Advances in Heavy Metal Recovery Technologies from Wastewater: Biosorption, Hybrid Systems and Crucial Economy

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Abstract. Metallic pollutants released from industry into aquatic environment has become a concern that progressively pollutes ecosystems and poses a risk to public health due to their toxicity, persistence nature, and non-biodegradability. Traditional wastewater treatment techniques essentially targets on contaminant elimination often overlooking the likely recovery of precious metals as secondary resources. In line with circular economy criterion, this review critically evaluates current advances in heavy metal recovery approaches, emphasizing the shift from pollutant removal to green resource recovery. Conventional physicochemical approaches, including ion exchange, chemical precipitation, membrane filtration, adsorption, and electrochemical processes, are checked in relation to their recovery potential, scalability, selectivity and practicable limitations. Emphasis is given to biosorption and other bio-based recovery methods owing to their low cost, environmental compatibility, regeneration efficiency, and applicability for recovering metals from dilute waste streams. In order to improve metal selectivity and recovery efficiency in complex wastewater system, emerging hybrid methods that integrate adsorption, membrane separation, electrochemical recovery, and biological processes are explored. The review further focuses on present day advancement in nanotechnology, artificial intelligence-assisted process optimization, and digital monitoring for remodelling performance and industrial scalability. Analysis centres around key challenges, which includes selective adsorption in multimetal process, electrode passivation and fouling of membrane. It also addresses techno-economic feasibility, material regeneration and the absence of standardized quality protocols for recovered metals. This review offers a thorough prespective of integrated heavy metal recovery techniques and their contribution to the advancement of circular wastewater management and environmental sustainability.

Keywords: Resource recovery, Heavy metals, Wastewater, Circular economy, Hybrid technologies

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1 Introduction

Heavy metal pollution of freshwater environments has become a major global environmental hazard, with the most significant contributors being rapid industrialization, urban development, and population growth. High levels of metallic effluents containing Cr, Pb, Cd, Hg, Ni, Cu, and Zn are produced by industrial processes such as electroplating [1], mining and metallurgical processing[2], tanning [3], battery-producing industries, dye production, and pigment industries. In contrast to organic pollutants, which can be biodegraded, heavy metals are non-biodegradable and persistent in the environment, where they bioaccumulate through food chains (trophic levels) and pose long-term ecological and human health risks [4]. Chronic exposure, even at trace levels, has been linked to neurologic disorders, renal and hepatic dysfunctions, reproductive toxicity, mutagenicity, and carcinogenicity [5]. Heavy metals are among such contaminants; hexavalent chromium [Cr(VI)] is classified as a human carcinogen, and cadmium and lead inhibit enzymatic and metabolic pathways, whereas mercury demonstrates pronounced neurotoxicity, in part due to its high affinity for biological tissues[6]. Excessive metal concentrations not only cause adverse effects on human health but also alter microbial community structure, reduce plant productivity, and impair aquatic ecosystem services [7].

Historically, wastewater treatment practices have operated within a linear “treat-and-dispose” framework that emphasizes meeting effluent limits for contaminant removal [8]. This is increasingly seen as unsustainable due to the generation of secondary waste, loss of potentially valuable materials to landfill, and high operational costs[9]. In recent years, the treatment of wastewater has witnessed a paradigm shift towards circular economy principles, with this waste increasingly perceived not simply as a waste stream but as valuable secondary resource reservoirs for water, energy, and nutrients, and even potentially profitable metals [10]. Recovery of metals like Cu, Ni, Zn, and Cr, as well as precious metals, from industrial effluents not only helps prevent environmental pollution but also reduces dependence on primary mining, conserves natural resources, and reduces the carbon footprint of metal production [11]. This “urban mining” framing places wastewater alongside other strategic feedstocks for critical raw materials, which may be politicised in terms of national defence and resource security [12].

Physical methods (membrane filtration and adsorption), chemical processes [precipitation, coagulation–flocculation, ion exchange, and electrochemical techniques], and biological approaches such as biosorption, phytoremediation, bioleaching, and biomineralization have all been researched for heavy metal removal and recovery [13]. Conventional methods such as chemical precipitation and ion exchange remain efficient for treating high-strength effluents, but they suffer from low selectivity, significant sludge generation, excessive reagent use, and difficulty in recovering metals [14]. Another drawback to biological methods, such as phytoremediation, is that they may take longer and produce secondary toxic by-products [15]. Biosorption, however, has drawn significant interest due to its operational simplicity, economic viability, high metal removal capacity at low concentrations, and the ability to recover metals by desorption and regenerate adsorbents[16]. Biogenic sorbents produced from microorganisms, agricultural residues, and industrial by-products are eco-friendly alternatives to synthetic materials[17]. The practical applicability of biosorption-based systems is limited by selectivity challenges in complex metal matrices, material stability issues, fouling, and reproducibility under real wastewater conditions[18].

To overcome these limitations, many recent studies have focused on hybrid treatment strategies that combine adsorption with membrane separation, electrochemical recovery, or advanced oxidation processes[19]. At present, the application of digital tools, such as artificial intelligence and machine learning, is increasingly recognized as a major tool for optimizing operating conditions, developing optimal control process strategies, and predictive modelling of multicomponent metal productivity systems[20]. When combined with techno-economic analysis and life-cycle assessment, these advances yield important insight into the environmental and financial performance of recovery-oriented wastewater treatment technologies, informing decisions for scale-up and industrial implementation[21]. Although high recovery rates and purity levels have been reported at the laboratory scale, large gaps remain in demonstrating success at both pilot- and full-scale systems with respect to recovery efficiency, metal purity, robust system design, and regulatory acceptance[22]. Existing reviews tend to focus on contaminant removal rather than on integrated recovery and valorization within circular economy concepts.

Within this framework, the current review provides an in-depth, critical overview of established and emerging technologies for heavy metal recovery from wastewater, with a particular focus on biosorption-based and hybrid systems. This review specifically seeks to: (i) assess recovery performances, selectivity, and scalability of current treatment technologies at laboratory and pilot scales; (ii) tease out mechanistic insights underlying metal uptake/release behaviour, elucidating limitations of biological and adsorption-based processes; as well as (iii) highlight technological, economic, and regulatory challenge perspectives that preclude scaling up operations. This review highlights recent research directions and potential future trends to guide the development of integrated, sustainable wastewater recovery systems compatible with circular economy goals.

2 Regulatory Limits and Global Discharge Standard

The disposal of heavy metals from wastewater is subject to extremely strict international regulations that prioritize protecting the environment and human health. This approach is conducive to the industry of sustainable development [23]. Organizations like the WHO, USEPA, EU Directive, and CPCB India have set strict limits on pollution from the discharge of toxic heavy metals, as shown in Table 1. These benchmarks are significant for controlling wastewater treatment in accordance with environmental standards and also direct modern technology development in wastewater treatment practice. These regulatory constraints can create a strong imperative to develop alternative ideas and improved process technologies for wastewater treatment and reuse. They motivate the development of superior methods in this domain.

Industries have now shifted to advanced treatment systems that can lower metal content to very low levels and process them into useful materials for reuse, while adhering to stringent standards. Cost treatment "in" Cost-Benefit analysis, is a waste. This result assists the industry in complying with current environmental standards and promotes materials sustainable utilization [24]. Government intervention may also be promoting the industries to utilize more efficient waste recovery options by tax reduction and green credits promotion[25]. Government intervention may also foster industry autonomy in adopting more effective waste recovery alternatives. These disposables are made using circular technologies that save energy and are good for the environment. Such financial regulations and state controls allow industries to comply with the law while also encouraging them to develop new green projects and invest in clean infrastructure.

Table 1. Regulatory limits for heavy metals in wastewater

Heavy Metal	**WHO**[26]	**USEPA [27]**	**EU Directive**[28]	**Indian CPCB [29]**
Arsenic (As)	0.01	0.01	0.01	0.2
Cadmium (Cd)	0.003	0.005	0.005	0.01
Chromium (Cr^{6+})	0.05	0.1	0.05	0.1
Copper (Cu)	2	1.3	2	3
Lead (Pb)	0.01	0.015	0.01	0.1
Mercury (Hg)	0.001	0.002	0.001	0.01
Nickel (Ni)	0.07	0.1	0.1	3
Zinc (Zn)	3	5	2	5
All values are in mg/L				

3 Sources and Nature of Heavy Metals in Wastewater

Heavy metals, being toxic, persistent , and bioaccumulating in nature cause health problems in humans, animals and become a matter of concerned when discharged into wastewater flow streams with out treatment [30], [31]. Knowledge of the sources of such contaminants is important for assessing these risks and designing appropriate mitigation strategies. Effluent discharge from the mining and metallurgical sectors owing to ore extraction and metal recovery also bring As, Pb, Cd, Cu & Zn into aquatic ecosystem [24], [34]. Rinse waters are generally high in free metal ions and chelated complexes1 so that electroplating and finishing facilities must use salt solutions of chromium, nickel, copper, cadmium and zinc to treat the surfaces for coating[35]. Both the textile and leather processing industries (such as tanning with chromium salt) are sources of wastewater that are filled with hazardous chemicals and metals. This results in significant contamination of the streams' discharge [36]. This spell is because of the leaching out of heavy metals such as lead, mercury, Cd, and Copper from improper handling (recycling and disposal) in E-waste [37]. Other sources of metal-polluted wastewater from wet scrubbers and fly ash ponds are power-generating plants, primarily coal-burning plants, because of the heavy metals like mercury, lead, and arsenic in their flue gases and ash [38]. Battery production, textiles and fertilizers are additional causes of special metal profiles on wastewater matrices[39]. These metals are particularly problematic as a result of their high level toxicity, environmental persistence, and established health effects at trace levels[40].

Fig.1. Major industrial and anthropogenic sources of heavy metals

4 Adsorption-Based Technologies for Heavy Metal Recovery

Adsorption, owing to its operational simplicity, flexibility, and high efficiency in removing heavy metals over a wide concentration range, is also one of the most widely studied and practically used methods for heavy metal removal and recovery from wastewater[41]. It is the process by which dissolved metal ions are accumulated on the surface of a solid adsorbent via physical or chemical interactions, such as electrostatic attraction, ion exchange, surface complexation, coordination bonding, and precipitation at the solid-liquid interface [42]. The adsorption mechanism is influenced by solution chemistry parameters, such as pH, ionic strength, temperature, contact time, initial metal concentration, and the physicochemical properties of the adsorbents. Among all these factors, pH is a dominant one, as it affects metal speciation in solution and induces surface charge on the adsorbent, which can dictate adsorption mechanisms and selectivity[43]. For example, oxoanionic species such as Cr(VI) are preferentially adsorbed at acidic conditions due to electrostatic attraction, while cationic metals such as Pb(II), Cd(II), Cu(II), and Ni(II) exhibit greater uptake at near-neutral pH via surface complexation and ion exchange[44].

Various adsorbents have been investigated, including activated carbon, natural clays, zeolites, industrial wastes, polymeric composites, metal oxides, and carbonaceous materials. Although activated carbon remains the gold standard adsorbent owing to its high surface area and porosity, its high cost and difficulty of regeneration have urged the search for low-cost alternatives[45]. Against this background, agricultural residues, biochars, and waste-borne materials are emerging as increasingly popular adsorbents due to their sustainability and cost utility. Surface modification and composite design, such as polymer-functionalized adsorbents and metal oxide–carbon hybrids, have recently been shown to considerably improve adsorption capacity, selectivity, and reusability[46].

From a resource recovery viewpoint, adsorption has a clear advantage over precipitation because metal regeneration and reuse are possible via controlled desorption steps[47]. The desorbing agent (e.g., dilute mineral acids, chelating agents, or alkaline solutions) can recover adsorbed metals with reasonable purity, enabling both the adsorbent and metal to be reused. Still, there are some practical limitations that remain, especially decreased adsorption efficiency in complex, multi-metal wastewater systems, potential interference from other ions during adsorption, and gradual recovery of adsorbent activity across multiple regeneration cycles[48]. In addition, adsorbent saturation and the disposal of spent materials remain important issues for large-scale use. To overcome these limitations, emerging studies have focused more on selective, multifunctional adsorbents that perform under realistic wastewater conditions[49]. Combining adsorption with complementary processes such as membrane filtration, electrochemical recovery, and advanced oxidation has become an increasingly adopted strategy to enhance overall treatment performance, metal selectivity, and process sustainability[50].

5 Biosorption and Bio-Based Recovery of Heavy Metals

Biosorption is a bioinspired adsorption-based process that employs non-living or living biomasses for the removal and recovery of heavy metals from aqueous environments. As a result, this method has received much attention and is considered an eco-friendly, cost-effective, and sustainable alternative to traditional physicochemical approaches for the remediation of dilute metal-bearing wastewaters[51]. Biosorbents, originating from bacteria, fungi, algae, yeast, and plants, are rich in functional groups (carboxyl, hydroxyl, phosphate, sulphate, and amino moieties) that aid in metal binding through different modes of association[52].

In contrast to traditional adsorption, biosorption is mainly a metabolism-independent process that permits the use of inactive or dead biomass without the provision of nutrients and strict operating conditions[53]. Metal uptake is primarily carried out through surface-mediated processes including ion exchange, electrostatic attraction, chelation, complexation and micro-precipitation. The contribution of these mechanisms varies with biomass composition, surface chemistry, and environmental conditions. For instance, polysaccharide- and protein-rich fungal and algal biomass bind strongly to divalent metal cations, while raw lignocellulosic biowastes exhibit bioaccumulation of oxyanionic species such as Cr(VI) via electrostatic and redox-mediated mechanisms [54]. Biosorption has considerable advantages in terms of recovery owing to its high regeneration efficiency and low generation of secondary waste. Metals fixed to the biomass could be (efficiently) desorbed by mild eluents, allowing multiple reuse cycles of the biosorbent[55]. Desorption efficiencies reported range from 60–90% and vary widely across metal–biosorbent systems and elution strategies. This characteristic allows biosorption to recover both the metal and biosorbent, rendering it a low-cost method and a fascinating tool for circular economy applications[56].

Although promising, large-scale biosorption still faces several technical constraints. Selectivity in multi-metal systems is another significant constraint, as co-existing ions frequently decrease the biosorption capacity under actual effluent conditions[57]. Long-term performance can be compromised by biomass instability, structural degradation during regeneration, and susceptibility to fouling. To overcome these obstacles, the alternative biosorbent systems have been introduced, including fixed-bed and immobilized biosorbent systems that offered mechanical stability, hydraulic stability, and high reusability [10]. Genetic engineering and biomass surface modification machinery have also contributed to the biosorption performance by manipulating functional group density and thereby metal specificity. Phytoremediation and microbial bioleaching are two complementary biological approaches for metal recovery. Some hyperaccumulator species of plants or metal-resistant microorganisms can selectively uptake or mobilize metals from contaminated water and sludge[58]. But their slow kinetics, land-use requirements, and post-harvest biomass handling constraints are impractical for high-throughput industrial wastewater treatment [58]. As a result, the biosorption-based systems, especially when integrated with adsorption, electrochemical recovery, or membrane processes, would be a more commonly used pathway for large-scale metal recovery. Future investigations on biosorption should focus on mechanistic insight in real wastewater scenarios, designing selective and robust biosorbents, and coupling with hybrid treatments[59]. Integration of biosorption with secondary metal purification approaches, including but not limited to electrowinning or crystallization, can improve the efficiency and economic feasibility for subsequent recovery of metals[60].

Table 2. Selected technologies for heavy metal removal and recovery

Technology	**Major Advantages**	**Key Limitations**	**Typical Metal Removal Efficiency (%)**	**Typical Metal Recovery Efficiency (%)**	**Ref**
Filtration Techniques (MF/UF/ NF/RO)	High selectivity; capable of simultaneous removal of multiple metals; compact and modular design; minimal chemical use	Membrane fouling; high energy demand; concentrate (brine) disposal issues	90–99	80–95	[63], [64], [65]
Adsorption Processes	Cost-effective, flexible, high efficiency, wide adsorbent availability (biochar, composites); easy operation and regeneration potential	Limited adsorption for highly concentrated effluents; regeneration losses; spent adsorbent disposal challenges	75–98	65–90	[66]
Ion Exchange	High selectivity; efficient for low concentrations; easily regenerable resins; suitable for metal recovery (Ni, Cu, Zn)	High resin cost; fouling and reduced capacity in complex matrices	80–99	70–95	[66]
Chemical precipitation and Coagulation–Flocculation	Simple, rapid, effective at high metal loads; metals can be recovered from sludge	High sludge generation: reagent optimization required; limited selectivity	70–95	60–90	[67]
Electrochemical Processes	High metal recovery and purity; selective recovery; low sludge generation; suitable for valuable metals; can be integrated with renewable energy	High energy consumption; electrode passivation; high capital cost; reduced efficiency at very low metal concentrations	85–99	85–98	[68], [69]

Hybrid Systems (Adsorption–Membrane, Ion Exchange–Precipitation, Electrochemical–Adsorption)	Emerging technology Combines advantages of multiple technologies; enhanced selectivity and recovery; reduced fouling and chemical consumption; suitable for complex industrial wastewater; improved process sustainability	Higher system complexity; higher initial investment; process optimization and integration required; scale-up challenge	95-99	90-99	[70], [71], [72], [73]

5.1 New technologies and hybrid approaches for Improved Heavy Metal Recovery

Physicochemical single-stage treatment methods have been limited by the complexities of industrial wastewater matrices, including competing ions, organic impurities, and high salinity, moisture content, and metal concentrations. Standalone separation processes are limited by the selectivity, recovery efficiencies, and stability under real wastewater conditions of current methods[61]. Consequently, hybrid and emerging treatment technologies have gained significant attention as innovative approaches to distinguishing weaknesses of individual processes while optimizing metal recovery and the sustainability of the system. Hybrid technologies combine two or more synergistic treatment mechanisms, such as physical, chemical or biological and electrochemical processes in one single treatment system as depicted in table 2. These systems take advantage of synergistic effects resulting in both improved separation efficiency for metals as well as less consumption of chemicals, generation of secondary wastes and the process being more robust[62]. The hybrid configurations have been extensively studied and comprise adsorption–membrane systems, ion exchange–precipitation units, electrochemical–adsorptive processes, biologic-assisted recovery platforms.

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5.2 Adsorption-Membrane and Ion Exchange-Precipitation Systems

The hybrid adsorption-membrane process has been recognized as an effective technique for heavy metal recovery[74]. The major adsorption pathways responsible for heavy metal uptake, including physical adsorption, surface complexation, ion exchange, redox reactions, and surface precipitation, are illustrated in Fig 2. In these systems, adsorption acts as a downstream recovery is accomplished by desorbing metals into solutions or removing them with electrochemistry, and is facilitated in a reduced volume for further processing through the subsequent use of membrane processes, such as nanofiltration or reverse osmosis[75]. This combination significantly increases overall recovery and reduces membrane fouling and chemical cleaning costs. While adsorption ensures high efficiencies of purification and easy operation, membrane methods ensure high recovery purity, albeit with high energy costs and membrane fouling. Hybrid adsorption-membrane methods solve these problems by combining metal adsorption with the membrane method of concentration and recovery, hence improving the efficiency of the whole process and reducing membrane fouling. Similarly, ion exchange-precipitation hybrid systems rely on the highly selective nature of ion exchange resins for dilute metal streams, combined with controlled precipitation to form insoluble precipitates that are recovered as solids. It is particularly tailored for treating complex industrial effluents with low concentrations of valuable metals, such as nickel, copper, and zinc. Yet optimization of regeneration chemistry and sludge management will still need to be done carefully to avoid this environmental double hazard.

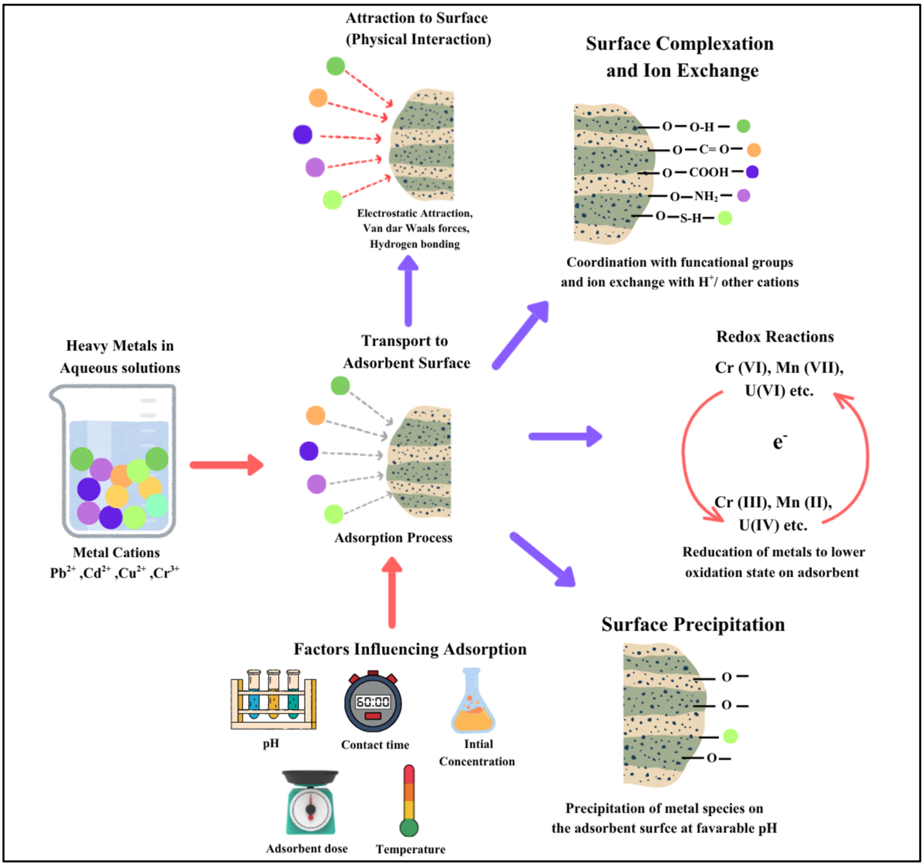

Fig 2. Schematic illustration of the adsorption mechanisms involved in heavy metal removal, including physical adsorption, surface complexation, ion exchange, redox reactions, and surface precipitation

5.3 Electrochemical-Assisted Hybrid Recovery Technologies

Electrochemical processes are particularly noteworthy as emerging recovery technologies because they can enable the simultaneous removal and recovery of metals with comparably high purity[76]. The integration of methods such as adsorption, membrane separation, and biological processes with electrochemical approaches can greatly enhance recovery selectivity and efficiency. For instance, in eco-physiological electrocoagulation–adsorption systems, coagulants are generated in situ to destabilize metal complexes, which subsequently adsorb onto high-affinity sorbents[77]. The approach reduces chemical consumption while enabling metals to be captured under dynamic waste-stream conditions. Notably, they are highly selective for target metal ions, particularly in electroplating and metallurgical wastewaters. These systems allowed selective ion transport across membranes under an electric field, enabling ions to be recovered in a controlled manner. Despite their advantages, electrochemical hybrid methods face significant energy consumption challenges and issues with electrode passivation and membrane degradation, which will be addressed through optimized reactor designs and appropriate integration with renewable energy sources.

5.4 Nanotechnology-Enabled Recovery Systems

Nanotechnology has contributed towards the development of a new generation of advanced materials that could effectively enhance heavy metal recovery due to their high surface area, tuneable surface chemistry, and high affinity towards metals. Numerous such as magnetic nanoparticles, graphene oxide, carbon nanotubes, MOFs, and nano-biochar composites, have demonstrated excellent performance for selective adsorption and recovery of metals, including Cr (VI), Pb (II), Cd (II), and Hg (II)[78]. Magnetic Nano adsorbents, in particular, offer a technical advantage: rapid separation and regeneration can be achieved with an external magnetic field, reducing solid–liquid separation costs. As efficient capture agents, nanomaterials can markedly improve the recovery of metals from hybrid systems at trace concentrations. Despite the trend toward large-scale application of these specialized nanomaterials, there is an urgent need for a life-cycle assessment (LCA) to evaluate their stability in complex real-world matrices, their potential for aggregation and bioaccumulation, their behaviour and fate in our environment, and their safety. But, with the emergence of green nanotechnology and bio-based strategies for synthesizing nanomaterials from plant extracts, biopolymers, and waste-derived precursors, some of these problems have been mitigated. Both studies favours reducing the environmental footprint of nanomaterial production while retaining high recovery performance, thereby rendering it suitable for circular-economy-based wastewater treatment applications.

5.5 Biobased and bio-hybrid systems: Integrated biological architectures

An innovative strategy for sustainable metal recovery from the environment is the intersection of biological processes with physicochemical technologies. Bioremediation and detoxification result from bioprocessing processes, such as biosorption followed by electrochemical recovery or adsorption-desorption cycles, which enable biological systems to be adapted to selective pre-concentration units that facilitate the effective recovery of metals. Microbial electrochemical systems (MES)-including microbial fuel cells and microbial electrolysis cells-are innovative systems in which microorganisms reduce or mobilize metals while generating either electrical power or other beneficial by-products. These systems offer the dual benefit of pollutant removal and energy/resource recovery, which aligns with circular economy principles[79]. Yet process stability, sluggish kinetics, and system complexity are challenges that now inhibit broad industrial deployment. By continuing to refine reactor optimizations, identify optimal microbial communities, and focus on systems-level integration, we will be on the path to unlocking the full capabilities of bio-hybrid recovery technologies.

5.6 Digitalization, artificial intelligence, and process intensification

Emerging digitalisation tools, such as artificial intelligence (AI), machine learning (ML), and more advanced process control systems, are being used to optimise hybrid recovery technologies. They enable real-time tracking and predictive optimization of key operational parameters, such as pH, flow rate, metal concentration, adsorbate dosage, and energy input. By analysing these large experimental and operational datasets, AI-driven models help create impressive operating windows that maximize metal restoration while minimizing energy consumption and operational costs[80]. Hybrid systems offer the dual benefit of combining different unit operations (or processes) to maximize scalability and efficiency, while process intensification approaches, such as continuous-flow reactors, microreactors, and modular treatment units, are also being integrated into these hybrid systems. Continuous systems offer superior process control to traditional batch operations with a much smaller footprint and higher mass transfer, making them an attractive candidate for scaling to industrial-scale wastewater treatment. Hand in hand with the digital optimization tools, these advanced systems comprise a powerhouse platform for next-generation metal recovery applications.

6 Challenges, Limitations, and Future Directions

Although considerable advancements have been made in the various technologies for the removal and potential recovery of heavy metals from wastewater, numerous scientific, technical, economic, and regulatory barriers still limit their field applications at an industrial scale. This is critical to advancing from laboratory-scale demonstrations to strong, commercial, viable, and sustainable resource recovery systems.

6.1 Technical and Process-Related Challenges

The major challenge in heavy metal recovery is the complex, highly dynamic nature of real-world industrial wastewater. In contrast to synthetic prepared solutions in a laboratory, real effluents typically contain multiple metal ions, very high levels of total dissolved solids, organic contaminants, and surfactants at varying concentrations, as well as varying pH. The selective and efficient recovery of contaminants from fly ash is dismally low under these conditions, especially in adsorption- and biosorption-based systems, due to competitive binding and fouling. Material degradation and fouling are also continuing significant issues in various technologies. Membrane systems face irreversible fouling and concentrate disposal problems, while repeated regeneration cycles lead to gradual capacity loss in ion exchange resins and adsorbents. Biosorption systems must address not only capacity but also performance over time, as biomass instability, structural breakdown, and reduced functional group availability can all reduce long-term efficacy. While electrochemical systems hold promise for metal recovery, several challenges, such as electrode passivation, high energy consumption, and short lifetime under continuous operation, have hindered their development. Scaling up the process is another big bottleneck[80]. Indeed, many recovery technologies have shown excellent performance in controlled lab-scale formulations but cannot maintain that efficiency when scaled up to pilot or industrial scales. Mass transfer constraints, hydraulic properties, reaction rates, and system integration challenges need to be methodically addressed via the optimization of reactor design and continuous-flow operating modalities.

6.2 Economic and Energy Constraints

Economic viability is the key determinant of all metal recovery technologies. Capital investment, operational, energy consumption, and regeneration costs are usually greater than the economic value of recovered metals, especially in low-concentration effluents. Energy-intensive processes, such as electrochemical treatment and advanced oxidation, are particularly difficult to implement in developing economies (where costs are highly sensitive). The absence of comprehensive techno-economic assessments (TEA) and life cycle assessments (LCA) for nascent and hybrid technologies impedes objective comparisons to justify investment. The lack of standardized evaluation frameworks makes it challenging to measure the actual environmental and economic gains from metal recovery approaches compared to traditional treatment methods.

6.3 Regulatory and Standardization Barriers

And a key challenge that is still not well addressed is the lack of standardised quality regulations for recovered metals. Regulations on the discharge of heavy metals into wastewater have been established worldwide, whereas very few exist for the purity, reuse, and commercialization of recovered metals. The lack of clear standardized market pathways discourages industries from adopting recovery-based approaches, as there are uncertainties in relation to market acceptance, liability and compliance. The diffusion of circular economy-based wastewater treatment practices is impeded by fragmented policy support and heterogeneous incentives between regions. To accelerate industrial uptake, there is a need for stronger regulatory harmonization across jurisdictions, including certification schemes that verify recovered materials (a process whereby waste becomes a resource), and financial incentives, such as tax deductions, carbon credits, and green finance mechanisms.

6.4 Research Gaps and New Opportunities

Future design research should focus on selective, durable, and regenerative recovery materials that are effective under realistic wastewater conditions. The development of surface functionalization, bioengineering, and material hybridization offers several approaches to improve selectivity and stability in multi-metal systems. Although scientific progress has been made towards this end, there is a particular need for an in-depth molecular-level understanding of adsorption and biosorption mechanisms to enable the rational design of materials. The realization of metal recovery integrated with other resource recovery processes, like water reuse and carbon capture, nutrient recovery, and bioenergy generation, represents a leap forward. These multifunctional systems can greatly enhance overall process economics and environmental performance, transforming wastewater treatment plants from costly disposal units into resource recovery hubs. Digital enablers like artificial intelligence, machine learning, and real-time sensing will play a critical role in addressing operational pain points. They can facilitate predictive process control and fault detection, helping optimize system performance to lower energy use and improve recovery efficiency. Digital twins and data-driven models may further support scale-up and risk assessment for industrial deployment.

6.5 Future Outlook toward Circular Economy Implementation

For heavy metal recovery from wastewater, interdisciplinary development must be cited by researchers, industry stakeholders, policymakers and regulatory bodies. Realigning laboratory-to-industry routes for this bridge will require alignment of technology validation, policy frameworks, and economic incentives. In the future, just-in-time deployment of integrated and energy-efficient systems with real-time monitoring will facilitate

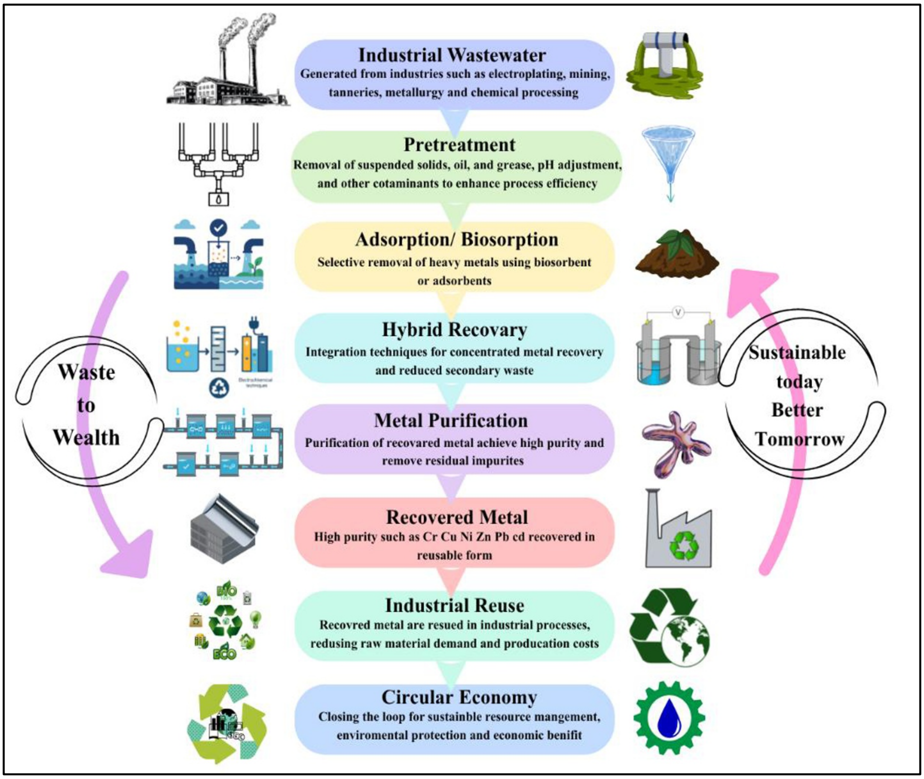

Fig 3. Schematic illustration of the integrated waste-to-wealth approach for sustainable heavy metal recovery and industrial wastewater reuse within a circular economy framework

a paradigm shift from discrete wastewater treatment technology to be directionally similar toward platform types infrastructure aligned with circular economy as shown in Fig 3. Such systems enable as well environmental pollution to be reduced, the dependence on primary metal resources to decrease, greenhouse gases reduced and a significant contribution towards building environments that are sustainable for all.

7 Conclusion

Treatment of heavy metal containing wastewater is a key part of sustainable environmental protection and resource conservation. With the increasing industrialization, traditional treatment methods that only target pollutant removal are no longer sufficient. This review brings attention to the need for shift from linear wastewater treatment paradigms towards resource recovery systems in which heavy metals are perceived as secondary resources and not persistent pollutants. Current technologies (physical, chemical, biological, hybrid) approach each wastewater source differently and none of these treatments are sufficient alone to solve the problems related to complex multiphasic industrial wastewaters. Traditional methods including chemical precipitation, membrane filtration, ion exchange, and electrochemical processes continue to work for the removal of metals; however, issues with selectivity, energy use, secondary waste generation and operational costs make them unfeasible for long-term sustainability. On the other hand, adsorption and biosorption based strategies are attractive for their ease of operation and low-cost deployment. These approaches enable metal recovery through regeneration and reuse cycles, especially when they form a component of hybrid treatment schemes. Recent trends such as material science, nanotechnology and bio-based systems have greatly improved both the efficiency and selectivity of metal recovery processes. These advancements allow for real-world performance under realistic wastewater conditions when coupled with hybrid configurations and process intensification strategies. The availability of digital tools like AI and ML can create additional avenues for continuously optimizing processes in real time, applying predictive control or scaling systems up/down, improving economic as well as environmental viability. Despite these developments, however, major barriers to widespread adoption, regulatory uniformity and economic sustainability still exist. Lack of quality standards for recovered metals, along with the limited techno-economic and life-cycle assessments, hinders large-scale industrial application. Closing these gaps will necessitate concerted efforts involving interdisciplinary research, enabling policy frameworks, and active partnerships between academia, industry, and regulatory authorities. Overall, future perspectives for heavy metals treatment should lead to the innovative development of integrated energy-efficient and digitally fuelled resource recovery systems in a circular economy framework. The multifunctional recovery facility has the potential to meet these measures at once by transforming wastewater treatment plants. Ongoing innovation, alongside strong policy support and stakeholder engagement, will be vital to ensure that heavy metal recovery technologies contribute fully to global sustainability targets.

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Declaration

Artificial Intelligence (AI) tools were used only for grammar correction and improving the readability and flow of the text.

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