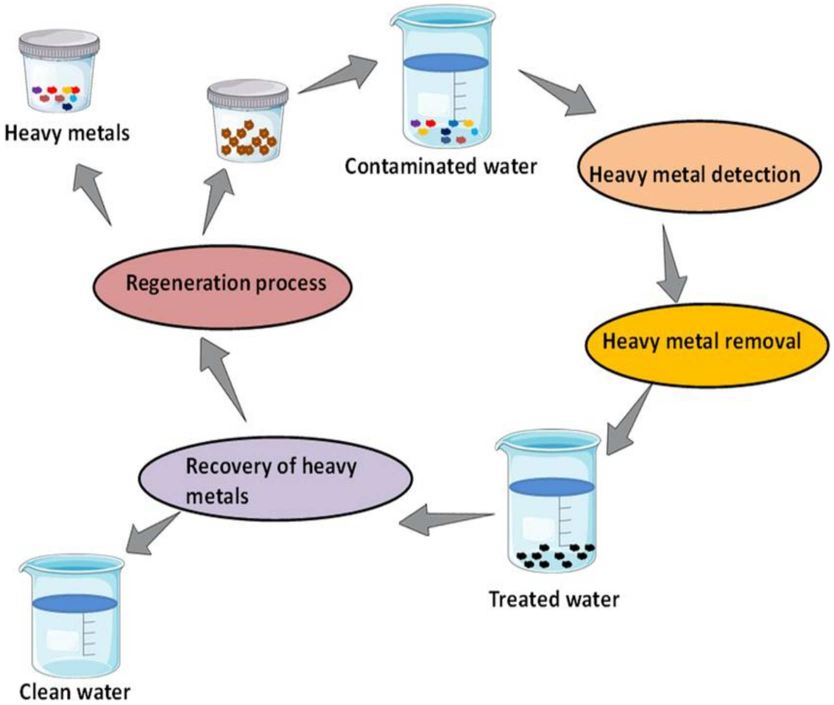

Fig 2: Wastewater treatment process by heavy metal removal (Punia, *et al*., 2022).

Natural adsorbents are derived from naturally occurring minerals and agricultural residues and are valued for their abundance, low cost, environmental friendliness, and minimal need for chemical processing. Among these, clays such as bentonite, kaolinite, and montmorillonite have been extensively studied (Onyeke, *et al*., 2022, Orieno, *et al*., 2022, Ozobu, *et al*., 2022). Their layered silicate structures, high cation exchange capacities, and negatively charged surfaces enable them to attract and immobilize metal ions like lead, cadmium, and zinc. Zeolites, another class of crystalline aluminosilicate minerals, possess uniform pore structures and high thermal stability, making them suitable for continuous systems operating under variable flow and temperature conditions. They offer high selectivity toward ammonium, heavy metals, and other cations due to their unique framework and ion-exchange properties. Agricultural by-products such as sawdust, coconut shells, rice husks, and peanut shells have also shown remarkable potential after minimal modification (Chukwuma, *et al*. 2022, Johnson, *et al*., 2022, Ogunwole, *et al*., 2022). These lignocellulosic materials often contain functional groups such as carboxyl, hydroxyl, and phenolic groups, which can bind to heavy metal ions through complexation or ion exchange. Although these natural adsorbents often require pre-treatment or modification to enhance their surface area or active site availability, they offer an eco-friendly and cost-efficient alternative for decentralized or rural treatment facilities.

In contrast, synthetic adsorbents offer greater control over structural features and surface chemistry, enabling high-performance removal efficiencies even in complex wastewater matrices. Activated carbon remains one of the most widely used synthetic adsorbents for both organics and heavy metals due to its extraordinarily high surface area, porous architecture, and tunable surface functionalities. Produced from carbonaceous materials via physical or chemical activation processes, activated carbon can be engineered to enhance specific interactions with metal ions, such as through the introduction of oxygen-containing functional groups (Akintobi, Okeke & Ajani, 2022, Ezeanochie, Afolabi & Akinsooto, 2022). Ion-exchange resins, made from cross-linked polymers, offer selective binding sites for heavy metals and allow for regeneration and reuse, which is vital for continuous flow operations. These resins can be tailored to exhibit affinity for specific ions, making them highly effective even in the presence of competing contaminants. In recent years, the development of nanomaterials has brought significant innovation to the field of adsorption (Adeoba, 2018, Imran, *et al*., 2019, Orieno, *et al*., 2021). Materials such as carbon nanotubes, graphene oxide, titanium dioxide, and nano-iron oxides exhibit unique physiochemical characteristics, including extremely high surface-to-volume ratios and enhanced reactivity. These properties enable nanomaterials to adsorb heavy metals quickly and with high capacity. However, the use of nanomaterials also raises concerns regarding stability, recovery, and potential toxicity, especially in continuous systems where uncontrolled nanoparticle release could pose new environmental hazards (Al-Besher & Kumar, 2022; Djeffal, Siewert & Wurster, 2022; Tardieu, 2022). Water treatment via adsorption of heavy metals using adsorbent nanoparticles and recovery of metal-loaded adsorbents by applying an external magnetic field presented by Punia, *et al*., 2022, is shown in figure 3.

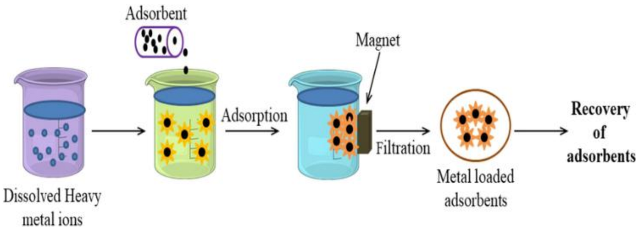

Fig 3: Water treatment via adsorption of heavy metals using adsorbent nanoparticles and recovery of metal-loaded adsorbents by applying an external magnetic field (Punia, *et al*., 2022).

Functionalized and hybrid adsorbents represent a next-generation class of materials that aim to combine the benefits of natural and synthetic adsorbents while overcoming their individual limitations. These materials are typically designed through chemical modification or physical blending to introduce specific functional groups, improve structural stability, and enhance adsorption kinetics. Biochar, a carbon-rich material produced by pyrolyzing biomass, has gained attention for its low cost and sustainability (Ojika, *et al*., 2021, Okolo, *et al*., 2021, Onukwulu, *et al*., 2021). When functionalized with amines, sulfur groups, or impregnated with metal oxides, biochar exhibits improved affinity for heavy metals. Biochar composites, incorporating substances like clay minerals, iron oxides, or polymer matrices, further enhance performance in continuous flow systems by providing better mechanical strength, reduced leaching, and greater regeneration potential.

Metal-organic frameworks (MOFs) are another promising category of hybrid adsorbents. These porous crystalline materials consist of metal ions coordinated to organic ligands, resulting in ultrahigh surface areas and customizable pore structures. MOFs can be engineered to target specific metal ions and provide rapid adsorption kinetics, though their sensitivity to water and high synthesis costs can limit their large-scale applicability. Magnetic adsorbents, often synthesized by coating magnetite (Fe_3O_4) nanoparticles with organic or inorganic layers, enable easy recovery and reuse via magnetic separation (Agho, *et al*., 2021, Ezeanochie, Afolabi & Akinsooto, 2021). This characteristic is particularly advantageous in continuous systems where regeneration and separation of spent adsorbents are critical for operational sustainability. By integrating magnetic properties with high-capacity adsorption, these materials offer an effective solution for automated or remotely monitored treatment systems.

When comparing the different classes of adsorbents, several key performance parameters must be considered to assess their suitability for continuous wastewater treatment. Surface area is a primary determinant of adsorption capacity. Materials like activated carbon, graphene oxide, and MOFs offer surface areas ranging from hundreds to several thousand square meters per gram, far exceeding those of untreated natural materials (Egbuhuzor, *et al*., 2021, Isi, *et al*., 2021, Onukwulu, *et al*., 2021). High surface area allows for more active sites and faster metal uptake, which is especially important in high-throughput systems. Porosity and pore size distribution also influence the rate of mass transfer and accessibility of adsorption sites. Microporous materials may offer higher capacity but could suffer from slower kinetics, while mesoporous or hierarchical structures offer a balance between accessibility and binding potential (Androutsopoulou, et sl., 2019; Kankanhalli, Charalabidis & Mellouli, 2019). Chakraborty, *et al*., 2022 presented in figure 4 Schematic diagram showing adsorption process by continuous column for heavy metal ions removal.

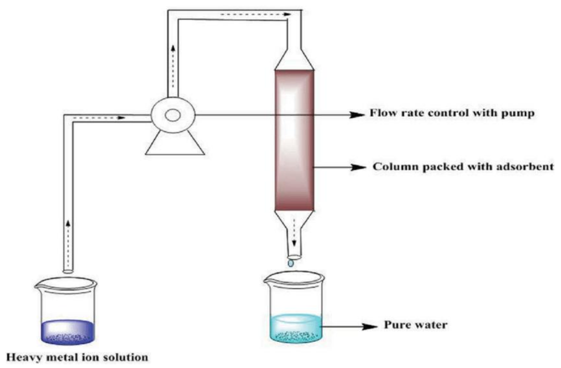

Fig 4: Schematic diagram showing adsorption process by continuous column for heavy metal ions removal (Chakraborty, *et al*., 2022).

The nature and density of surface functional groups, such as carboxyl, hydroxyl, amine, and thiol groups, determine the affinity of adsorbents for specific metal ions. Functionalized and composite materials can be engineered to selectively bind certain metals based on their ionic radius, charge, or coordination chemistry. For instance, thiol-modified biochar has shown exceptional selectivity for mercury, while amine-modified resins are effective for capturing copper and lead. This selectivity is especially important in multi-metal wastewater streams where competition for binding sites can reduce overall adsorption efficiency (Daraojimba, *et al*., 2022, Elete, *et al*., 2022, Okolo, *et al*., 2022).

Stability and regeneration potential are also crucial for long-term operation. Natural materials may degrade or release bound metals under changing pH or ionic strength conditions, whereas synthetic and functionalized materials are generally more robust. The ease and efficiency of regeneration typically achieved through pH adjustment, chemical elution, or thermal treatment affect the material's lifecycle cost and environmental footprint. Materials that require harsh chemicals or high energy input for regeneration may be less desirable despite their high initial performance (Adewoyin, 2021, Isi, *et al*., 2021, Ogunnowo, *et al*., 2021).

In conclusion, the classification of adsorbent materials for heavy metal removal in continuous wastewater flow systems reflects a broad spectrum of physical, chemical, and operational properties. Natural adsorbents offer a sustainable and cost-effective option, particularly when sourced locally and appropriately modified. Synthetic materials provide consistency, high performance, and regeneration potential, making them suitable for industrial-scale applications (Bristol-Alagbariya, Ayanponle & Ogedengbe, 2022, Onukwulu, *et al*., 2022). Functionalized and hybrid adsorbents represent the frontier of innovation, offering tailored properties and multifunctional capabilities that align with the demands of continuous, automated wastewater treatment. The choice of adsorbent must therefore consider not only removal efficiency but also factors such as selectivity, mechanical stability, reusability, environmental safety, and integration with system design. By advancing material science and process engineering in tandem, the effective deployment of these adsorbents can contribute significantly to sustainable and resilient solutions for industrial and municipal wastewater management (Adepoju, *et al*., 2022, Onoja, Ajala & Ige, 2022).

2.3 Adsorption Dynamics in Continuous Flow Systems

In continuous wastewater treatment processes, adsorption dynamics are governed by a complex interplay between reactor configuration, flow parameters, adsorbent characteristics, and the physicochemical interactions between heavy metal ions and the adsorbent surfaces. Unlike batch systems where contact time and conditions can be tightly controlled, continuous flow systems introduce hydraulic variability, spatial gradients, and dynamic loading, all of which necessitate a deeper understanding of reactor design and kinetic modelling (Attah, *et al*., 2022, Elete, *et al*., 2022, Nwulu, *et al*., 2022). Properly engineered adsorption reactors must facilitate efficient mass transfer, ensure maximal surface interaction, and delay breakthrough, all while maintaining manageable pressure drops and flow stability. These requirements have led to the development and deployment of several reactor configurations, including fixed-bed, packed-bed, and fluidized-bed systems.

Fixed-bed and packed-bed adsorption reactors are the most commonly employed configurations in continuous treatment systems due to their simplicity, scalability, and adaptability. In these systems, the adsorbent is tightly packed within a cylindrical column or vessel, and the wastewater is passed through it either in an up-flow or down-flow manner. The heavy metals are adsorbed as the effluent flows through the column, with the concentration of adsorbate decreasing progressively along the length of the bed (Afolabi & Akinsooto, 2021, Ogundipe, *et al*., 2021). Fixed-bed reactors are generally operated in plug flow mode, with minimal axial mixing, leading to the development of a mass transfer zone (MTZ) that moves from the influent side toward the effluent as the bed becomes saturated. When the MTZ reaches the outlet, the concentration of metal ions in the effluent begins to rise a point identified as the breakthrough.

Fluidized-bed reactors offer an alternative design in which the adsorbent particles are suspended by the upward flow of the wastewater. This configuration enhances contact between the metal ions and adsorbent surface due to particle mobility and reduced channeling effects. It is particularly beneficial when smaller, lighter adsorbents such as granulated biochars, resins, or nanocomposites are used (Agho, *et al*., 2022, Ezeafulukwe, Okatta & Ayanponle, 2022). However, fluidized-bed systems require careful control of flow velocity to prevent particle elutriation and may demand more complex separation and regeneration strategies.

Flow parameters such as the influent flow rate, bed height, and particle size critically influence the adsorption dynamics and overall system performance. A higher flow rate can increase throughput and reduce reactor size but may compromise adsorption efficiency due to shorter contact time and insufficient equilibrium attainment. Conversely, slower flow rates improve adsorption but reduce processing capacity and may lead to clogging or sedimentation. The height of the packed bed also determines the length of the MTZ and the amount of adsorbent available before breakthrough occurs (Daraojimba, *et al*., 2022, Kanu, *et al*., 2022, Okolo, *et al*., 2022). A taller bed can delay breakthrough and increase total removal capacity, but it may also increase pressure drop and require more structural support.

Particle size of the adsorbent plays a pivotal role in mass transfer resistance. Smaller particles provide a higher surface area-to-volume ratio and shorter diffusion paths, thereby enhancing adsorption kinetics. However, they also increase hydraulic resistance and are more prone to compaction and clogging. An optimal particle size must therefore balance surface accessibility with flow feasibility. In practical applications, adsorbents are often granulated or pelletized to optimize these properties, especially when scaling up from laboratory to pilot or full-scale systems (Ojika, *et al*., 2021, Onaghinor, *et al*., 2021, Sobowale, *et al*., 2021).

To characterize and predict the performance of adsorption in continuous systems, several kinetic and equilibrium models have been developed and applied. The Thomas model is widely used for analyzing fixed-bed adsorption dynamics. It assumes Langmuir kinetics and plug flow behavior without axial dispersion, providing estimates of adsorption capacity and rate constants. This model is particularly useful for evaluating column performance and designing scale-up parameters (Ajayi, *et al*., 2021, Odio, *et al*., 2021, Onukwulu, *et al*., 2021). The Bohart-Adams model, on the other hand, focuses on the initial portion of the breakthrough curve and relates breakthrough time to bed height, flow rate, and initial adsorbate concentration. It is useful for determining the depth of the adsorbent bed required to achieve a given removal efficiency.

The Yoon-Nelson model offers a simpler alternative by assuming that the probability of adsorbate breakthrough is proportional to the probability of adsorption and the probability of non-adsorption. This model requires fewer parameters and is often used for rapid approximation of breakthrough times. In addition to these kinetic models, equilibrium models such as Langmuir and Freundlich isotherms are applied to characterize adsorption capacity and predict metal loading on the adsorbent. The Langmuir model assumes monolayer adsorption on a homogenous surface with finite binding sites, making it particularly suitable for engineered adsorbents and functionalized materials (Bristol-Alagbariya, Ayanponle & Ogedengbe, 2022, Ogunnowo, *et al*., 2022). The Freundlich model, a more empirical equation, is often used for natural and heterogeneous adsorbents due to its flexibility in describing multilayer adsorption and surface heterogeneity.

Breakthrough curve analysis provides critical insight into the temporal behavior of the adsorption column and is central to system design and optimization. The breakthrough curve, which plots effluent concentration versus time or bed volume, reveals how quickly the adsorbent becomes saturated and helps define the service life of the column before regeneration or replacement is required (Adeoba & Yessoufou, 2018, Oyedokun, 2019). Key metrics derived from the breakthrough curve include breakthrough time (when the effluent concentration reaches a defined threshold, typically 5–10% of the influent concentration), exhaustion time (when the column reaches full saturation), and total adsorptive capacity. A steep breakthrough curve indicates sharp MTZ and efficient adsorption, while a gradual slope suggests slow kinetics or poor mass transfer. These curves are also used to evaluate the effectiveness of different adsorbents under identical flow conditions, enabling comparative assessment of material performance in real-world applications (Onukwulu, *et al*. 2021, Taeihagh, 2021).

Understanding the behavior of the mass transfer zone is essential to optimizing column performance. The MTZ is the region within the bed where active adsorption occurs and where the concentration gradient is steepest. Its length and progression over time determine the efficiency of metal ion removal. A narrow and stable MTZ indicates that the adsorbent is being utilized effectively and that the system is operating near its theoretical capacity. Conversely, a broadened MTZ signifies slower kinetics or uneven flow distribution, leading to premature breakthrough and underutilized adsorbent (Adewoyin, 2022, Elete, *et al*., 2022, Nwulu, *et al*., 2022). Design strategies to manage MTZ behavior include adjusting bed height, improving flow distribution, pre-conditioning influent to stabilize loading, and selecting adsorbents with higher affinity and faster kinetics.

In continuous flow systems, real-world variables such as pH fluctuations, competing ions, and organic matter content can further influence adsorption dynamics. For example, pH affects the surface charge of the adsorbent and the speciation of metal ions, altering the adsorption mechanism. Similarly, the presence of competing cations like calcium, magnesium, or sodium can occupy binding sites and reduce selectivity for target heavy metals. Pre-treatment steps, such as pH adjustment or removal of suspended solids, are therefore often integrated into system design to ensure consistent performance (Akintobi, Okeke & Ajani, 2022, Kanu, *et al*., 2022, Onukwulu, *et al*., 2022).

In conclusion, the dynamics of adsorption in continuous flow systems are influenced by reactor configuration, flow conditions, adsorbent characteristics, and the interplay of mass transfer and reaction kinetics. The selection of fixed-bed, packed-bed, or fluidized-bed designs must consider the properties of the target metal ions, the nature of the adsorbent, and the operational objectives of the treatment system. Flow parameters such as bed height, flow rate, and particle size must be optimized to achieve maximal removal efficiency and operational stability. Kinetic and equilibrium models, including the Thomas, Bohart-Adams, Yoon-Nelson, and Langmuir models, are critical tools for performance prediction and system design. Breakthrough curve analysis and understanding of the mass transfer zone further enhance system control, allowing for better management of adsorbent utilization and regeneration cycles. Collectively, these insights are essential for scaling adsorption technologies from laboratory to industrial-scale wastewater treatment applications, especially where continuous operation and regulatory compliance are non-negotiable (Standardisation, 2017; Truby, 2020).

2.4 Performance Evaluation

The performance evaluation of adsorbent materials for heavy metal removal in continuous wastewater flow systems involves a detailed examination of their adsorption capacity, operational stability under variable water chemistry, and their metal-specific selectivity and efficiency. Unlike batch systems where conditions can be tightly controlled and uniform, continuous flow systems introduce variables such as fluctuating flow rates, residence times, and influent compositions, all of which significantly influence adsorption behavior. This necessitates a comprehensive and nuanced assessment of how each material performs under realistic, often challenging, operational conditions. Through systematic review, various studies have highlighted the key determinants of performance and the implications for practical deployment in industrial and municipal wastewater treatment facilities (Adepoju, *et al*., 2022, Okolie, *et al*., 2022).

Adsorption capacity under continuous flow conditions serves as a fundamental metric for assessing the viability of an adsorbent material. This capacity, typically expressed in milligrams of metal ion adsorbed per gram of adsorbent (mg/g), reflects the amount of contaminant that can be removed before breakthrough occurs. In continuous flow reactors such as fixed-bed or packed-bed columns, this value is often lower than that recorded under batch conditions due to limitations in contact time and the influence of mass transfer constraints (Edwards, Mallhi & Zhang, 2018, Tula, *et al*., 2004, Vindrola-Padros & Johnson, 2022). However, advanced materials such as activated carbon, functionalized biochars, ion exchange resins, and nanomaterials have shown competitive capacities even under dynamic flow. For instance, biochar modified with iron oxide has demonstrated continuous flow adsorption capacities exceeding 50 mg/g for arsenic (As^{3+}), while thiol-functionalized silica nanoparticles have achieved over 80 mg/g for mercury (Hg^{2+}) in column studies.

Factors such as bed height, particle size, flow rate, and influent concentration further influence adsorption capacity. Increasing bed height prolongs contact time and delays saturation, effectively enhancing metal uptake. Meanwhile, smaller particle sizes offer larger surface areas but may lead to higher pressure drops and clogging risks. Optimization of these variables is necessary to achieve a balance between high capacity, operational feasibility, and long-term stability. Additionally, regeneration potential must be factored into performance evaluation, as adsorbents that maintain their capacity across multiple cycles present more sustainable and cost-effective options (Bristol-Alagbariya, Ayanponle & Ogedengbe, 2022, Onukwulu, *et al*., 2022).

Water chemistry plays a crucial role in determining the efficiency and selectivity of adsorbent materials. Among the most influential factors are pH, temperature, and the presence of competing ions. pH affects both the ionization state of the metal species and the surface charge of the adsorbent. For example, lead (Pb^{2+}) and cadmium (Cd^{2+}) show optimal adsorption at near-neutral pH, where their ionic forms are stable and adsorbent surfaces are more negatively charged, enhancing electrostatic attraction (Adeoba, etal., 2018, Omisola, *et al*., 2020). Conversely, chromium in its hexavalent form (Cr^{6+}), typically present as CrO_4^{2-} or $HCrO_4^-$, is better adsorbed at acidic pH levels due to protonation of functional groups that facilitate anion exchange.

Temperature influences adsorption by affecting diffusion rates, reaction kinetics, and thermodynamic equilibria. Higher temperatures generally enhance adsorption in endothermic systems but may degrade the structure of bio-based or polymeric adsorbents. This duality necessitates thermal optimization specific to each material and wastewater composition. Additionally, competing ions such as Ca^{2+}, Mg^{2+}, Na^+, and K^+ commonly found in natural or industrial waters can significantly interfere with metal uptake by occupying binding sites or altering surface charge distributions. Selectivity becomes especially important in multi-metal systems, where prioritization of target pollutants is needed (Ajiga, Ayanponle & Okatta, 2022, Noah, 2022, Ogundipe, Sangoleye & Udokanma, 2022). Functionalized materials designed with specific ligands, such as amine, carboxyl, or thiol groups, have demonstrated greater resilience to such competition due to their enhanced binding affinities.

Evaluating metal-specific removal efficiency is essential to understanding the practicality of various adsorbents in real-world applications. Each heavy metal ion possesses distinct chemical characteristics ionic radius, charge density, hydration energy that influence its interaction with adsorbent surfaces. For instance, lead (Pb^{2+}), due to its relatively large size and low hydration energy, tends to bind strongly to negatively charged or polar functional groups. As a result, many adsorbents report high removal efficiencies for lead, with values often exceeding 90% in continuous systems (Onaghinor, *et al*., 2021, Orieno, *et al*., 2022, Sobowale, *et al*., 2022). Cadmium (Cd^{2+}), while similar in behavior, often shows slightly lower removal rates due to weaker interactions and greater susceptibility to competitive displacement.

Chromium, particularly in its hexavalent state (Cr^{6+}), poses unique challenges due to its anionic form and redox activity. Effective removal often requires simultaneous reduction to the trivalent state (Cr^{3+}), followed by precipitation or adsorption. This dual mechanism demands not only high surface affinity but also catalytic or redox-active sites, which are present in certain modified biochars, iron-based nanocomposites, and redox-active polymeric resins (Ajayi, *et al*., 2020, Ofori-Asenso, *et al*., 2020). Removal efficiencies for Cr^{6+} vary widely depending on whether reduction is facilitated, with reported values ranging from 60% to over 95% in optimized systems.

Arsenic (As^{3+} and As^{5+}) represents another problematic contaminant, often requiring specific surface chemistry for effective capture. Iron-impregnated adsorbents, aluminum oxides, and hybrid nanomaterials have shown superior performance for arsenic removal due to their ability to form stable surface complexes. In continuous flow studies, these materials have achieved removal efficiencies exceeding 90%, even in the presence of phosphate and sulfate, which often compete with arsenic for adsorption sites.

A critical distinction in performance evaluation arises when comparing single-metal versus multi-metal removal scenarios. Laboratory studies frequently evaluate adsorbent materials using synthetic wastewater containing only one target metal at a time. While this approach simplifies analysis and facilitates mechanistic understanding, it fails to replicate the complexity of real industrial or municipal effluents, which often contain multiple heavy metals and other interfering substances (Bristol-Alagbariya, Ayanponle & Ogedengbe, 2022, Nwulu, *et al*., 2022). In multi-metal systems, competitive adsorption becomes a dominant factor. For example, lead may outcompete cadmium and zinc for binding sites on biochar or activated carbon due to its higher electronegativity and affinity. This competitive hierarchy reduces the overall efficiency of the system and necessitates the use of selective adsorbents or multi-stage treatment trains. Studies comparing performance under single-metal and multi-metal conditions consistently show a decline in removal efficiencies for secondary or less competitive metals. For instance, an adsorbent that achieves 95% removal of copper in a single-metal system may show only 60–70% removal in the presence of lead and cadmium. Understanding these competitive interactions is crucial for designing reactors, optimizing adsorbent dosage, and determining the need for pre-treatment or sequential adsorption columns (Francis Onotole, *et al*., 2022). Advanced materials that incorporate multiple functional groups or hierarchical structures capable of accommodating diverse metal species offer a promising solution to this challenge.

In conclusion, evaluating the performance of adsorbent materials for heavy metal removal in continuous wastewater flow systems requires a multifaceted approach that considers adsorption capacity, water chemistry, metal-specific affinities, and competitive interactions. Continuous systems introduce dynamic operational challenges that demand robust, selective, and regenerable adsorbents (Adepoju, *et al*., 2021, Okolie, *et al*., 2021, Sobowale, *et al*., 2021). While natural materials offer sustainable and cost-effective solutions, synthetic and functionalized adsorbents provide superior selectivity and efficiency, particularly under complex or variable conditions. Future research must emphasize real-world applicability by prioritizing studies under multi-metal scenarios, exploring long-term performance under continuous flow, and integrating economic and environmental assessments to guide material selection and system design. Such a comprehensive evaluation framework is essential for advancing adsorption technologies toward scalable, efficient, and sustainable heavy metal remediation.

2.5 Regeneration and Reusability of Adsorbents

Regeneration and reusability are central considerations in the practical application of adsorbents for heavy metal removal in continuous wastewater flow systems. Adsorption offers a sustainable approach for metal ion removal, but the challenge of adsorbent disposal or replacement due to capacity saturation can lead to high operational costs and environmental concerns. Therefore, the ability to regenerate and reuse adsorbents repeatedly is a crucial factor in determining their long-term viability, economic efficiency, and environmental sustainability in large-scale wastewater treatment processes. Various regeneration techniques have been developed and studied to enhance the reusability of adsorbents, including thermal, chemical, biological, and microwave-assisted methods. Each of these approaches offers distinct advantages and limitations, and their effectiveness can vary depending on the nature of the adsorbent material, the type of metal contaminants, and the operational conditions.

Thermal regeneration is one of the most commonly employed techniques for adsorbent recovery, particularly for carbon-based materials such as activated carbon, biochar, and other porous materials. This process involves heating the spent adsorbent to high temperatures, typically between 500 and 800°C, to desorb the adsorbed metal ions. The elevated temperatures break the bonds between the metal ions and the adsorbent surface, allowing the metals to be released into a gas phase or condensed for disposal (Ogunyankinnu, *et al*., 2022, Kolade, *et al*., 2022). Thermal regeneration is highly effective for adsorbents with high thermal stability, such as activated carbon and metal oxides, and is commonly used in industrial settings where large quantities of adsorbent need to be processed. However, this method has significant energy costs associated with it and can lead to the degradation of the adsorbent material over time, particularly if the regeneration temperature is too high or the process is repeated frequently.

Furthermore, the need for specialized equipment, such as furnaces or rotary kilns, adds to the capital and operational costs, making thermal regeneration less suitable for small-scale or decentralized applications.

Chemical regeneration involves the use of chemical agents to break the metal-adsorbent bonds and release the adsorbed metals. Common reagents include acids, alkalis, or complexing agents, depending on the nature of the metal ions and the adsorbent. For instance, hydrochloric acid or sulfuric acid may be used to regenerate activated carbon loaded with heavy metals like lead or cadmium, while chelating agents such as EDTA (ethylenediaminetetraacetic acid) may be used to remove transition metals like copper or nickel (Ilori & Olanipekun, 2020). The use of chemical regeneration allows for lower regeneration temperatures compared to thermal methods and can be more energy-efficient. However, the process often requires large quantities of chemicals, which can increase operational costs and introduce waste disposal challenges. Additionally, repeated exposure to harsh chemicals can alter the surface chemistry of the adsorbent, potentially reducing its adsorption capacity over successive cycles (Ajibola & Olanipekun, 2019, Olanipekun & Ayotola, 2019). The choice of chemical regeneration method is also dependent on the metal species being targeted, as some metals form strong bonds with adsorbents that are difficult to break even with strong reagents.

Biological regeneration is a more environmentally friendly and potentially cost-effective method for adsorbent recovery. This technique uses microorganisms to degrade or mobilize adsorbed metals, effectively "cleaning" the adsorbent material for reuse. Microorganisms such as bacteria, fungi, or algae can bioaccumulate or bioadsorb heavy metals, and they may also produce extracellular compounds, such as biofilm matrices, that aid in the release of metal ions from the adsorbent surface (Olanipekun, 2020; West, Kraut & Ei Chew, 2019). Biological regeneration is especially beneficial for the treatment of organic or biodegradable adsorbents like biochar or activated carbon that may be sensitive to chemical treatments. Moreover, biological methods are energy-efficient and sustainable, as they generally operate under mild conditions (e.g., ambient temperature and pressure). However, the effectiveness of biological regeneration is often slower than thermal or chemical methods and can be influenced by environmental factors such as pH, temperature, and the presence of other contaminants. Additionally, the biological regeneration process may not be suitable for all metal types, particularly for metals that are strongly bound to the adsorbent or that are toxic to the microorganisms involved in the regeneration process.

Microwave-assisted regeneration has emerged as an innovative and energy-efficient alternative to traditional thermal regeneration methods. In this technique, adsorbents are exposed to microwave radiation, which generates rapid heating and localized temperature increases. The microwave energy causes the desorption of metal ions by enhancing the thermal vibrations of adsorbent particles, thereby facilitating the release of adsorbed metals. Microwave-assisted regeneration has several advantages over conventional thermal methods, including faster heating rates, lower energy consumption, and more uniform temperature distribution (Belot, 2020; Olanipekun, Ilori & Ibitoye, 2020). This method has been successfully applied to carbon-based adsorbents such as activated carbon and biochar, as well as to metal oxide adsorbents. However, the high initial setup cost for microwave equipment and the limited understanding of how microwave energy interacts with different adsorbents or metal ions can pose challenges in scaling this method for commercial applications. Additionally, the regeneration cycles may not be as robust as those achieved with thermal or chemical methods, particularly when dealing with adsorbents with complex surface structures or when exposed to high concentrations of metals.

The impact of regeneration on the adsorption capacity of the material over multiple cycles is a key factor in evaluating the long-term performance and economic feasibility of adsorbents. With each regeneration cycle, the adsorbent's physical and chemical properties can degrade, reducing its ability to adsorb metals effectively. In many cases, the adsorption capacity diminishes with repeated use, primarily due to the gradual loss of surface area, pore structure, and functional groups that are responsible for binding metal ions (Kolade, *et al*., 2021; Ramdoo, *et al*., 2021). For example, activated carbon may experience a reduction in micropore volume and surface area after several thermal regeneration cycles, while biochar may lose its functional groups due to chemical treatments. Additionally, the regeneration process itself may lead to the accumulation of residual metal ions in the adsorbent, further diminishing its capacity to adsorb new contaminants.

The number of effective regeneration cycles depends on the type of adsorbent material, the metal species being adsorbed, and the regeneration method employed. For instance, synthetic adsorbents like ion-exchange resins and activated carbon typically offer more cycles of reuse than natural adsorbents such as clays and agricultural by-products, which may suffer from irreversible degradation after just a few regeneration cycles (Akang, *et al*., 2019; Ezenwa, 2019). Additionally, the efficiency of regeneration declines with each cycle due to the irreversible adsorption of certain metals or the modification of adsorbent properties, making it important to determine an optimal number of cycles for each material before replacement becomes more cost-effective than further regeneration.

The economic and environmental implications of adsorbent reuse and regeneration are significant, as they directly affect the sustainability and cost-effectiveness of wastewater treatment processes. From an economic perspective, the ability to regenerate and reuse adsorbents can substantially reduce the operational costs associated with adsorbent replacement. In large-scale industrial systems, where significant volumes of wastewater need to be treated continuously, regeneration offers substantial savings in terms of material costs and disposal fees (Otokiti, *et al*., 2022; Oyewola, *et al*., 2022). Moreover, the reduction of chemical and energy consumption through optimized regeneration methods contributes to lower operational costs over time. However, the initial investment in regeneration equipment, such as thermal furnaces or chemical reactors, can be substantial, and the need for periodic maintenance and calibration of regeneration systems adds to the ongoing operational costs.

From an environmental standpoint, the regeneration of adsorbents helps to minimize waste generation and supports the principles of circular economy by reducing the need for fresh adsorbent materials and limiting the environmental burden associated with adsorbent disposal. However, the environmental benefits of regeneration can be offset if the regeneration process itself produces harmful by-products, such as toxic gases from thermal regeneration or wastewater contaminated with desorbed metals. To mitigate these impacts, research into greener regeneration techniques, such as biological regeneration or the use of environmentally friendly chemicals, is crucial (Ochinanwata, 2019; Negi, 2021; Otuoze, Hunt & Jefferson, 2021). Furthermore, careful consideration must be given to the environmental costs of producing and maintaining regeneration equipment, as well as the long-term sustainability of the regeneration process.

In conclusion, the regeneration and reusability of adsorbents are vital for the economic and environmental sustainability of continuous wastewater treatment systems. The effectiveness of regeneration techniques whether thermal, chemical, biological, or microwave-assisted depends on the nature of the adsorbent material and the specific contaminants being targeted. Regeneration inevitably impacts the adsorption capacity of materials over time, and a careful balance must be struck between regeneration cycles and material replacement to optimize long-term performance. By advancing regeneration technologies and integrating them with optimized system designs, it is possible to enhance the reusability of adsorbents, reduce operational costs, and mitigate environmental impacts, paving the way for more sustainable and efficient heavy metal removal in wastewater treatment.

2.6 Recent Advances and Innovations

Recent advances in adsorbent materials for heavy metal removal in continuous wastewater flow systems have been marked by innovations in material design, integration with emerging technologies, and more efficient operational strategies. As industries increasingly face stringent environmental regulations, the development of adsorbent materials that offer higher capacity, selectivity, cost-effectiveness, and ease of regeneration has become a key area of focus. The incorporation of advanced materials such as 3D-printed adsorbents, magnetic separation technologies, and nanotechnology-enabled systems has the potential to revolutionize the efficiency and scalability of heavy metal removal processes (Ijeomah, 2020; Qi, *et al*., 2017). Additionally, the integration of these materials with real-time monitoring and control systems promises to enhance operational stability, reduce waste, and optimize treatment outcomes.

One of the most exciting areas of recent innovation is the development of 3D-printed adsorbents and smart materials. 3D printing, or additive manufacturing, has allowed researchers to design adsorbents with highly tailored geometries, surface areas, and pore structures that can be optimized for specific adsorption tasks. This process enables the fabrication of adsorbents that not only have the desired physical properties but also possess complex architectures such as hierarchical pore structures, interconnected networks, and customizable surface functionalities (Babatunde, 2019; Olukunle, 2013; Danese, Romano & Formentini, 2013). For example, 3D-printed adsorbents can be designed with macro and micropores arranged in such a way as to facilitate enhanced mass transfer and improved flow characteristics in continuous systems. These properties are critical in ensuring efficient contact between the adsorbent and contaminants in wastewater. Additionally, the precise control over material composition in 3D printing allows for the incorporation of functional groups, such as carboxyl, amine, or thiol groups, which can further enhance the adsorbent's affinity for specific heavy metals like lead, arsenic, or mercury.

Furthermore, 3D printing can be used to create "smart materials" that respond dynamically to environmental conditions. These materials can change their structure or properties in response to pH variations, temperature changes, or contaminant concentration fluctuations. For example, adsorbents that can reversibly change their adsorption capacity in response to environmental cues are a significant step toward the creation of adaptive systems capable of adjusting to varying contaminant loads in real-time (Lu, 2019; Simchi-Levi, Wang & Wei, 2018). This adaptability ensures more efficient and sustainable wastewater treatment, reducing the need for constant system adjustments or recalibrations. The integration of 3D printing with functionalization techniques, such as coating adsorbent particles with nanoparticles or functional polymers, further enhances the performance and specificity of these materials.

In parallel, magnetic separation has emerged as a game-changer in adsorbent recovery and reusability. Magnetic adsorbents, often synthesized by functionalizing adsorbent materials with magnetite (Fe_3O_4) or other magnetic nanoparticles, allow for easy separation of the adsorbent from treated effluent using external magnetic fields. This method is particularly advantageous in continuous flow systems, where the ease of adsorbent recovery significantly reduces operational downtime and maintenance costs (Qrunfleh & Tarafdar, 2014; Wang, *et al*., 2016). Magnetic adsorbents can be easily regenerated, often with minimal loss in efficiency, simply by applying a magnetic field to recover the adsorbent for subsequent cycles. In addition to the recovery process, magnetic nanoparticles can enhance adsorption kinetics due to their high surface area and small particle size, allowing for faster and more efficient metal removal.

Magnetic adsorbents are also being combined with nanotechnology to create even more advanced systems for heavy metal removal. Nanomaterials, such as carbon nanotubes, graphene oxide, and metal oxide nanoparticles, possess unique physicochemical properties, including high surface-to-volume ratios, enhanced reactivity, and high stability, which make them ideal candidates for adsorbent modification (Mwangi, 2019; Zohuri & Moghaddam, 2020). By functionalizing these nanoparticles with specific ligands or metals, researchers can design adsorbents that selectively target heavy metals, improving removal efficiency and minimizing competition between metal ions. Additionally, the small size and large surface area of these nanomaterials enhance the adsorption capacity and kinetics, making them ideal for continuous flow systems where rapid removal of contaminants is required.

One notable advancement in nanotechnology-enabled adsorbents is the development of hybrid materials that combine magnetic properties with other functionalities, such as catalytic activity or selective metal ion binding. These hybrid adsorbents not only facilitate the removal of metals but can also catalyze reactions that aid in breaking down or transforming contaminants. For example, magnetic nanocomposites incorporating iron oxide and copper oxide can adsorb heavy metals while simultaneously catalyzing the reduction of Cr(VI) to Cr(III), a less toxic form (Duan, Edwards & Dwivedi, 2019; Tien, 2017). This approach offers a dual advantage of adsorption and chemical transformation, making it a promising solution for more complex wastewater treatment scenarios.

Recent innovations also extend to the integration of adsorbents with real-time monitoring and control systems, creating intelligent and adaptive treatment processes. Real-time monitoring using sensors to measure key parameters such as pH, temperature, flow rate, and contaminant concentration enables the dynamic adjustment of dosing rates, flow velocities, and other operational parameters (Javaid, *et al*., 2022; Richey, *et al*., 2022). By integrating these sensors with machine learning algorithms or predictive models, the system can continuously adapt to changes in influent quality, automatically optimizing adsorption efficiency and minimizing the use of chemicals and adsorbent material.

The integration of real-time monitoring with adsorbent materials can also help in tracking the performance of the adsorbent over time, including monitoring breakthrough curves and identifying the need for regeneration or replacement. This allows for more precise and efficient management of resources, reducing both operational costs and the environmental impact associated with adsorbent disposal and replacement (Korteling, *et al*., 2021; Zhang & Lu, 2021). Additionally, by incorporating predictive analytics and artificial intelligence (AI) into the control systems, operators can anticipate potential system failures or inefficiencies, allowing for preemptive adjustments and minimizing unplanned downtime.

The combination of smart adsorbents and real-time monitoring has the potential to revolutionize the way continuous wastewater treatment systems operate. For example, an integrated system could automatically adjust the bed height in fixed-bed columns or alter the particle size of magnetic adsorbents in response to changes in effluent characteristics. This adaptability could help maintain high levels of metal removal efficiency, even in the face of fluctuating pollutant concentrations or operational conditions (Jarrahi, 2018; Terziyan, Gryshko & Golovianko, 2018). Moreover, these smart systems could enable greater flexibility in the scale-up of adsorption technologies from laboratory or pilot-scale experiments to full-scale industrial applications, reducing the barriers to implementing advanced adsorption systems in diverse industrial sectors.

In addition to the technical advancements, there is a growing focus on the economic and environmental sustainability of these innovations. 3D-printed adsorbents and magnetic nanomaterial systems are generally more efficient in terms of material usage and regeneration potential, offering long-term cost savings compared to traditional adsorbent materials. The reduced need for adsorbent replacement and the potential for easier recovery of spent adsorbents through magnetic separation translate into lower operational costs, especially in large-scale continuous flow systems (Affognon, *et al*., 2015; Misra, *et al*., 2020). Furthermore, the integration of real-time monitoring and adaptive control can reduce the use of chemicals and optimize the lifetime of adsorbents, which contributes to more sustainable practices in wastewater treatment.

However, challenges remain in the commercialization and widespread adoption of these technologies. The production costs of 3D-printed adsorbents and nanomaterials are still relatively high, and large-scale manufacturing methods need to be developed to make these materials economically viable for widespread use. Similarly, while magnetic separation offers significant operational advantages, the initial costs of the magnetic equipment and the energy required for certain regeneration processes can still be prohibitive (Akande & Diei-Ouadi, 2010; Morris, Kamarulzaman & Morris, 2019). Moreover, regulatory frameworks and industry standards must evolve to accommodate and promote the use of these innovative materials, ensuring that they meet safety, performance, and environmental guidelines.

In conclusion, recent advances in adsorbent materials for heavy metal removal in continuous wastewater flow systems have been transformative, with innovations in 3D printing, magnetic separation, and nanotechnology offering new possibilities for improving treatment efficiency, reducing costs, and enhancing sustainability (Gianni, Lehtinen & Nieminen, 2022; Helo & Hao, 2022). The integration of smart materials with real-time monitoring and adaptive control systems will further optimize the performance and scalability of these technologies, making them more effective and accessible for large-scale applications. However, the economic feasibility, scalability, and regulatory acceptance of these innovations remain challenges that must be addressed before their full potential can be realized in industrial wastewater treatment.

2.7 Challenges and Research Gaps

The use of adsorbent materials for heavy metal removal in continuous wastewater flow systems is gaining traction due to its efficiency, cost-effectiveness, and sustainability. However, despite considerable progress in research and development, significant challenges and research gaps remain, particularly in the areas of scale-up, fouling, clogging, adsorbent degradation, life cycle assessment (LCA), and the real-world applicability of these materials in industrial settings (De Almeida, dos Santos & Farias, 2021; Yigitcanlar, Mehmood & Corchado, 2021). Addressing these challenges is essential to ensure that adsorbents can be reliably and efficiently deployed in large-scale wastewater treatment systems, providing effective solutions for the removal of heavy metals in diverse industrial contexts.

Scale-up from laboratory studies to full-scale industrial applications remains one of the most significant challenges in the use of adsorbent materials for continuous flow systems. Most studies on adsorbent materials are conducted under controlled laboratory conditions, where factors such as flow rate, influent concentration, temperature, and pressure can be tightly regulated. However, translating these results to real-world systems introduces a variety of complexities (Ahiaba, 2019; Hodges, Buzby & Bennett, 2011). In a continuous flow system, the contact time between the adsorbent and metal ions is typically shorter, and the influent characteristics may vary due to changes in production schedules, seasonal fluctuations, or the presence of additional contaminants. Therefore, the performance of adsorbents may be significantly reduced when scaled up, due to issues such as poor contact time, uneven flow distribution, and higher variability in contaminant load (Yue, You & Snyder, 2014; Oyedokun, 2019). Furthermore, as the adsorbent material is used over extended periods, its ability to effectively adsorb heavy metals may decrease due to factors such as saturation, structural changes, and loss of surface area. Research is needed to better understand how these materials behave in large-scale systems and how to optimize their performance in real industrial settings.

Fouling, clogging, and adsorbent degradation are significant operational issues that affect the efficiency and longevity of adsorbent materials in continuous wastewater flow systems. Fouling occurs when suspended solids, organic matter, or other pollutants accumulate on the surface of the adsorbent, blocking active adsorption sites and reducing its efficiency. This can lead to a reduced flow rate, increased pressure drop, and the need for frequent maintenance or cleaning (Jagtap, *et al*., 2020; Sibanda & Workneh, 2020). Clogging is another issue that arises when fine particles or large aggregates form and obstruct the flow paths within the adsorbent bed, resulting in uneven distribution and flow maldistribution. Adsorbent degradation is also a concern, as repeated exposure to harsh chemicals, pH fluctuations, and high flow rates can cause the adsorbent material to break down or lose its structural integrity. For example, activated carbon may suffer from pore blockage or irreversible loss of surface area, while natural adsorbents such as biochar or agricultural by-products may undergo physical degradation or loss of functional groups (An, Wilhelm & Searcy, 2011; Kandziora, 2019). The occurrence of fouling, clogging, and degradation not only reduces the lifespan of the adsorbent but also increases operational costs, as adsorbents may need to be replaced or regenerated more frequently. Research is needed to develop more durable adsorbent materials, improve regeneration techniques, and implement effective fouling control strategies that ensure long-term stability and performance.

Life cycle assessment (LCA) and end-of-life disposal are essential considerations when evaluating the sustainability of adsorbent materials for heavy metal removal. While adsorbent materials such as activated carbon, biochar, and synthetic resins may offer high removal efficiencies in laboratory and pilot-scale studies, their environmental impact over the entire life cycle including production, transportation, use, and disposal must be carefully assessed. For instance, the production of activated carbon requires significant energy inputs and may involve the use of non-renewable resources, raising concerns about its overall sustainability (Chaudhuri, *et al*., 2018; Stathers & Mvumi, 2020). Additionally, after the adsorbent becomes saturated with heavy metals, its disposal or regeneration poses environmental challenges. If not properly handled, the adsorbent may become a source of secondary pollution, as heavy metals may leach back into the environment during disposal or regeneration. Some adsorbents, particularly those that are non-biodegradable, may accumulate in landfills, contributing to environmental degradation (An, Wilhelm & Searcy, 2011; Kandziora, 2019). Furthermore, while some regeneration methods can restore adsorbent materials, others may lead to the accumulation of toxic residues or the degradation of the adsorbent structure, reducing its capacity for reuse. Life cycle assessments that account for the environmental costs associated with adsorbent production, regeneration, and disposal are needed to provide a more complete picture of the sustainability of different materials (Koroteev & Tekic, 2021 Yigitcanlar, *et al*., 2021). Additionally, research into more sustainable adsorbents, such as those derived from renewable resources or those with a lower environmental footprint, is essential to reducing the overall impact of adsorbent-based heavy metal removal technologies.

One of the significant research gaps in the field of adsorbent materials for heavy metal removal is the limited number of studies that examine the behavior of these materials under real industrial wastewater matrices. Many studies rely on synthetic wastewater solutions containing a single heavy metal or a mixture of known contaminants at controlled concentrations, which does not reflect the complexity of real wastewater. In industrial settings, wastewater often contains a wide range of contaminants, including not only heavy metals but also organic compounds, surfactants, oils, and other substances that can interfere with the adsorption process (Khalifa, Abd Elghany & Abd Elghany, 2021; Nahr, Nozari & Sadeghi, 2021). The presence of multiple competing ions, for example, can reduce the adsorption efficiency for specific heavy metals due to competition for active sites on the adsorbent surface. Moreover, real wastewater can vary widely in terms of pH, temperature, and flow rate, further complicating the adsorption process. Adsorbent materials that perform well under controlled, synthetic conditions may not always exhibit the same level of efficiency when exposed to complex and variable real-world wastewater matrices (Kuang, *et al*., 2021; Sircar, *et al*., 2021). Additionally, the interactions between adsorbents and other contaminants in the wastewater may affect the regeneration process, as certain chemicals may interfere with desorption or cause the adsorbent to degrade more rapidly. Research that focuses on testing adsorbents under realistic, variable conditions is essential for determining their true effectiveness in industrial applications and for identifying the factors that influence their performance (Shah, Li & Ierapetritou, 2011; Urciuoli, *et al*., 2014). These studies will help bridge the gap between laboratory-scale studies and full-scale industrial applications, providing a clearer understanding of the challenges associated with using adsorbents in complex, dynamic wastewater streams.

Another key challenge is the need for better standardization and performance metrics for adsorbent materials in real wastewater treatment systems. While various adsorption models, such as the Langmuir and Freundlich isotherms, are used to evaluate adsorbent performance in laboratory conditions, these models may not fully capture the complexities of continuous flow systems or account for the dynamic interactions between different contaminants. Furthermore, there is a lack of standardized testing protocols for assessing the long-term stability, fouling resistance, and regeneration potential of adsorbents in continuous systems (Alam, *et al*., 2022; Kumar, *et al*., 2022). Without consistent performance metrics, it is difficult to compare the effectiveness of different adsorbents or to determine the optimal conditions for their use in industrial applications. Researchers need to develop standardized protocols for testing adsorbents in real-world conditions, taking into account the variability of wastewater characteristics, operational parameters, and the full life cycle of the adsorbent (Balana, Aghadi & Ogunniyi, 2022; Raja Santhi & Muthuswamy, 2022).

In conclusion, while significant progress has been made in the development of adsorbent materials for heavy metal removal in continuous wastewater flow systems, there are still several challenges and research gaps that need to be addressed. Scale-up issues, fouling and clogging, adsorbent degradation, life cycle impacts, and limited real-world testing are some of the key barriers to the widespread adoption of these technologies (Dauvergne, 2022; Lin, Lin & Wang, 2022). Overcoming these challenges will require interdisciplinary research, including material science, chemical engineering, environmental sustainability, and process optimization (Das Nair & Landani, 2020; Krishnan, Banga & Mendez-Parra, 2020). Only through a comprehensive approach that addresses both the technical and environmental aspects of adsorbent-based wastewater treatment can we move closer to achieving efficient, sustainable, and cost-effective solutions for heavy metal remediation.

3. Conclusion and Recommendations

In conclusion, the systematic review of adsorbent materials for heavy metal removal in continuous wastewater flow systems has highlighted significant advancements and ongoing challenges in the field. Adsorbent materials have proven to be a promising solution for heavy metal removal, offering advantages such as high efficiency, selectivity, and relatively low environmental impact compared to conventional treatment methods. However, the successful implementation of adsorbent-based technologies in large-scale industrial settings requires overcoming several key barriers, including issues related to scale-up, fouling, clogging, degradation, and the variability of real-world wastewater compositions.

Major findings from the review include the importance of optimizing adsorbent materials to handle complex wastewater matrices, the potential of novel materials such as 3D-printed adsorbents, and the growing use of magnetic separation and nanotechnology to enhance adsorbent performance and ease of recovery. The review also underscored the need for better understanding of the long-term stability, regeneration potential, and economic feasibility of adsorbents, particularly when dealing with continuous flow systems under real industrial conditions. Additionally, while many adsorbent materials have shown high removal efficiencies under controlled conditions, their performance in real-world settings with multiple contaminants and fluctuating operating conditions remains an area that requires further investigation.

Future research should focus on addressing the gaps related to the scalability of adsorbent technologies, particularly in terms of optimizing contact time, flow conditions, and adsorbent material properties to ensure maximum efficiency in continuous flow systems. Research should also explore more sustainable regeneration methods, such as biological or microwave-assisted regeneration, which could provide a lower environmental footprint and reduce operational costs. There is also a need for studies that assess the life cycle of adsorbent materials, including the environmental impacts of their production, regeneration, and disposal. Furthermore, more research is required on the behavior of adsorbents under multi-metal contamination scenarios, which are more representative of real industrial wastewater, to better understand competitive adsorption and selectivity.

For industrial adoption, it is essential to develop standardized testing protocols for adsorbent materials, ensuring that they are rigorously evaluated under dynamic, real-world conditions before being deployed in large-scale systems. Industry must also prioritize the development of materials that can be easily regenerated and reused, offering long-term cost-effectiveness and sustainability. Integration of these advanced materials with real-time monitoring and control systems would further enhance their performance by allowing adaptive treatment processes that respond dynamically to changes in influent characteristics.

Policy and engineering implications for water treatment sustainability are far-reaching. Regulatory bodies should focus on fostering the adoption of innovative adsorbent technologies by setting clear standards and guidelines for performance evaluation and encouraging the use of sustainable materials. Policymakers should also incentivize research and development in this field, supporting initiatives that promote the use of renewable resources and low-energy regeneration methods. Engineering practices must incorporate lifecycle assessments of adsorbent materials to ensure that the benefits of heavy metal removal are not outweighed by the environmental impacts of material production and disposal.

Ultimately, the continued development and application of adsorbent materials for heavy metal removal in continuous wastewater flow systems hold considerable promise for advancing water treatment technologies. By addressing the identified challenges and closing existing research gaps, the adoption of these materials can contribute to more sustainable, efficient, and cost-effective solutions for wastewater treatment, benefiting both industrial operations and the environment.

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