

RESEARCH ARTICLE

Artificial Intelligence in Bio-Recovery of Noble Metals: A Sustainable Strategy for Circular Economy

Sanjib Sahoo^{1#}, Nitish Kumar Bhol^{1#}, Namrata Kanungo^{1#}, Sanatan Majhi¹, Jyotsnarani Pradhan^{1*}, Jagneshwar Dandapat^{1,2*}

¹Department of Biotechnology, Utkal University, Bhubaneswar, 751004, Odisha, India

²Centre of Excellence in Integrated Omics and Computational Biology, Utkal University, Bhubaneswar, 751004, Odisha, India

Abstract

Noble Metals (NMs) such as gold, silver, platinum, palladium and rhodium are essential for various technological applications. Their traditional methods of extraction are resource-intensive and environmentally invasive challenging their prospective utilisation. As global demand for these metals are increasing with simultaneous e-waste generation, eco-friendly and sustainable recovery approaches are the need of hour. Bio-recovery is a method of extraction of metals from waste through biosorption, bioaccumulation and bio reduction by utilizing microorganisms, algae and fungi. This offers an alternative green and cost-effective strategy allowing efficient and optimum recovery (up to 80-95%) of noble metals even at low concentrations with adsorption capacities ranging from ~50 mg g⁻¹ to ~170 mg g⁻¹. Further, the use of toxic chemicals or high energy inputs are minimized using this approach. This review explores the efficacy of various eukaryotes microalgae (*C. vulgaris* and *S. obliquus*), fungi (*A. niger* and *P. chrysogenum*), plants (*B. juncea* and *E. crassipes*), protozoa and invertebrates in the recovery mechanism of NMs from industrial waste, e-waste and contaminated environments. Despite notable progress, challenges remain in scalability, metal recovery efficiency, downstream processing and economic feasibility. Such bio-recovery process empowered with Artificial Intelligence (AI) and machine learning can complement the outcome by providing a cutting-edge, eco-friendly strategy for managing noble metal resources. This communication further highlights the different available approaches for recovery of various NMs and their amalgamation with AI tools and intelligent computing. AI tools such as machine learning, neural networks and bioinformatics platforms can optimize process parameters (pH, temperature and nutrient supply) predict microbial performance and automate real-time monitoring with high predictive accuracy (upto 90% accuracy) to maintain ideal conditions for recovery. Our review would provide strategic insights into understanding the efficiency and scalability of noble metal recovery through the combination of AI and green biotechnology thereby contributing towards the circular economy. Future progress will depend on interdisciplinary collaborations and continued innovation at the intersection of microbiology, engineering and artificial intelligence.

***Corresponding Author:** Jyotsnarani Pradhan, Jagneshwar Dandapat, Professor, Department of Biotechnology, Utkal University, Bhubaneswar, 751004, Odisha, India; Email: jd.biotech@utkaluniversity.ac.in

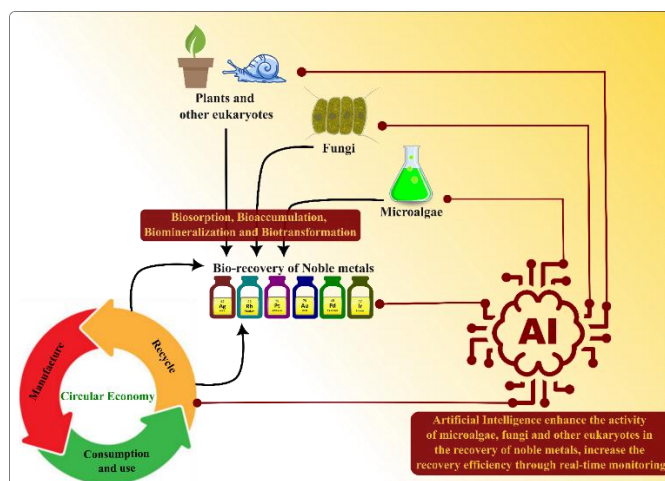
Received Date: August 11, 2025, **Accepted Date:** August 28, 2025, **Published Date:** August 30, 2025

Citation: Sahoo S, Bhol NK, Kanungo N, et al. Artificial Intelligence in Bio-Recovery of Noble Metals: A Sustainable Strategy for Circular Economy. *Int J Bioinform Intell Comput*. 2025;4(2):196-223.



This open-access article is distributed under the terms of the Creative Commons Attribution Non-Commercial License (CC BY-NC) (<http://creativecommons.org/licenses/by-nc/4.0/>), which permits reuse, distribution and reproduction of the article, provided that the original work is properly cited and the reuse is restricted to non-commercial purposes.

Graphical Abstract



Key Words: Artificial Intelligence (AI); Machine learning; Noble metals; Bio-recovery; e-Waste; Biosorption; Bioaccumulation; Bioreduction; Biomineralization; Circular economy

1. Introduction

Noble Metals (NMs), are characterized by their exceptional resistance to corrosion and oxidation, along with high economic value [1]. Their unique physicochemical properties render them vital across multiple sectors beyond traditional applications like jewellery or coinage [2]. In particular, Platinum (Pt), Palladium (Pd), Rhodium (Rh), Gold (Au), Silver (Ag) Ruthenium (Ru) are indispensable for catalytic converters in the automotive industry, microelectronics fuel cell technology [2–4]. These high-value metals are extensively used in computers, mobile phones, industrial catalysts are emerging as clean energy technologies [5,6]. However, the global supply of NMs remains limited, as they are sparsely/scarcely distributed in the Earth's crust and are becoming harder to extract through primary mining. The demand for NMs is quite higher than their existing resources, prompting urgent attention to alternative recovery methods.

Given the ecological damage caused by traditional mining practices, such as land degradation, carbon emissions water contamination, there is a growing emphasis on the development of greener, circular strategies for resource management. Recovery of NMs from electronic waste (e-waste) is emerging as a sustainable solution. E-waste is currently the fastest-growing solid waste stream globally, with over 62 million tonnes generated in 2022 alone [7]. These discarded electronics have substantial amount of precious and rare earth metals, yet less than a quarter of recoverable metals are recycled, leading to significant economic and environmental losses [8,9].

Traditional e-waste management techniques such as landfilling, incineration crude acid leaching is still widely practiced, particularly in developing countries [10]. These methods pose serious environmental threats through the release of hazardous gases, soil contamination water pollution. Even in industrialized nations, e-waste is frequently exported to underdeveloped regions under informal recycling schemes, exacerbating environmental injustice and perpetuating unsustainable practices [11,12]. Consequently, the need for green, efficient scalable recovery technologies is more pressing than ever.

To address these issues, the global scientific community has shifted towards green extractive metallurgy, an umbrella term encompassing environmentally friendly approaches like hydrometallurgy, biometallurgy hybrid methods. These processes aim to recover valuable metals with minimal environmental impact. Biometallurgy, in particular, leverages biological organisms such as microalgae, fungi hyperaccumulator plants to biosorb, bioaccumulate, or bioleach metals from waste streams. Microalgae, for example, have demonstrated remarkable capacity for NM uptake through surface adsorption and intracellular sequestration. Similarly, filamentous fungi like *Aspergillus* and *Penicillium* can solubilize metals using organic acids. Phytomining, which involves plants to extract metals from contaminated soil, offers a cost-effective and ecologically benign solution for metal recovery [13,14] (Figure 1).

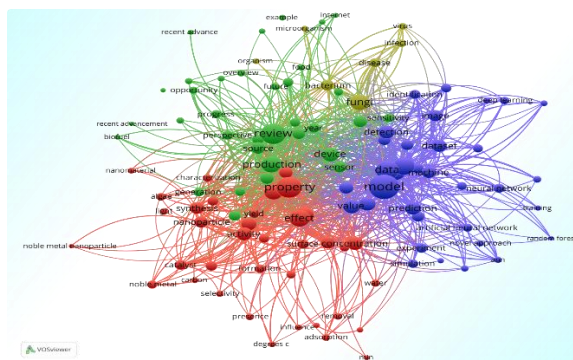


Figure 1: Network diagram illustrating common keywords from articles related to “Artificial Intelligence” and “Noble Metals”, “Noble Metals-microalgae”, “Noble Metals-fungi”, “Noble Metals-plants” published between 2000 and 2025, as indexed in the Web of Science database.

Despite the promise of these biological strategies, several practical challenges limit their industrial applications. The biological mechanisms underlying metal uptake are complex and highly sensitive to environmental conditions [15]. Bioleaching processes are generally slow, difficult to optimize manually often yield inconsistent results. Additionally, most existing studies are limited to laboratory-scale experiments there is a lack of large-scale, integrated bioprocess designs. This disconnect between lab-based research and real-world implementation represents a major research gap [16]. Moreover, there is minimal integration of computational intelligence especially artificial intelligence with bioremediation efforts. While AI is transforming numerous fields through data-driven modeling, prediction optimization, its potential remains underutilized in the context of NM recovery from e-wastes. Recent bioleaching or biosorption studies rely heavily on empirical, trial-and-error approaches, which are time-consuming and resource-intensive. Furthermore, the lack of predictive models that can simulate microbial behavior, metabolic flux system responses under varied conditions hinders the ability to scale up bioremediation processes effectively [17]. This review aims to address this critical research gap by exploring the intersection of AI, green extractive metallurgy bio-recovery of noble metals. It proposes a novel conceptual framework where artificial intelligence not only complements but also enhances the biological recovery mechanisms. By incorporating AI into the design and control of bio-based recovery platforms, it becomes possible to simulate complex interactions, predict system behavior identify optimum conditions for metal uptake, ultimately increasing recovery efficiency and reducing operational complexity [18–20] (Figure 2).

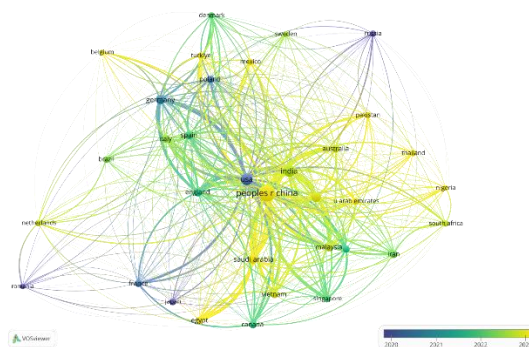


Figure 2: Network diagram illustrating list of co-authors from different geographical areas who have published articles between 2000 and 2025 related to “Artificial Intelligence” and “Noble Metals”, “Noble Metals-microalgae”, “Noble Metals-fungi”, “Noble Metals-Microalgae”, as indexed in the Web of Science database.

AI-driven technologies, particularly machine learning, can analyze large experimental datasets to detect patterns and correlations that are not easily discernible through conventional analysis. For instance, ML models can optimize parameters like pH, temperature, biomass density metal concentration for efficient bioleaching [21]. Moreover, AI can help to identify new microbial strains with enhanced metal uptake capabilities or propose genetically engineered pathways through synthetic biology. In Microbial Cell Factories (MCFs), AI-aided gene editing and protein engineering are already revolutionizing the Design-Build-Test (DBT) cycle, evolving it into more advanced Design-Build-Test-Learn-Predict (DBTLP) framework [22]. Recent breakthroughs in Large Language Models (LLMs) such as GPT-4, Alpha Fold BERT have further expanded the scope of AI in biology [23,24]. These models can be trained on genomic, proteomic metabolic data to enable enzyme function prediction, genome annotation metabolic pathway design. Such tools are highly relevant to bioleaching and biosorption, as they can inform the development of tailored enzymes or artificial proteins with higher affinity for specific metals [25]. Moreover, AI can support the automation of microbial screening, optimize media compositions facilitate real-time monitoring of bioleaching processes, contributing to higher efficiency and reproducibility. The review also explores AI's application in water treatment- a complementary domain to e-waste recovery. AI has proven effective in modeling contaminant adsorption, predicting treatment efficacy optimizing chemical usage [26,27]. These methodologies can be adapted to manage waste effluents generated during NM recovery, ensuring that green processes do not inadvertently contribute to secondary pollution. However, for AI to be fully effective in these domains, challenges such as limited access to high-quality datasets, lack of standardization in experimental protocols the need for interdisciplinary collaboration must be addressed. Thus, this review fulfills a dual purpose of consolidating current knowledge on biological recovery strategies for noble metals highlighting the transformative role of AI in optimizing these green technologies. Bringing in insights from environmental science, synthetic biology, computational modeling metallurgical engineering, the review offers a roadmap for developing intelligent, eco-friendly economically viable NM recovery systems [28]. The scope of this review extends to both academic researchers and industrial stakeholders. It encourages the adoption of AI-driven strategies for bioremediation, highlights areas for future research advocates for policy frameworks that support sustainable resource recovery. It would eventually contribute towards the broader goals of the circular economy, climate resilience responsible technological innovation. In conclusion, the integration of AI with green bio-recovery techniques represents a paradigm shift in sustainable metal extraction. As the demand for noble metals continues to rise with the growth of digital and green technologies, intelligent recovery systems will be essential for ensuring long-term material security and environmental stewardship. This review not only provides a comprehensive analysis of

current methodologies but also envisions a future where data-driven, biologically trained procedures will drive the next generation of resource recovery platforms.

2. Microalgae-Based Recovery of Noble Metals from Waste: A Sustainable Biotechnological Approach

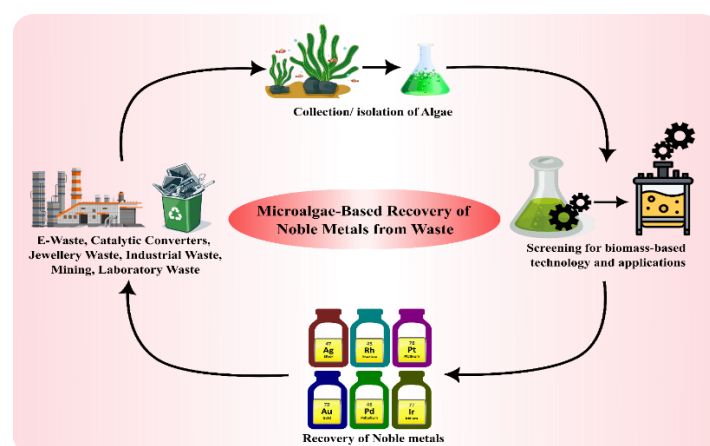
2.1. Microalgae as a green tool for metal detoxification

Rapid industrialization, urban expansion population growth has significantly increased the discharge of Heavy Metals (HMs) into aquatic ecosystems [29]. These contaminants, originating from industries like mining, metallurgy, electroplating, electronics agriculture, not only damage aquatic life but also accumulate in the food chain, leading to serious health risks such as pulmonary dysfunction, cardiovascular issues, kidney failure cellular toxicity in both humans and animals. Due to the limitations of conventional metal remediation techniques including high cost, inefficiency at low concentrations the production of secondary waste researchers is actively exploring eco-friendly alternatives. Microalgae, unicellular or simple multicellular photosynthetic organisms found in both freshwater and marine environments, offer a sustainable and cost-effective solution for heavy metal remediation. Their advantages include rapid growth, low nutritional requirements, high surface-area-to-volume ratio efficient metal binding (Figure 3). Both live and dead microalgal biomass exhibit significant potential for HM removal through passive (biosorption) and active (bioaccumulation) mechanisms. Their ability to function in aerobic and anaerobic environments further enhances their versatility [30]. The metal-binding efficiency of microalgae is largely attributed to the functional groups, such as carboxyl, hydroxyl, amino, phosphate sulfate groups, present in their cell walls, composed of lipids, proteins polysaccharides. These functional moieties serve as active sites for metal interaction, facilitating ionic exchange, complexation electrostatic attraction [31]. Additionally, various physicochemical parameters including pH, temperature, biomass concentration, initial metal concentration the presence of competing ions significantly influence the metal uptake efficiency.

Microalgae have demonstrated the ability to detoxify a wide range of metals. For example, *Chlorella vulgaris* and *Scenedesmus obliquus* can effectively adsorb lithium, while *S. incrassatus* detoxifies hexavalent chromium. Similarly, *Scenedesmus quadricauda* has been used for zinc removal *Chlamydomonas reinhardtii* has shown potential for lanthanide biosorption [32]. These findings support the implementation of algal-based systems like algal ponds and bioreactors, which have been found to be significantly more efficient than conventional wastewater treatment setups. Hybrid systems combining microalgae and sulfate-reducing bacteria also show promise for enhanced bioremediation performance. In addition to native strains, genetically modified microalgae have been investigated for improved metal uptake. Through modification of genes encoding metal-binding proteins like metallothioneins and phytochelatins, researchers aim to enhance bioaccumulation capacity [33,34]. Immobilization strategies using materials like calcium alginate have also been employed to stabilize biomass and improve recovery rates for metals like cadmium and copper. Moreover, microalgae-derived nanoparticles have emerged as innovative platforms for metal detoxification due to their high surface area and reactivity. Despite these promising developments, some challenges remain. High concentrations of metals can inhibit algal growth, affecting overall remediation efficiency. Additionally, the cost associated with downstream processing for metal recovery and biomass reuse is quite significant. Nonetheless, the multifunctionality, adaptability ecological compatibility of microalgae makes them a powerful biotechnological tool in sustainable metal recovery [35] (Table 1).

Table 1: Comparative summary of noble metal recovery using different microalgae and cyanobacterial species.

Microalgae species	Target noble metal ions	Optimal operating range (pH, T)	Biosorption/uptake capacity	Kinetics	Regeneration / reuse cycles	References
<i>Chlorella vulgaris</i>	Au ³⁺ , Pt ⁴⁺ , Pd ²⁺ , Ag ⁺	pH 4–6, T 25–30 °C	80–120 mg/g (Au ³⁺); 50–70 mg/g (Pt ⁴⁺)	Rapid, equilibrium in 30–60 min (pseudo-second order)	Up to 4–5 cycles with ~70% efficiency retention	[36–38]
<i>Scenedesmus obliquus</i>	Au ³⁺ , Ag ⁺ , Pt ⁴⁺	pH 5–7, T 25–35 °C	60–100 mg/g (Au ³⁺); 40–60 mg/g (Ag ⁺)	Moderate, equilibrium in 1–2 h	3–4 cycles with 60–70% recovery	[39,40]
<i>Spirulina platensis</i> (cyanobacterium)	Au ³⁺ , Pd ²⁺ , Ag ⁺	pH 4–6, T 20–30 °C	70–110 mg/g (Au ³⁺); 55–65 mg/g (Pd ²⁺)	Fast uptake, ~45 min equilibrium	4–6 cycles, efficiency loss <20%	[41–43]
<i>Nannochloropsis oculata</i>	Pt ⁴⁺ , Pd ²⁺ , Au ³⁺	pH 5–7, T 25–28 °C	50–80 mg/g (Pt ⁴⁺ , Pd ²⁺)	Moderate, ~1–2 h equilibrium	3–4 cycles, ~65% efficiency retained	[44]
<i>Chlamydomonas reinhardtii</i>	Au ³⁺ , Ag ⁺ , Pt ⁴⁺	pH 5–6, T 20–28 °C	40–70 mg/g (Au ³⁺ , Ag ⁺)	Slower, ~2–3 h equilibrium	2–3 cycles; regeneration efficiency drops significantly	[45]
<i>Anabaena cylindrica</i> (cyanobacterium)	Au ³⁺ , Ag ⁺ , Pt ⁴⁺	pH 4–6, T 25–30 °C	60–90 mg/g (Au ³⁺ , Ag ⁺)	Fast initial uptake (30–60 min)	4–5 cycles, stable retention	[46]

**Figure 3:** Schematic representation of microalgae-based recovery of noble metals from waste.

2.2. Biosorption: mechanism and efficiency in metal recovery using microalgae

Biosorption is a non-metabolic, passive process where biological materials, living or dead, act as sorbents to remove contaminants from aqueous environments [36]. This process involves mechanisms such as surface complexation, electrostatic interaction, ion exchange, precipitation physical adsorption. It primarily depends on the interaction between the target contaminant (sorbate) and the biological surface (biosorbent), continuing until equilibrium is achieved. The success of biosorption depends on the chemical composition and surface characteristics of microalgal cell walls, particularly the presence of negatively charged functional groups that bind positively charged metal ions [37]. Components such as Extracellular Polymeric Substances (EPS), comprising proteins, lipids polysaccharides, play a critical role in enhancing adsorption efficiency by modifying surface properties and improving structural integrity. For instance, *Chlorella vulgaris* has demonstrated the ability to achieve nearly 100% removal of metronidazole, a pharmaceutical contaminant, via biosorption. Microalgal species exhibit variation in biosorption performance based on cell wall composition, surface area, porosity ion exchange capacity. Positively charged metal ions are especially attracted to the negatively charged surfaces of algal cells, reinforcing the utility of microalgae for HM removal [38]. Studies confirm that smaller-sized microalgae tend to have a higher surface-to-volume ratio, thereby offering more binding sites and enhancing removal efficiency. Dead algal cells retain the biosorption capacity of live cells, providing a practical advantage by eliminating the need for maintaining viable biomass. These dead cells are not only less sensitive to toxic concentrations of metals but can also be reused after desorbing the adsorbed metals, making biosorption a cost-effective and environment- friendly process [39]. For example, species like *Chlorella prenioidisa* and *Scenedesmus obliquus* have the potency of removal of about 70% of copper and zinc after 192 hours. Several algae, including *Anabaena*, *Spirogyra*, *Phormidium Oscillatoria*, have shown resilience to HM stress. In response, microalgae upregulate antioxidant enzymes and synthesize chelating agents to minimize cellular damage. The passive biosorption process is not only fast and reversible but also highly effective for low-concentration pollutants without the generation of toxic by-products [40]. These attributes position biosorption as a prime technology for future industrial-scale metal recovery systems.

2.3. Bioaccumulation: energy-dependent uptake of metal ions

In contrast to biosorption, bioaccumulation is an active, metabolism-dependent process that involves the uptake of metal ions through energy-driven transport systems across the cellular membrane. This two-step process begins with the adhesion of metals to the cell surface, followed by internalization and intracellular sequestration via complex formation with biomolecules like proteins and peptides [41]. Microorganisms employed for bioaccumulation must demonstrate high metal tolerance, adaptability to polluted environments efficient intracellular binding mechanisms. Among the key factors influencing the process are pH, contact time, biomass concentration, initial metal concentration temperature. Bioaccumulation often involves specialized metal-binding proteins like metallo thioneins and phytochelatins, which chelate metals intracellularly to mitigate toxicity [42]. For example, genetically engineered *Escherichia coli* expressing MTs from *Corynebacterium glutamicum* showed enhanced biosorption for Pb^{2+} and Zn^{2+} .

Likewise, engineered *Pseudomonas putida* expressing MTs was effective in Cu^{2+} binding. These intracellular proteins serve dual purposes, i.e., detoxifying the metal ion and storing it in a non-toxic form within vacuoles or cytoplasmic compartments. The capacity of microalgae

for bioaccumulation can be enhanced through genetic engineering, optimization of growth conditions incorporation into bioreactor systems. However, the method is slower compared to biosorption and is highly sensitive to environmental stress [43]. Furthermore, maintaining live algal biomass under optimal conditions poses operational challenges, especially at scale. Nevertheless, when coupled with biosorption or applied in hybrid systems, bioaccumulation can substantially increase the overall efficiency of HM removal. Microalgae's ability to alter gene expression, release chelators synthesize EPS in response to metal exposure makes them dynamic tools in environmental detoxification [44].

Microalgae represent a promising, nature-inspired solution for the green recovery of noble and heavy metals from aqueous systems and e-waste leachates. Through passive biosorption and active bioaccumulation, various microalgal species can remove and immobilize a wide range of toxic metals. These processes are governed by several factors such as cell wall composition, growth conditions external environment [45]. While biosorption is rapid, non-metabolic effective even in dead cells, bioaccumulation offers a deeper mechanism of intracellular metal binding, albeit with more operational complexity. Recent advances, including immobilization, bioreactor integration, genetic modification nanotechnology, are paving the way towards industrial-scale deployment of microalgae in metal remediation [46]. The main research gap lies in the limited transition of lab-scale microalgal systems to scalable, real-world applications. Most studies remain empirical, lacking integration with computational tools or predictive models for process optimization. Furthermore, the cost associated with biomass processing and recovery needs to be addressed. To fill this gap, future directions should include AI-assisted modeling of algal growth and metal uptake kinetics, development of robust multi-species consortia implementation of smart bioreactor systems for dynamic control. This review section highlights microalgae as a low-cost, adaptable efficient bioresource capable of supporting sustainable strategies for noble metal recovery and wastewater remediation in alignment with circular economy principles.

2.4. Genetic and metabolic engineering tools for microalgal strain improvement

Recent advancements in molecular biology and synthetic biology have significantly expanded the potential for genetically engineering microalgae to improve their performance in photosynthesis, carbon fixation, bioproduct synthesis Heavy Metal (HM) bioremediation. Although *Chlamydomonas reinhardtii* remains the primary model for genetic manipulation, genome sequencing of numerous other microalgal species now provides valuable insights and resources for engineering diverse strains [47]. The availability of high-throughput sequencing, genome reconstruction, bioinformatics multi-omics platforms has made it possible to systematically reprogram microalgal metabolic pathways to enhance stress tolerance and environmental performance. Modern genetic engineering relies on several precise molecular tools such as Zinc-Finger Nucleases (ZFNs), transcription activator-like effector nucleases (TALENs), CRISPR/Cas systems, Cre/loxP recombination RNA interference (RNAi). Additionally, modular cloning systems like golden gate and molo have enabled high-throughput gene stacking and construction of complex synthetic circuits in species such as *Chlamydomonas* and *Nannochloropsis* [48,49]. These tools are supported by a range of inducible, constitutive synthetic promoters, reporter genes vector systems tailored for microalgal applications. These techniques allow gene knockout, knockdown, or overexpression, with new developments supporting marker-free and transgene-free mutants. Protein engineering is also gaining attention through techniques like directed evolution, fusion protein designs de novo construction, which can introduce or optimize functions such as catalytic activity or metal binding. Artificial intelligence and machine learning are being increasingly used to

predict structure-function relationships in proteins, enabling more precise and accelerated engineering efforts. These computational approaches benefit from training on existing protein datasets to enhance enzyme functionality and stability [50].

Multi-omics techniques, encompassing genomics, transcriptomics, proteomics, metabolomics interactomics, offer deep insights into the dynamic responses of microalgae to environmental stresses. Public databases such as phytozome, KEGG, alga-pr. As chlamycys contain extensive omics datasets that aid researchers in identifying candidate genes for engineering. Genome-scale metabolic models based on Flux Balance Analysis (FBA) have also emerged, enabling the rational design of high-efficiency algal cell factories [51]. These models have already proven useful in optimizing hydrogen production and photosynthetic performance in *C. reinhardtii*. Advanced sequencing techniques like illumina-based rna-seq and microarrays now allow gene expression profiling without prior sequence knowledge [52]. Meta-omics approaches, such as metagenomics, metatranscriptomics metaproteomics, are particularly powerful for studying microbial consortia in contaminated environments. These techniques reveal metal transporters, transcription factors enzymes involved in HM resistance, aiding the discovery of new genetic targets for improving bioremediation capacity. Despite the rapid progress in genetic tools and multi-omics, a significant gap remains between our molecular understanding of microalgal stress responses and the successful engineering of strains for practical heavy metal bioremediation. Comprehensive knowledge of microalgal physiology under metal stress is essential for tailoring strains effectively. Additionally, sequencing new strains and developing strain-specific genetic toolkits are crucial for expanding the scope of engineered microalgae for real-world applications [53].

3. Fungal-Mediated Recovery of Noble Metals: A Sustainable Biotechnological Approach

Noble metals including silver, gold, platinum, palladium, rhodium, ruthenium is characterized by exceptional resistance to oxidation and corrosion. Despite their low natural abundance in the Earth's crust, these metals are critically important due to their diverse applications across various industries. While in early times, these were valued for production of decorative uses such as jewellery and coinage, they now serve essential roles in electronics, catalysis high-performance technologies due to their unique chemical properties [54]. Traditionally, the recovery of these metals was relied on mining and refining processes. Though extracting NMs from primary sources is effective, these conventional techniques come at a steep environmental cost. Mining operations often result in habitat destruction, soil erosion significant heavy metal contamination. In addition, refining activities consume vast amounts of energy and emit substantial greenhouse gases such as carbon dioxide and methane, contributing to climate change. These practices have also contributed to the alarming increase in electronic waste, which paradoxically contains high concentrations of recoverable NMs. Given these drawbacks, there is a growing shift towards biological methods for NM recovery, which offer a greener and more sustainable alternative [55]. Among the various biotechnological options such as the use of bacteria, algae plants, fungi have emerged as particularly promising agents for metal recovery. Their innate tolerance to metal stress, adaptability to harsh environments ability to secrete metal-binding compounds make them suitable candidates for bioremediation and bioleaching applications [56].

3.1. Mechanisms of fungal-mediated nm recovery

Fungal systems interact with metal ions through several well-established mechanisms: biosorption, bioaccumulation, biotransformation/biomineralization (Figure 4). These processes differ in their metabolic dependence, localization of metals, efficiency, collectively contribute to the fungi's ability to recover valuable metals from waste streams, industrial effluents, contaminated environments [57]. Fungal-mediated recovery of noble metals offers a sustainable alternative for metal recycling, with fungi facilitating both direct and indirect mineral formation, including elemental metals such as Ag, Se, and Te. Filamentous fungi display variable tolerance to precious metals, with platinum showing minimal growth inhibition, while gold is most toxic. Complementary electrochemical strategies demonstrate high uptake capacity (>200 mg/g), strong selectivity (>5 against competing ions), and low energy consumption (<5 kJ/g-PGM). Additionally, innovative green methods, such as transition metal dichalcogenide papers, enable spontaneous extraction of Au, Pd, Pt, Ag, and Ru from complex samples without the need for reductants or heating.

3.1.1. Biosorption: Biosorption refers to the passive binding of metal ions onto the fungal cell surface. This process is primarily facilitated by the functional groups present in fungal cell walls, including carboxyl, hydroxyl, amino, phosphate groups derived from polysaccharides (like chitin and glucans), proteins, lipids [58] (Figure 4). These moieties allow fungi to trap metal ions through mechanisms such as ion exchange, complexation, chelation, micro-precipitation. Fungal species such as *Aspergillus niger*, *Saccharomyces cerevisiae*, *Penicillium chrysogenum* have demonstrated significant potential to adsorb Au^{3+} , Pt^{2+} , Pd^{2+} , Ag^{+} ions from aqueous solutions and mining waste. In particular, ion exchange involves the displacement of bound cations on the fungal surface by noble metal ions, enabling selective recovery [59]. Similarly, chelation and complexation stabilize the binding of metals through strong interactions with cell wall ligands, improving both specificity and retention [60]. In cases where metal ions have low solubility, biosorption can lead to micro-precipitation, the formation of insoluble clusters of metal ions that facilitate easier separation. These weakly bound metals can be desorbed and recovered, offering an energy-efficient and low-cost approach to NM reclamation.

3.1.2. Biomineralization and biotransformation: Biomineralization is an active, metabolically driven process through which fungi transform dissolved metal ions into stable mineral structures or elemental forms. This mechanism involves four sequential steps: surface adsorption, cellular uptake, enzymatic reduction, nanoparticle formation/precipitation. Upon initial contact, metal ions adhere to the fungal cell surface through electrostatic interactions. The ions are then internalized via membrane transporters and directed into intracellular compartments, such as vacuoles. Here, enzymatic systems, NADH-dependent reductases and glutathione reductases, catalyze the reduction of metal ions. A well-known example is the reduction of Au^{3+} to elemental gold (Au^0) by *Fusarium oxysporum*, leading to the formation of gold nanoparticles. Following reduction, the nucleation of metal atoms occurs either intracellularly or extracellularly, eventually forming nanocrystals. These particles can be sequestered within the fungal cell wall or expelled into the surrounding medium. For instance, *Trichoderma viride* facilitates the extracellular precipitation of Pt^{2+} and Pd^{2+} , simplifying downstream recovery. Biotransformation, closely related to biomineralization, refers to the fungal capacity to chemically modify metal ions, enhancing their extractability [61]. These processes are particularly useful for converting soluble metal ions into more manageable particulate forms, which can then be harvested using conventional separation techniques (Figure 4).

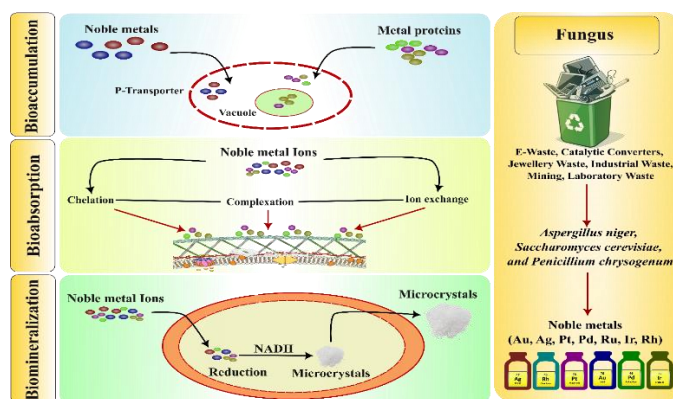


Figure 4: Mechanisms of fungal-mediated recovery of noble metals from waste sources.

3.1.3. Bioaccumulation: In contrast to biosorption, bioaccumulation is an active, energy-dependent process in which fungi internalize and store metal ions within cellular compartments. This mechanism is especially relevant for the recovery of noble metals from industrial effluents, e-waste mining wastewater. Metal uptake is mediated by ATP-driven transporters, such as p-type ATPases, which selectively pump ions like Cu^{2+} and Ag^+ into the cell. Once inside, metal ions are often bound by metallothioneins, sulfur-rich proteins with a high affinity for noble metals such as gold and silver. These act as buffers, reducing metal toxicity while facilitating metal storage. The compartmentalization of metal ions within vacuoles or other organelles helps to reduce oxidative stress in the cell and allows for the controlled accumulation of valuable elements. In some cases, internalized metal ions undergo further enzymatic reduction to elemental forms, contributing to nanoparticle formation similar to the biomineralization process [62].

Recent advancements in genetic engineering, synthetic biology metabolomics have opened up new avenues for enhancing fungal metal recovery. Engineered fungal strains with upregulated metal-binding proteins, modified transport systems, or enhanced enzymatic pathways could significantly improve the efficiency and selectivity of NM bioleaching. For instance, bioengineered strains of *Aspergillus* or *Penicillium* may be developed to overexpress specific reductases or metallothioneins, resulting in superior uptake and transformation capabilities. Similarly, integrating omics-based insights with machine learning models could facilitate predictive design of high-performing fungal strains optimized for specific industrial waste streams [63].

Furthermore, the combination of fungal biosorption and bioaccumulation with downstream techniques, such as electrochemical recovery or green solvents, could establish hybrid systems that are both economically viable and environmentally friendly. Fungal-mediated recovery of noble metals offers a sustainable and promising alternative to conventional mining and refining. Through mechanisms such as biosorption, bioaccumulation biomineralization, fungi can efficiently capture, transform store valuable metals from a variety of waste sources. Their intrinsic properties, including metal resistance, adaptability secretion of binding agents, make them ideal candidates for eco-friendly recovery platforms. As technological innovations in synthetic biology and systems biology continue to evolve, the optimization of fungal strains for noble metal recovery is expected to become more precise and scalable [64]. Harnessing these capabilities could contribute significantly to closing the resource loop, reducing environmental degradation supporting the global transition to a circular economy (Table 2).

Table 2: Comparative schematic of fungal-mediated noble metal recovery pathways-biosorption, biomineralization, and bioaccumulation.

Parameter	Biosorption	Biomineralization	Bioaccumulation
Process nature	Passive surface adsorption of metal ions on fungal cell walls	Conversion of soluble ions into insoluble nanoparticles/minerals	Active intracellular transport and sequestration
Rate of recovery	Fast (minutes–hours)	Moderate–slow (hours–days)	Slowest (hours–days)
Selectivity	Low selectivity, binds multiple cations (Au^{3+} , Pt^{4+} , Cu^{2+} , Pb^{2+})	Moderate selectivity, redox potential-driven (Au^{3+} , Pt^{4+} , Ag^+)	High selectivity via metal transporters and detoxification
Energy requirement	Energy-independent (non-metabolic)	Partially energy-dependent (enzyme-mediated)	Energy-dependent (requires metabolism)
Binding sites / Mechanism	Cell wall functional groups ($-\text{OH}$, $-\text{NH}_2$, $-\text{COOH}$, $-\text{SH}$)	Enzyme-mediated reduction and nucleation of nanoparticles	Transporters, metallothioneins, glutathione, vacuolar sequestration
Product form	Metal ions bound on cell walls (desorbable)	Extracellular/intracellular nanoparticles (Au^0 , Pt^0 , AgNPs)	Intracellular complexes/nanoparticles
Reusability of biomass	High (biomass regeneration possible)	Moderate (precipitation may damage cells)	Low (requires cell disruption)
Industrial potential	Wastewater treatment, large-scale removal	Green synthesis of nanomaterials	Selective recovery from trace solutions

4. Plant-Based Recovery of Noble Metals: Phytomining and Phytoremediation Approaches

Plants offer an eco-friendly alternative for the recovery of Noble Metals (NMs) through techniques like phytomining and phytoremediation, which utilize the natural ability of certain species to extract or stabilize metals from soil and water. These methods present a sustainable and low-cost solution compared to traditional mining practices, which are often environmentally destructive and economically unfeasible in low-grade ore regions. Phytomining involves cultivating metal-accumulating plants, especially on metal-rich but agriculturally unsuitable lands, to absorb metals from the soil. After harvesting, the biomass is incinerated to produce “bio-ore” from which metals like nickel, cobalt, cadmium, zinc, selenium, manganese, thallium noble metals such as gold and silver can be recovered [65]. This strategy is particularly beneficial for areas affected by mining waste or metal smelting operations it has been widely applied in nickel-rich ultramafic soils using hyperaccumulator species. The resulting biomass contributes to metal recovery and bioenergy production, making the approach economically and ecologically valuable. Phytoremediation, on the other hand, is the broader technique of using plants to clean up contaminated environments. Certain hyperaccumulator plants naturally evolved to thrive in metal-rich soils and can uptake and tolerate heavy metal stress. These plants absorb metals through their roots and store them in shoots, leaves, or flowers, enabling both detoxification and resource recovery. Examples include *Brassica juncea* (Indian mustard) for gold, *Eichhornia crassipes* (water hyacinth) for silver *Helianthus annuus* (sunflower) for both gold and silver [66]. Phytomining is a sustainable plant-based method for recovering noble and critical metals from low-grade ores, secondary sources, and metal-rich soils. It relies on hyperaccumulator plants that extract and concentrate metals such as nickel, gold, and rare earth elements, with over 450 nickel-hyperaccumulator species identified. Plants like *Alyssum murale* can yield up to $100 \text{ kg Ni ha}^{-1} \text{ y}^{-1}$. Harvested biomass is incinerated, and the ash processed via hydrometallurgy to produce compounds like nickel sulfate. This approach not only recovers valuable metals but also aids soil remediation, carbon capture, and bioenergy generation, though efficiency, scalability, and economic viability remain key challenges. Phytoextraction refers to the uptake and accumulation of metals into plant tissues from soil or water, while rhizofiltration

specifically targets removal of metal ions from aqueous media using root systems. In rhizofiltration, metals either adhere to or are absorbed by the roots, which are then harvested for metal recovery. Plants like *Oryza sativa* (rice), *Chrysopogon zizanioides* (vetiver), and *Salix spp.* (willows) are also being studied for their potential in noble metal remediation. Overall, these green technologies provide promising alternatives for recovering valuable noble metals while simultaneously addressing environmental pollution in a sustainable manner. With advancements in genetic engineering and phytotechnology, their efficiency and applicability are expected to improve further.

5. Recovery of Noble Metals Using Non-Conventional Eukaryotes

The extraction of Noble Metals (NMs), such as gold, silver, platinum-group metals are critical for various industrial applications including electronics, mining chemical manufacturing. However, conventional recovery methods like chemical precipitation, solvent extraction ion exchange are often limited by low selectivity, generation of hazardous waste high energy consumption. In this context, leveraging the bio capabilities of non-conventional eukaryotic organisms, other than plants, fungi algae, has emerged as an innovative and eco-friendly strategy for sustainable NM recovery. Biological noble metal extraction demonstrates varying levels of scalability. Biosynthesis of nanoparticles by microbes and plants shows potential, though scalability data is limited. Pilot-scale tests with acid-stable nanomagnets achieved over 80% platinum removal at 0.1 m³ scale. More advanced progress has been made with methylobacterium extorquens AM1, which consistently recovers rare earth elements at 10 L scale without harsh conditions. Engineered strains further improve efficiency through enhanced phosphate metabolism and lanthanophore production, enabling sustainable recovery from complex waste sources like e-waste. These eukaryotes can selectively bind and accumulate metal ions from complex aqueous or solid waste environments, making them highly suitable for urban mining and circular economy approaches. Research has shown that certain yeasts and unicellular fungi possess metal-binding membranes and metabolic pathways that allow for the efficient biosorption and bioaccumulation of noble metals. Some eukaryotes also support electrochemical recovery techniques, combining biological selectivity with industrial feasibility [68].

5.1. Protozoa

Protozoans such as *Tetrahymena* and *Paramecium* show high potential in NM recovery due to their negatively charged cell surfaces rich in proteins and polysaccharides [69]. These surfaces strongly interact with metal ions like gold and silver. Additionally, endocytosis allows for the internal sequestration of metals into vacuoles, often mediated by metal-binding proteins such as metallothioneins [70]. These mechanisms make protozoa particularly promising for bio-recovery from complex waste streams and wastewater.

5.2. Invertebrates

Invertebrates, including mollusks, crustaceans' earthworms, naturally bioaccumulate metals in their tissues and exoskeletons. Filter-feeders such as mussels and oysters extract metals from aquatic environments, while chitin in crustacean shells acts as an effective metal-binding substrate. Earthworms process large amounts of soil and accumulate metals within/inside their gut lining [71]. These features make invertebrates viable candidates for sustainable recovery of noble metals from contaminated soils, mining residues industrial effluents.

5.3. Animal cell lines

Animal cell lines engineered to express metal-specific proteins offer controlled systems for recovering noble metals. These cells can internalize metals through receptor-mediated endocytosis and are suitable for use in bioreactors, particularly in high-value waste streams such as those from electronic devices [72].

5.4. Symbiotic eukaryotes

Certain symbiotic systems, such as protozoa coupled with bacteria, have shown enhanced NM recovery capabilities. The eukaryotic host facilitates adsorption and transport, while the microbial partner mediates metal reduction, increasing bioavailability and overall recovery efficiency [73]. This cooperative mechanism reduces the need for chemical inputs and enhances environmental sustainability.

5.5. Aquatic invertebrates, amphibian reptiles

Marine and freshwater invertebrates, including sea cucumbers, mollusks crustaceans, as well as amphibians and reptiles, show promising metal accumulation traits [74]. These organisms absorb metals via filtration, ingestion, or cutaneous absorption, concentrating them in tissues or scales. While less studied, amphibians and reptiles offer untapped potential for NM recovery from aquatic systems, with possible industrial applications in wastewater treatment and environmental remediation. The use of diverse eukaryotic organisms for noble metal recovery represents a sustainable, cost-effective scalable alternative to traditional extraction techniques. Their natural metal-binding abilities, compatibility with biotechnological enhancements minimal environmental impact position them as vital components in next-generation green recovery systems [75]. Biohydrometallurgy provides a sustainable and cost-effective method for recovering metals from ores, electronic waste, and other secondary sources. Using prokaryotes and eukaryotes, metals such as PGMs and REEs can be extracted through biosorption, biotransformation, and precipitation. A two-stage bioprocess employs acidophiles for base metal recovery, followed by cyanide-producing microbes for precious and rare metals. Despite challenges in treating complex waste streams, microbial technologies show strong potential for environmentally friendly and economically viable metal recovery, encouraging further research and development. Further research into optimization, bioreactor integration genetic enhancement will broaden their application and improve recovery efficiency.

6. Integration of Artificial Intelligence in Noble Metal Recovery: Opportunities, Advances Challenges

The demand for sustainable and resource-efficient recovery of noble metals has sparked interest in integrating advanced technologies like artificial intelligence and machine learning [76] (Figure 5). Traditional metal extraction processes, especially bioleaching, a microbial-assisted technique used to extract metals from ores and industrial waste, face challenges due to their reliance on manual optimization and empirical adjustments. These traditional approaches struggle to capture the dynamics and complex nature of microbial interactions that affect metal recovery [77]. To address these challenges, machine learning frameworks have been proposed as a modern, data-driven solution capable of simulating these biological intricacies. Recent research highlights AI's growing role across diverse domains with notable

performance gains. In agriculture, AI models optimize crop yield and resource management with 92.6% accuracy, MAE of 0.440, and RMSE of 0.200. For air quality monitoring, Random Forest models achieved superior results with an R^2 of 98.08% and MSE of 1.97, outperforming neural networks and boosting algorithms. In wastewater treatment, ensemble methods like XG Boost, Gradient Boosting, and Light GBM combined with feature selection enhanced prediction accuracy. Gradient Boosting best predicted Total Suspended Solids, while XG Boost excelled in Biochemical Oxygen Demand forecasting, consistently surpassing Decision Tree baselines across applications. This review aims to explore the integration of AI in noble metal recovery and wastewater treatment and highlights its potential to reshape sustainability in industrial biotechnology and environmental management.

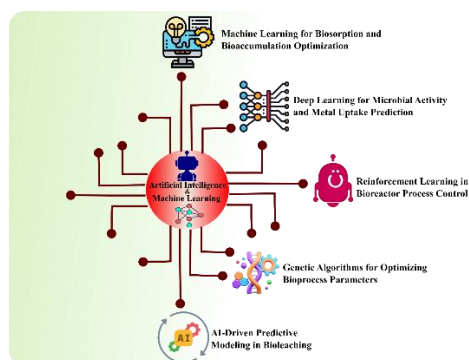


Figure 5: Artificial Intelligence (AI) and Machine Learning (ML) strategies applied in the biorecovery of noble metals.

6.1. Aquatic invertebrates, amphibian reptiles

AI provides a compelling solution by modeling these nonlinear systems and predicting optimal process conditions [78]. With AI, complex microbial interactions, metabolic fluxes environmental dependencies can be simulated and adjusted dynamically, thereby enhancing metal extraction efficiency and reducing environmental impact (Figure 5). Furthermore, Microbial Cell Factories (MCFs), engineered microbial systems used for value-added bioproduction, are being increasingly optimized using AI tools. Conventional synthetic biology workflows, which include gene editing, high-throughput screening pathway design, have traditionally required significant manual labor and time. The introduction of AI transforms this pipeline into a more streamlined Design-Build-Test-Learn-Predict (DBTLP) framework [79]. AI algorithms can analyze vast datasets, recognize patterns make highly probable predictions about biological outcomes, expediting the development of robust microbial systems for metal recovery. Recent research highlights the potential of integrating artificial intelligence with bioleaching to improve metal recovery from electronic waste. Machine learning models such as random forest regression predict recovery rates with 77% accuracy, reducing experimental costs, while gradient boosting using RGB sensor data achieved 84% accuracy for copper recovery from circuit boards. Support vector machines and neural networks further optimize bio-Fenton processes for extraction. By enhancing efficiency and cost-effectiveness, AI-driven bioleaching offers a sustainable approach for recovering metals like copper, uranium, and gold, supporting circular economy initiatives.

6.2. AI-aided microbial engineering and functional protein design

One of the transformative applications of AI in this domain is its role in genome mining and protein engineering. AI models can efficiently annotate genomic data, predict enzyme

functions identify genes associated with metal transport or binding. For example, by analyzing the active sites and binding pockets of enzymes, AI can facilitate the discovery of biocatalysts capable of binding with specific noble metals [80]. Artificial intelligence also supports de novo protein design, allowing the development of novel enzymes tailored for specific reactions. Through structural modeling and predictive learning, AI creates synthetic proteins with enhanced metal-binding or degradation capabilities. Furthermore, AI-enabled pathway prediction, especially retro biosynthesis models, assist in constructing efficient biosynthetic routes, which are essential for bio-based noble metal recovery. A notable example is the development of Mut Compute, a machine learning-based protein engineering tool using 3D convolutional neural networks [81]. This tool predicted functional mutations in PETase enzymes, leading to variants with high plastic degradation potential. Similar models could be applied to develop microbial enzymes capable of leaching and binding noble metals efficiently [82].

6.3. Large Language Models (LLMs) in bioengineering

The rise of Large Language Models (LLMs) such as GPT-4, BERT other transformer-based architectures have opened new frontiers in AI-biology integration. Trained on diverse biological datasets, including genome sequences, proteomic profiles metabolic pathways, these models are being used for sequence annotation, structure prediction functional analysis. LLMs can interpret biological language, infer regulatory elements even propose metabolic routes for targeted biosynthesis. Applications of LLMs in microbial engineering for noble metal recovery may soon include real-time decision-making in strain design, prediction of toxic metal interactions simulation of environmental conditions affecting bioleaching processes [83]. These AI systems are also expected to support personalized engineering of microbial consortia tailored to specific metal wastes.

6.4. Role of AI in industrial wastewater treatment

Wastewater, especially from industrial sources, is a major contributor to environmental degradation. A large percentage of this wastewater, often containing toxic heavy metals and persistent organic pollutants, is discharged untreated into aquatic ecosystems, affecting both biodiversity and human health [84]. Traditional treatment technologies like coagulation, membrane filtration adsorption have limitations in adaptability and efficiency. AI models offer a promising avenue to overcome these limitations. Machine learning techniques such as linear regression, decision trees neural networks are increasingly being used to simulate complex parametric relationships in wastewater systems [85,86]. These models facilitate accurate predictions of pollutant behavior, treatment efficiency operational performance. Additionally, real-time optimization through AI enables dynamic response to changes in inflow quality or treatment conditions, improving consistency in treated water quality (Figure 6).

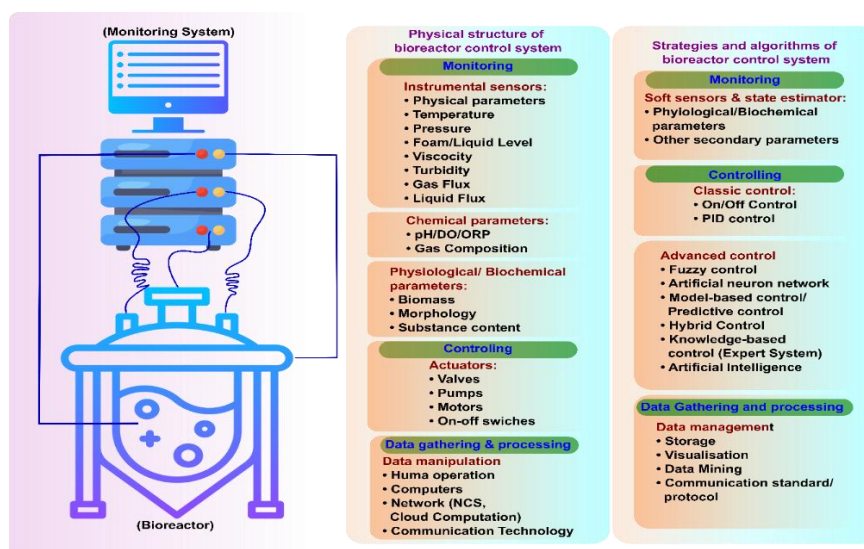


Figure 6: Integrated smart bioreactor system representing monitoring, controlling, and data-processing strategies for optimized and adaptive operation.

6.5. Smart wastewater treatment systems

AI-driven Waste Water Treatment Plants (WWTPs) are capable of autonomous operation, from pollutant detection to process control. Advanced systems use Recurrent Neural Networks (RNNs), Convolutional Neural Networks (CNNs) fuzzy logic algorithms to optimize various stages of treatment, such as chemical dosing, aeration sludge recycling [87]. These AI models are trained on large datasets, allowing them to predict and mitigate operational anomalies or equipment failure before they occur. Hybrid AI approaches, such as Artificial Neural Network (ANN) combined with Genetic Algorithms (GA) or Support Vector Regression (SVR) with Particle Swarm Optimization (PSO) offer enhanced accuracy and resilience. Such methods are invaluable in handling the nonlinear, multivariate time-varying nature of wastewater data. Moreover, AI-enhanced adsorption modeling tools help researchers and policymakers evaluate the environmental impact of adsorption-based treatments, providing scientific guidance for technology deployment and compliance with environmental regulations [88].

7. Challenges in AI Deployment for Environmental Applications

Despite the success of AI in microbial production and wastewater treatment, several challenges remain. One major hurdle is the quality and availability of training data. Most machine learning models require large, diverse well-annotated datasets for effective learning. Biological and environmental systems often present noisy, incomplete, or heterogeneous data, which can reduce the reliability of predictions [89]. Another limitation is the lack of interpretability in complex models such as deep neural networks. While these models offer high accuracy, their decision-making processes are often considered "black boxes," which can limit their acceptance in regulated industries. Efforts are underway to develop explainable AI methods to enhance transparency and trust in AI predictions, especially for high-stakes applications like environmental monitoring and waste remediation [90,91].

A critical research gap lies in the absence of a unified AI platform for integrated monitoring, modeling optimization of both biological recovery and wastewater treatment systems. Most current studies focus on isolated applications such as protein design or pollutant tracking,

with limited emphasis on system-wide optimization. Additionally, few studies have explored the simultaneous recovery of noble metals from wastewater containing mixed pollutants, a scenario commonly encountered in e-waste recycling and metallurgical industries [92]. This review addresses these gaps by proposing a multidisciplinary AI framework that merges microbial engineering with wastewater treatment. By leveraging AI for both metal recovery and effluent purification, future systems can achieve circular economy goals, recovering valuable resources while protecting environmental health.

8. Progress in AI-Based Environmental Research

Over the past decade, scientific publications on AI in wastewater treatment and environmental monitoring have increased substantially. Between 2016 and 2023, over 2965 articles were indexed in the Scopus and Elsevier databases on this topic, with a subset of 100 studies selected for in-depth evaluation. This growing volume of research reflects the recognition of AI's potential in improving sustainability, efficiency cost-effectiveness of treatment systems [93]. Most of these studies utilized keywords such as “artificial neural network”, “genetic algorithm”, “support vector machine” “wastewater treatment” [94]. However, comprehensive reviews evaluating the comparative performance of these models across different wastewater scenarios remain limited. Future research should prioritize standardized evaluation frameworks to benchmark AI tools and facilitate their industrial adoption.

9. Societal and Sustainable Development Implications

AI-driven recovery and treatment systems align closely with several UN Sustainable Development Goals (SDGs)—notably Goal 6 (Clean Water and Sanitation), Goal 11 (Sustainable Cities and Communities) Goal 12 (Responsible Consumption and Production) [95]. By minimizing chemical use, enhancing recycling efficiency reducing wastewater discharge, AI-based solutions support environmentally friendly and socially responsible technologies. Furthermore, these approaches contribute to Industry 4.0 by integrating intelligent automation, real-time analytics decision support into traditionally manual sectors. The confluence of AI with environmental engineering exemplifies the future of sustainable industrial ecosystems, where digital tools amplify the effectiveness of green technologies [96].

The integration of artificial intelligence into noble metal recovery and wastewater treatment presents a revolutionary step toward sustainable resource management. AI enables predictive modeling, real-time optimization automated control in complex biological and chemical systems [97]. From engineering protein-based biosorbents to optimizing industrial wastewater treatment, AI transforms manual, resource-intensive processes into smart, data-driven solutions. Despite existing challenges, such as data limitations and model transparency, the future of AI in environmental biotechnology is promising. Continued advancements in AI algorithms, coupled with growing biological datasets and interdisciplinary collaboration, are expected to unlock unprecedented capabilities in metal recovery and pollution remediation [98]. As this review emphasizes, the convergence of AI with environmental science holds immense potential to reshape how we reclaim resources and safeguard ecosystems in the era of digital sustainability.

10. Conclusion

The recovery of Noble Metals (NMs) such as gold, silver, platinum, palladium, rhodium ruthenium has become increasingly critical due to their essential roles in high-tech applications and limited natural reserves. The exponential rise in electronic waste generation, coupled with the declining efficiency and environmental cost of traditional mining, necessitates sustainable, innovative solutions. This review synthesizes interdisciplinary advancements in biological and Artificial Intelligence (AI)-driven strategies for noble metal recovery and wastewater treatment, presenting a forward-looking vision rooted in the principles of circular economy and environmental stewardship. Biological recovery systems, including microalgae, fungi, plants non-conventional eukaryotes offer eco-friendly alternatives to toxic chemical leaching and energy-intensive metallurgical processes. Microalgae have demonstrated significant promise due to their rapid growth, adaptability ability to biosorb and bioaccumulate metal ions through functional groups in their cell walls. Similarly, fungi offer robust systems for biosorption, bioaccumulation biomineralization, facilitating efficient recovery of NMs from leachates and industrial waste. Plant-based techniques such as phytomining and phytoremediation present low-cost solutions for large-scale recovery, particularly in contaminated soils. Additionally, lesser-explored eukaryotic organisms including protozoa, invertebrates symbiotic consortia, open new avenues for selective metal binding and intracellular sequestration. Despite their promise, these biotechnologies are often hampered by slow kinetics, inconsistent outcomes limited scalability.

This is where AI integration plays a transformative role. AI, particularly machine learning and deep learning models, enhances the efficiency, predictability scalability of biological recovery systems. From protein design and genome annotation to predictive modeling of bioleaching kinetics, AI can decode complex biological networks and optimize system variables such as pH, temperature, biomass concentration metal load. AI-powered Microbial Cell Factories (MCFs) and synthetic biology platforms are evolving with Design-Build-Test-Learn-Predict (DBTLP) frameworks, accelerating the development of custom microbes and enzymes tailored for NM recovery. Large Language Models (LLMs) like GPT-4 and Alpha Fold have further enriched this landscape by offering protein structure prediction, functional annotation metabolic pathway engineering. In addition to recovery, the integration of AI into wastewater treatment aligns seamlessly with sustainability goals. Smart wastewater treatment plants, driven by AI algorithms like neural networks and fuzzy logic, can adaptively manage chemical dosing, sludge processing pollutant monitoring in real-time. These systems not only increase operational efficiency but also reduce the carbon footprint, chemical use secondary pollution risks. Hybrid AI models combining support vector machines, genetic algorithms particle swarm optimization offer enhanced performance in handling nonlinear environmental data. Moreover, AI helps address the dynamic and multi-variable nature of real-world wastewater scenarios, paving the way for autonomous, intelligent resilient environmental infrastructure.

Despite these technological advancements, challenges persist, particularly around the availability of high-quality datasets, interpretability of AI model's standardization of experimental protocols. There is also a pressing need to bridge the gap between laboratory-scale innovations and industrial-scale implementation. This review highlights these research gaps while proposing AI-enhanced, biologically inspired recovery platforms that are data-driven, modular environmentally compatible. Thus, the convergence of biotechnology and artificial intelligence offers a ground-breaking opportunity to transform noble metal recovery and wastewater treatment into smart, sustainable circular processes. The future of resource management lies in such integrative frameworks that blend the precision of AI with the adaptability of biology, enabling us to meet rising industrial demands while protecting

planetary health. This review not only consolidates current progress but also charts a roadmap for future research, industry innovation policy development aimed at global sustainability and green technological evolution.

CRediT Authorship Contribution Statement

Sanjib Sahoo: Writing - review & editing, Writing - original draft, Nitish Kumar Bhol: Writing - review & editing, Writing - original draft. Namrata Kanungo: Writing - original draft, Writing - review & editing, Conceptualization. Sanatan Majhi: Conceptualization. Jagneshwar Dandapat & Jyotsnarani Pradhan: Writing - review & editing, Writing- original draft, Conceptualization.

Acknowledgement

We thank all the authors of the original work and the reviewers for their time and kindness in reviewing this paper. We also thank DBT-Govt. of India, New Delhi; the Department of Biotechnology (supported by DBT-Govt. of India), Utkal University; the Centre of Excellence in Integrated Omics and Computational Biology, Utkal University; and the World Bank-Odisha Higher Education Program for Excellence and Equity, Govt. of Odisha, India.

References

1. Cai S, Yang R. Noble metal-based nanozymes. In: Yan X(eds). Nanozymology. Springer Singapore, Singapore; 2020;pp:331-65.
2. Guerra MF. Physicochemical approaches to gold and silver work, an overview: searching for technologies, tracing routes, attempting to preserve. Phys Sci Rev. 2019;4:23-8.
3. Chidunchi I, Kulikov M, Safarov R, et al. Extraction of platinum group metals from catalytic converters. Heliyon. 2024;10:1-26.
4. Gao F, Goodman DW. Model catalysts: simulating the complexities of heterogeneous catalysts. Annu Rev Phys Chem. 2012;63:265-86.
5. Raabe D. The materials science behind sustainable metals and alloys. Chem Rev. 2023;123:2436-08.
6. Zheng S, Yang S, Chen J, et al. New progresses in efficient, selective environmentally friendly recovery of valuable metal from e-waste and industrial catalysts. Adv Sustain Syst. 2024;8: 2300512.
7. Rajpoot S. The Growing environmental risks of e-waste: a review. In: Güngör A, et al., (eds). Advances in Environmental Engineering and Green Technologies. IGI Global, Noida, India. 2025;pp:309-36.

8. Sethurajan M, Van Hullebusch ED, Fontana D, et al. Recent advances on hydrometallurgical recovery of critical and precious elements from end of life electronic wastes-a review. *Crit Rev Environ Sci Technol*. 2019;49:212–75.
9. Li Z, Diaz LA, Yang Z, et al. Comparative life cycle analysis for value recovery of precious metals and rare earth elements from electronic waste. *Res Con Rec*. 2019;149:20-30.
10. Osibanjo O, Nnorom IC. The challenge of electronic waste (e-waste) management in developing countries. *Waste Manag Res J Sustain Circ Econ*. 2007;25:489–501.
11. Amuzu D. Environmental injustice of informal e-waste recycling in agbogbloshie-accra: urban political ecology perspective. *Local Environ*. 2018;23:603–18.
12. Iles A. Mapping environmental justice in technology flows: computer waste impacts in Asia. *Glob Environ Polit*. 2004;4:76–107.
13. Kikis C, Thalassinou G, Antoniadis V. Soil phytomining: recent developments—a review. *Soil Syst*. 2024;8:8.
14. Akinbile BJ, Makhubela BCE, Ambushe AA. Phytomining of valuable metals: status and prospective-a review. *Int J Environ Anal Chem*. 2023;103:3913–33.
15. Wu X, Cobbina SJ, Mao G, et al. A review of toxicity and mechanisms of individual and mixtures of heavy metals in the environment. *Env Sci Pollut Res*. 2016;23:8244–59.
16. Neubauer P, Anane E, Junne S, et al. Potential of integrating model-based design of experiments approaches and process analytical technologies for bioprocess scale-down. In: Herwig C, et al., (eds). *Digital Twins: Applications to the Design and Optimization of Bioprocesses*. Springer International Publishing, London, UK; 2021;pp.1–28.
17. Scheibe TD, Mahadevan R, Fang Y, et al. Coupling a genome-scale metabolic model with a reactive transport model to describe in situ uranium bioremediation. *Microb Biotechnol*. 2009;2:274–86.
18. Aryanfar Y, Castellanos HG, Hammoodi KA, et al. Cleaner and sustainable circular economy approaches for bio-based product recovery from industrial effluents in a biorefinery. *Environ Prog Sustain Energy*. 2024;43:e14483.
19. Bin ADA, Sun X, Gupta VK, et al. Advances, synergy perspectives of machine learning and biobased polymers for energy, fuels biochemicals for a sustainable future. *Energy Fuels*. 2024;38:1593–617.

20. Alum EU. AI-driven biomarker discovery: enhancing precision in cancer diagnosis and prognosis. *Discov Oncol.* 2025;16:313.
21. Rane NL, Paramesha M, Choudhary SP, et al. Machine learning and deep learning for big data analytics: a review of methods and applications. *Partners Univ Int Innov J.* 2024;2:172-97.
22. Gong X, Zhang J, Gan Q, et al. Advancing microbial production through artificial intelligence-aided biology. *Biotechnol Adv.* 2024;74:108399.
23. Zhang Q, Ding K, Lv T, et al. Scientific large language models: a survey on biological & chemical domains. *ACM Comput Surv.* 2025;57:138-61.
24. Lee J, Yoon W, Kim S, et al. BioBERT: a pre-trained biomedical language representation model for biomedical text mining. *Bioinform.* 2020;36:1234-40.
25. Sieber A, Spiess S, Rassy WY, et al. Fundamentals of bio-based technologies for selective metal recovery from bio-leachates and liquid waste streams. *Front Bioeng Biotechnol.* 2025;12:1528992.
26. Fan M, Hu J, Cao R, et al. A review on experimental design for pollutants removal in water treatment with the aid of artificial intelligence. *Chemo.* 2018;200:330-43.
27. Gheibi M, Masoomi SR, Magala MU, et al. The application of artificial intelligence in adsorption process of heavy metals: a systematic review. *Environ Ind Lett.* 2024;2:57-78.
28. Khosravi A, Zarepour A, Iravani S, et al. Sustainable synthesis: natural processes shaping the nanocircular economy. *Environ Sci Nano.* 2024;11:688-707.
29. Wu Q, Zhou H, Tam NFY, et al. Contamination, toxicity and speciation of heavy metals in an industrialized urban river: implications for the dispersal of heavy metals. *Mar Pollut Bull.* 2016;104:153-61.
30. Hamed I. the evolution and versatility of microalgal biotechnology: a review. *Compr Rev Food Sci Food Saf.* 2016;15:1104-23.
31. Eldridge DS, Crawford RJ, Harding IH. The role of metal ion-ligand interactions during divalent metal ion adsorption. *J Colloid Interface Sci.* 2015;454:20-6.
32. Yang G, Wilkinson KJ. Biouptake of a rare earth metal by *chlamydomonas reinhardtii* – bioavailability of small organic complexes and role of hardness ions. *Environ Pollut.* 2018;243: 263-9.

33. Balzano S, Sardo A, Blasio M, et al. Microalgal metallothioneins and phytochelatins and their potential use in bioremediation. *Front Microbiol.* 2020;11:517.
34. Li X, Ren Z, Crabbe MJC, et al. Genetic modifications of metallothionein enhance the tolerance and bioaccumulation of heavy metals in *Escherichia coli*. *Ecotoxicol Environ Saf.* 2021;222:112512.
35. Mahlangu D, Mphahlele K, De Paola F, et al. Microalgae-mediated biosorption for effective heavy metals removal from wastewater: a review. *Water.* 2024;16:718.
36. Parades-Aguilar J, Agustin-Salazar S, Cerruti P, et al. Agro-industrial wastes and their application perspectives in metal decontamination using biocomposites and bacterial biomass: a review. *World J Microbiol Biotechnol.* 2025;41:16.
37. Monteiro CM, Castro PML, Malcata FX. Metal uptake by microalgae: underlying mechanisms and practical applications. *Biotechnol Prog.* 2012;28:299–311.
38. Danouche M, Ghachtouli NE, Arroussi HE. Phycoremediation mechanisms of heavy metals using living green microalgae: physicochemical and molecular approaches for enhancing selectivity and removal capacity. *Heliyon.* 2021;7:e07609.
39. Bilal M, Rasheed T, Sosa-Hernández JE, et al. Biosorption: an interplay between marine algae and potentially toxic elements – a review. *Mar Drugs.* 2018;16:65.
40. Ugya AY, Imam TS, Li A, et al. Antioxidant response mechanism of freshwater microalgae species to reactive oxygen species production: a mini review. *Chem Ecol.* 2020;36:174–93.
41. Parmar KS, Patel KM. Biosorption and bioremediation of heavy metal ions from wastewater using algae: a comprehensive review. *World J Microbiol Biotechnol.* 2025;41:262.
42. Daifullah AAM, Girgis BS, Gad HMH. A study of the factors affecting the removal of humic acid by activated carbon prepared from biomass material. *Colloids Surf Physicochem Eng Asp.* 2004;235:1–10.
43. Chojnacka K. Biosorption and bioaccumulation the prospects for practical applications. *Environ Int.* 2010;36:299–307.
44. Naveed S, Li C, Lu X, et al. Microalgal extracellular polymeric substances and their interactions with metal(loid)s: a review. *Crit Rev Environ Sci Technol.* 2019;49:1769–802.

45. Monteiro CM, Castro PML, Malcata FX. Metal uptake by microalgae: underlying mechanisms and practical applications. *Biotechnol Prog.* 2012;28:299–311.
46. Ranjbar S, Malcata FX. Is genetic engineering a route to enhance microalgae-mediated bioremediation of heavy metal-containing effluents? *Mol.* 2022;27:1473.
47. Grama SB, Liu Z, Li J. Emerging trends in genetic engineering of microalgae for commercial applications. *Mar Drugs.* 2022;20:285.
48. Kong F, Yamaoka Y, Ohama T, et al. Molecular genetic tools and emerging synthetic biology strategies to increase cellular oil content in *chlamydomonas reinhardtii*. *Plant Cell Physiol.* 2019;60:1184–96.
49. Melero-Cobo X, Gallemí M, Carnicer M, et al. MOCLORO: an extension of the *chlamydomonas reinhardtii* modular cloning toolkit for microalgal chloroplast engineering. *Physiol Plant.* 2025;177:e70088.
50. Dou Z, Sun Y, Jiang X, et al. Data-driven strategies for the computational design of enzyme thermal stability: trends, perspectives prospects. *Acta Biochim Biophys Sin.* 2023;55:343–55.
51. Ahlawat YK, Srivastava V, Samani M, et al. Computational strategies for maximizing biomass and metabolite yields for bioproduction. In: Kumar L, Bharadvaja N, Singh R, et al(eds). *Medicinal and Aromatic Plants*. Springer Nature, Switzerland. 2024;pp.143–61.
52. Browne DR. Systems analysis of metabolism and physiology of the oil-producing green alga *botryococcus braunii* race b (showa).
<https://www.proquest.com/openview/7f5315d0938ad84194bacb8d13d1adfc/1?pq-origsite=gscholar&cbl=18750&diss=y>
53. Xiao X, Li W, Jin M, et al. Responses and tolerance mechanisms of microalgae to heavy metal stress: a review. *Mar Environ Res.* 2023;183:105805.
54. Chatenet M, Pollet BG, Dekel DR, et al. Water electrolysis: from textbook knowledge to the latest scientific strategies and industrial developments. *Chem Soc Rev.* 2022;51:4583–762.
55. Bajpai A, Meshram A, Biswas K. *Beneficiation and Management of Technological Waste: Opportunities and Challenges*. (1stedn), CRC Press, London, UK. 2025.
56. Zhang X, Shi H, Tan N, et al. Advances in bioleaching of waste lithium batteries under metal ion stress. *Bioresour Bioproc.* 2023;10:19.

57. Lopez-Fernandez M, Jroundi F, Ruiz-Fresneda MA, et al. Microbial interaction with and tolerance of radionuclides: underlying mechanisms and biotechnological applications. *Microb Biotechnol*. 2021;14:810–28.
58. Sağ Y. Biosorption of heavy metals by fungal biomass and modeling of fungal biosorption: a review. *Sep Purif Methods*. 2001;30:1–48.
59. Shakya M, Sharma P, Meryem SS, et al. Heavy metal removal from industrial wastewater using fungi: uptake mechanism and biochemical aspects. *J Environ Eng*. 2016;142:C6015001.
60. Vandebossche M, Jimenez M, Casetta M, et al. Remediation of heavy metals by biomolecules: a review. *Crit Rev Environ Sci Technol*. 2015;45:1644–704.
61. Gadd GM. Geomycology: biogeochemical transformations of rocks, minerals, metals and radionuclides by fungi, bioweathering and bioremediation. *Mycol Res*. 2007;111:3–49.
62. Zheng S, Yang S, Chen J, et al. New progresses in efficient, selective environmentally friendly recovery of valuable metal from e-waste and industrial catalysts. *Adv Sustain Syst*. 2024;8:2300512.
63. Pócsi I. Toxic metal/metalloid tolerance in fungi – a biotechnology-oriented approach. In: Banfalvi G, (eds). *Cellular Effects of Heavy Metals*. Dordrecht: Springer, Netherlands. 2011;pp:31–58.
64. Kumar V, Dwivedi SK. Mycoremediation of heavy metals: processes, mechanisms affecting factors. *Environ Sci Pollut Res*. 2021;28:10375–412.
65. Mehta J, Choudhury M, Chakravorty A, et al. Recycle strategies to deal with metal nanomaterials by using aquatic plants through phytoremediation technique. In: Makhoulf ASH, Ali GAM(eds). *Waste Recycling Technologies for Nanomaterials Manufacturing*. Springer International Publishing, Netherland. 2021;pp.589–616.
66. Nwadinigwe AO, Ugwu EC. Overview of Nano-phytoremediation Applications. In: Ansari AA, et al., (eds). *Phytoremediation*, Springer International Publishing, Netherland. 2018;pp.377–82.
67. Nakbanpote W, Jitto P, Taya U, et al. *Chrysopogon zizanioides* (vetiver grass) for abandoned mine restoration and phytoremediation: Cogeneration of economical products. In: Prasad MNV (eds). *Bioremediation and Bioeconomy*, (2nd edn). Elsevier, UK. 2024;pp.385–417.

68. Newsome L, Falagán C. The Microbiology of Metal Mine Waste: Bioremediation Applications and Implications for Planetary Health. *GeoHealth*. 2021;5:e2020GH000380.
69. Zhang L, Yin W, Shen S, et al. ZnO nanoparticles interfere with top-down effect of the protozoan paramecium on removing microcystis. *Environ Pollut*. 2022;310:119900.
70. Jakob G, Stephens E, Feller R, et al. Triggered exocytosis of the protozoan *Tetrahymena* as a source of bioflocculation and a controllable dewatering method for efficient harvest of microalgal cultures. *Algal Res*. 2016;13:148–58.
71. Newman MC, McIntosh AW. *Metal Ecotoxicology: Concepts and Applications*. (1stedn), CRC Press, London, New York. 2020.
72. Ranjbar S, Malcata FX. Is genetic engineering a route to enhance microalgae-mediated bioremediation of heavy metal-containing effluents? *Mol*. 2022;27:1473.
73. Zhang Y, Hong Y, Wang X. Recent advances on using functional materials to increase the pollutant removal capabilities of microalgae and bacteria: especially for their symbiotic systems. *Curr Pollut Rep*. 2023;9:272–91.
74. Chiarelli R, Roccheri MC. Marine invertebrates as bioindicators of heavy metal pollution. *Open J Met*. 2014;4:93–106.
75. Bahrulolum H, Ahmadian G. *Bacillus subtilis* surface display technology: applications in bioprocessing and sustainable manufacturing. *Biotechnol Biofuels Bioprod*. 2025;18:34.
76. Lin K, Wei S. Advancing the industrial circular economy: the integrative role of machine learning in resource optimization. *J Green Econ Low-Carbon Dev*. 2023;2:122–36.
77. Verma S, Bhatt P, Verma A, et al. Microbial technologies for heavy metal remediation: effect of process conditions and current practices. *Clean Technol Environ Policy*. 2023;25:1485–507.
78. Kuhar N, Kumria P, Rani S. Overview of applications of artificial intelligence in diverse fields. application of artificial intelligence in wastewater treatment. Springer, netherland. 2024;pp.41–83.
79. Kwon KK, Lee J, Kim H, et al. Advancing high-throughput screening systems for synthetic biology and biofoundry. *Curr Opin Syst Biol*. 2024;37:100487.

80. Khan AZ, Bilal M, Rasheed T, et al. Advancements in biocatalysis: from computational to metabolic engineering. *Chin J Catal.* 2018;39:1861–68.
81. Diaz DJ. Accelerating the biotechnology revolution with machine learning-guided protein engineering.
<https://repositories.lib.utexas.edu/items/a0010156-6b2e-4891-959f-fdaac36409cd>
82. Jayasekara SK, Joni HD, Jayantha B, et al. Trends in silico guided engineering of efficient polyethylene terephthalate hydrolyzing enzymes to enable bio-recycling and upcycling of PET. *Comput Struct Biotechnol J.* 2023;21:3513–21.
83. Zhang J, Yang Y, Si J, et al. Artificial intelligence in the discovery and modification of biological elements in medicinal plants. *Med Plant Biol.* 2025;4:1–10.
84. Manasa RL, Mehta A. Wastewater: sources of pollutants and its remediation. *Env Biotech.* 2020;2:197-219.
85. Alprol AE, Mansour AT, Ibrahim MEED, et al. Artificial intelligence technologies revolutionizing wastewater treatment: current trends and future prospective. *Wat.* 2024;16:314.
86. Aghdam E, Mohandes SR, Manu P, et al. Predicting quality parameters of wastewater treatment plants using artificial intelligence techniques. *J Clean Prod.* 2023;405:137019.
87. Lai J. Research on prediction algorithm of effluent quality and development of integrated control system for waste-water treatment. *Sci Rep.* 2025;15:19257.
88. Satyam S, Patra S. Innovations and challenges in adsorption-based wastewater remediation: a comprehensive review. *Heliyon.* 2024;10:e29573.
89. Camacho DM, Collins KM, Powers RK, et al. Next-generation machine learning for biological networks. *Cell.* 2018;173:1581–92.
90. Akhtar MAK, Kumar M, Nayyar A. Socially Responsible Applications of Explainable AI, Towards Ethical and Socially Responsible Explainable AI. Springer Nature, Switzerland. 2024.
91. Tettey DJ, Chrisben D, Victoria MC, et al. Responsible AI deployment in sustainable project execution: ensuring transparency, carbon efficiency and regulatory alignment. *Int J Sci Res Arch.* 2025;14:1686–705.
92. Rai V, Liu D, Xia D, et al. Electrochemical approaches for the recovery of metals from electronic waste: a critical review. *Recycl.* 2021;6:53.

93. Rossi GJ, Rojas-Perilla N, Krois J, et al. Cost-effectiveness of artificial intelligence as a decision-support system applied to the detection and grading of melanoma, dental caries diabetic retinopathy. *J Netw Open*. 2022;5:e220269.
94. Fels EA, Mandi L, Kammoun A, et al. Artificial intelligence and wastewater treatment: a global scientific perspective through text mining. *Water*. 2023;15:3487.
95. Guevara S, Julián IP. Sustainable consumption and production: a crucial goal for sustainable development reflections on the spanish sdg implementation report. *J Sustain Res*. 2019;1:e190019.
96. Coito T, Firme B, Martins MSE, et al. Intelligent sensors for real-time decision-making. *Autom*. 2021;2:62–82.
97. Bhardwaj A, Kishore S, Pandey DK. Artificial intelligence in biological sciences. *Life*. 2022;12:1430.
98. Ali M, Shabbir K, Ali S, et al. A new era of discovery: how artificial intelligence has revolutionized the biotechnology. *Nepal J Biotechnol*. 2024;12:1–11.