International Journal of Research in Engineering, Science and Management
Volume 8, Issue 5, May 2025
https://www.ijresm.com | ISSN (Online): 2581-5792

Microalgal Biosorption of Heavy Metals: A Bibliometric Review

Uddipto Islam Naireet*
BRAC University, Dhaka, Bangladesh

***Abstract*: With their non-biodegradable and highly toxic forms, continual presence of heavy metals such as cadmium, lead, mercury, and chromium, raises an ever-present environmental problem in the world. The high cost and environmental cost of the traditional forms of treatment has sparked an explosion of interest in biological alternatives. Microalgal biosorption has been gaining momentum in the recent years as an attractive and eco-friendly method for treating heavy metal. A thorough bibliographic review is performed, assessing the advancement of microalgal biosorption in controlling heavy metals over the past two decades. Using bibliometric resources, we examine the trend in the number of publications, the most cited researchers, institutions, and countries, and evaluate the interplay of different keywords and collaborative structures. The interest among scholars has since 2010 been reflected in research articles on the topic. Cadmium is a metal of choice for research in bio adsorption, as Chlorella, Scenedesmus and Spirulina are preferred candidates for such studies. Importance of cell wall functional groups, extracellular polymeric substances and environmental parameters in enhancing biosorption efficiency has been highlighted by critical mechanistic research findings. Although early laboratory results are encouraging, limitations in terms of biomass recovery, scalability, and economics restrict such applications on a large scale in practical situations. By reflecting on the advance and development of the discipline, this paper outlines major research themes at the cutting-edge, and highlights key research gaps in dire need of attention. Many of the top aims for future research efforts include the improvement of genetic engineering, the introduction of hybrid treatment systems, and lifecycle analyses all with the goal to increase contributions to environmental biotechnology from microalgae. This review is of great benefit to the researchers, environmental engineers and policy makers seeking to develop sustainable plans to counter heavy metal pollution.**

***Keywords*: Adsorption effectiveness, Biomass yield, Practicality, Financial viability assessment, Genome-enhancement techniques, Transdisciplinary treatment method.**

1. Introduction

The persistent hazard of heavy metal pollutions is one of the primary environmental issues humans are facing in the 21st century. Different from organic pollutants that are degradable, heavy metals are persistent in the environment, hence persisting in presenting a huge long-term threat to both ecological and public fortunes (Correa et al., 2017). Development and urbanization, with poor waste management have led to extensive emission of hazardous metals including cadmium, lead, chromium, mercury, and arsenic to air, water and land environments (Cheng et al., 2024). Over time, exposure to such heavy metals may cause a variety of harmful health implications ranging from neurotoxicity to the emergence of cancer to organ damage.

Existing approaches to removing heavy metals include chemical precipitation, ion exchange, membrane filtration and electrochemical procedures (Gu, 2023). Although these techniques have some degree of effectiveness, they tend to be expensive, require extensive energy inputs, and cause the formation of secondary pollutants that require attention. As a result of these shortcomings, the discipline of bioremediation, using biological agents, has received more emphasis (Zada et al., 2022). Microalgae have received attention as efficacious biosorbents, mostly because of their high metal-binding capability, rapid multiplication, and suitability in different environmental conditions. The capacity of microalgae to accumulate heavy metals by passive and active uptake, makes them useful for application in sewage treatment and environment restoring (Rinanti et al., 2017). This review provides a close bibliometric analysis of global trends of micro algal biosorption of heavy metals. This research method referred to as bibliometrics employs numerical tools in analyzing patterns and relations within scientific papers. It provides a uniquely informative insight; indicates leading research teams; shows the most recent research fields of interest (Wilan et al., 2019). With the help of bibliometric tools and a systematic literature review, we aim to gauge the progress of the field, identify current focal areas, and reveal critical unsolvable issues and subsequent moves.

It is distinguished by its multi-layered approach to methodology. Bibliometric methods and network analyses, together with thematic clustering, enable us to provide a longer view of the field than individual laboratory experiments or close biosorption mechanisms (da Rosa et al., 2018). We want to provide both researchers and practitioners with useful insights which will help make more considered choices for sustainable environmental management.

A. Heavy Metal Pollution and Biosorption Fundamentals

1) The nature and origin of heavy metal contamination

The term ‘heavy metals’ refer to elements that have atomic weight over 20 and density more than 5 g/cm ^{3}. Some metals, such as zinc (Zn), copper (Cu), and iron (Fe), are essential for

*Corresponding author: uddiptonaireet@gmail.com

necessary biological activity at microdoses, while cadmium (Cd), lead (Pb), mercury (Hg), and arsenic (As) have no proven value and are harmful to the organism even in low doses(Anastopoulos & Kyzas, 2015). Heavy metals are persistent, and they are unable to be digested by biological processes, so they are contained in the environment for decades available to pass through the ecosystems of air, water, soil and organisms.

Anthropogenic sources of heavy metals are well-known to be:

- *Mining and Metallurgical Activities:* In the metal ore extraction and processing, massive amounts of waste containing heavy metals are spilt into near water supply.
- *Industrial Effluents:* Chromium and Nickel and Cadmium are commonly used in industries that produce wastewater such as the industries for electroplating, battery making, textile dyeing and tanning industries (Kavisri et al., 2023).
- *Agricultural Practices:* International use of phosphate fertilizers and pesticides causes high heavy metal levels in the soil.
- *Urban Runoff and E-Waste:* Runoff from landfills and improperly disposed electronic waste are becoming growth areas of heavy metal contamination.

By getting concentrated in the food chains and increasing these levels, the heavy metals can give harmful effects on human and wildlife health; these ranging from possible damage to the nervous system, endocrine interference and the risks of cancer.

B. The Traditional Remediation Strategies and their Limitations

A lot of approaches integrating physical and chemical strategies to heavy metal contaminants have been invented. These include:

- *Chemical precipitation:* It is directed at conversion of metal ions present in solution into precipitated solids.
- *Ion exchange:* Deploys resin materials for swapping the metal ions in wastewater.
- *Adsorption:* Deploys activated carbon among other materials to bind heavy metals on surfaces.
- *Membrane filtration:* Reverse osmosis and nanofiltration, both utilitarian, are used to remove metals from aqueous solutions.

These are very effective under ideal conditions but usually raise interracial concerns like:

- A large amount of energy and chemicals is required for application.
- Incomplete removal of trace-level contaminants.
- Generation of secondary waste products.
- problems, which appear in an attempt to separate and remove distinct metal ions from complex compositions.
- High operational and maintenance costs

C. Concept of Biosorption

Biosorption includes non-active metal ions sorption onto the surface and inner portions of bio-matter. Bio sorption is carried out without the need to resort to cellular metabolism and it is mainly driven by physio-chemical interactions rather than microscopic properties:

- Ion exchange
- Complexation
- Binding of metal ions that are aided by van der Waals forces
- Micro-precipitation

Biomass used in biosorption may be either alive and piling up metals biologically (bioaccumulation) or dead where metals are passively absorbed passive uptake (Thongpitak et al., 2019). Several factors influence biosorption performance, these factors include type of biosorbent, metal chemistry and environmental parameters such as pH and temperature and presence of competing ions.

D. Microalgae as Biosorbents

Microalgae are single cellular photosynthetic organisms used to live both in fresh water and the marine environment. They are gaining interest as biosorbents for several reasons:

- Surface to volume ratio of the object is very large and this makes it possible to have numerous locations for metal attachment (Lee et al., 2016).
- The availability of a huge number of functional groups such as hydroxyl, carboxyl, sulfate, amine on their surface.
- A potential to grow fast and require minimal nutrients.
- Possibilities of using the gained biomass for biofuel production, or other value-added procedures, after biosorption.

A number of high potential decontaminants such as Chlorella vulgaris, Scenedesmus obliquus, Spirulina platensis, and Anabaena spp among others have been extensively studied for uptake of metals like Pb^{2+}, Cd^{2+}, Ni^{2+}, Cu^{2+} (Pathak et al., 2018). Moreover, microalgae show tremendous adaptability in its surroundings, which allows its cultivation in nonarable land using wastewater nutrients, thereby enhancing rally ecological values of biosorption.

E. Relevance of a Bibliometric Approach

Despite the high volume of laboratory-scale research and increasing attention on the practical applications, the absence of unified understanding of research trends, priority areas of interest, and collaboration networks could impede developments in this sphere (Esmaili et al., 2023). A bibliometric approach adds a systematic and evidence-based approach for:

- Trace back the journey of research progress in the field.
- Spotlight most renowned researchers, editorial venues, and institutions involved in promoting developments.
- Discover the emerging topics and relatively unstudied subjects in the area.

- Allow participants to make educated decisions regarding future research goals.

2. Role of Microalgae in Biosorption

A. Type Diversity of Microalgae and Their Appropriateness for Biosorption

The taxonomically diverse collection of photoautotrophs that comprise eukaryotes (like green algae) and prokaryotes (such as cyanobacteria) is at the foundation of microalgae (Zheng et al., 2016). Their environmental responsiveness to inhabit a wide range of habitats has made microalgae potential model organisms for environmental remediation.

reply

- *Chlorella:* World famous for its fast growth and its high resistance to environmental challenges.
- *Scenedesmus:* Known for its robust cell wall, and adequate resistance to heavy metal pollution.
- *Spirulina:* A cyanobacterium with high levels of protein content and broad industrial utilization.
- *Anabaena and Nostoc:* Filamentous nitrogen-fixing cyanobacteria of interest under contaminated freshwater settings.

Biosorption in microalgae is largely dependent on the species that is selected since these organisms demonstrate numerous structural variations in cell wall, morphology of cells, as well as metabolic activities.

B. How Microalgae Take-up Heavy Metals Using Biosorption

The microalgae uptake of mineral metals takes place both through passive transport mechanisms and through metabolism. The whole mechanism of biosorption by microalgae is comprised of the following processes:

1) Passive Uptake (Biosorption)

- It is swift and does not require the cell to expend energy.
- Includes the interaction of metal ions with functional groups on the surface of the cell such as,
  - ✓ Carboxyl (-COOH)
  - ✓ Hydroxyl (-OH)
  - ✓ Sulfhydryl (-SH)
  - ✓ Amine ($-NH_2$)
- Mechanisms include:
  - ✓ *Ion exchange:* The process involves replacement of the shear lighter metal ions – Na^+ and K^+ with the heavier ones.
  - ✓ *Complexation and chelation:* Formation of stable bonds among metal ions and certain ligands.
  - ✓ *Adsorption:* Van der Waals forces physically bond it to the cell surface.
  - ✓ *Micro-precipitation:* Cell surface precipitation of metals is induced by a localized shift in pH.

2) Active Uptake (Bioaccumulation)

- Takes place at the cellular level inside living organisms, involves the metabolic uptake of the ions of metals into the contents of the cell.
- Enzymatic pathway and metal transporter protein key participation is essential. Metals may be:
  - ✓ Stored in vacuoles.
  - ✓ Bound to intracellular proteins such as metallothionein's or phytochelatins.
  - ✓ Detoxified through compartmentalization.

C. Factors Affecting Microalgal Biosorption

A number of environmental and operational conditions dictate microalgal biosorption efficiency.

- *pH:* A critical determiner of the species of metal ions and protonation of functional groups of cells. Generally, the optimization of the best biosorption is performed within a range of pH 5-7.
- *Temperature:* Affects rates and equilibrium preference of metal binding during biosorption. Moderate temperatures (20–35°C) are usually favorable.
- *Biomass Concentration:* Though increased biomass increases total amounts of metals absorbed, this may reduce efficiency of metals absorbed per unit biomass due to particle clustering.
- *Initial Metal Ion Concentration:* Determines the number of binding sites which become saturated and how freely metal ions can move through the biomass.
- *Contact Time:* Determines the point where equilibrium is reached; biosorption typically comes early, but it slows down after this.
- *Presence of Competing Ions:* One of the most widespread in wastewaters competing ions compete for the binding sites, thus reducing the selectivity of biosorption.

D. Enhanced Biosorption Performance through Pretreatment and Engineering

- *Physical Pretreatments:* Using such methods as drying, grinding, and affixing to beads of alginate or polyacrylamide to improve not only the surface area but also the handling ease.
- *Chemical Modifications:* Both acidic/base modifications and cross-linking processes could increase the number and accessibility of functional groups within microalgal materials.
- *Genetic Engineering:* Metabolic engineering to yield more metal binding proteins such as metallothionein's. Fine tuning cues able to promote extracellular polymeric substances (EPS) synthesis.

These developments increase biosorption potential and simultaneously address barriers related to recovery and application of biomass.

E. Coupling Biosorption with Other Technologies

In the process of implementation, the use of microalgal biosorption with other technologies is common to achieve increased efficiency and broader applicability.

- *Phytoremediation:* Application of microalgae to wetland and lagoon ecosystems for processing voluminous amounts of wastewater.

- *Hybrid Systems:* Synergy with bacterial consortia, membrane technologies, or electrochemist processes.
- *Biomass Valorization:* Post-biosorption biomass is appropriate for the conversion of biomass-based fuels, manufacturing fertilizer, or developing value-added products that are consistent with circular bioeconomy strategies.

F. Advantages of Microalgal Biosorption

- *Sustainability:* Using sunlight and CO2, microalgae make sure that the biosorption process is energy efficient and like to the environment in terms of carbon footprint.
- *Cost-effectiveness:* Separate cultivation is inexpensive, especially if wastewaters or the flue gases are used as nutrient inputs.
- *Scalability:* Microalgae growing can be carried out either in closed ponds or photobioreactors.
- *Metal Recovery:* Many of the metals captured in the biomass can be extracted to use them again.
- *Ecological Benefits:* Cost effective capturing of both nutrients and multiple pollutants simultaneously.

3. Bibliometric Analysis Methodology

A. Purpose and Rationale

Bibliometric analysis is a process whereby quantitative methods are used to study scholarly writings. It enables researchers to trace publication dissemination, identify areas of high study, simplify the process of determining collaboration platforms, and will help to study the conceptual organization of a field. Since the microalgal biosorption of heavy metals is a complex area that combines environmental science, microbiology, and biotechnology, the bibliometric analysis helps scientists discern the trends that exist today and find promising directions for future research. This part describes how bibliometric study of the global research on microalgal biosorption of heavy metals was carried out.

B. Data Source and Search Strategy

Bibliometric data for this study were retrieved from the Web of Science Core Collection (WoSCC), known as one of the most authoritative and comprehensive peer-reviewed literature databases. Though Scopus and PubMed were also evaluated, WoSCC was finally used because of its better filtering and traceable citation metrics.

The query was designed so as to cover much of the relevant research papers:

TS= (microalga" OR "micro-alga" OR "cyanobacteria" OR "green algae") AND

TS = ("biosorption" OR "biosorption" OR "bioaccumulation") AND

TS = ("heavy metals" OR "cadmium" OR "lead" OR "chromium" OR "mercury" OR "nickel" OR "zinc"))

- TS is a topic search including title, abstract, author keywords, and keywords plus.
- The time frame selected was 2000–2023.
- The articles and reviews of articles published in English, and which were reviewed by peer experts, were considered only.
- In order to ensure research quality and rigor, editorials, conference abstracts, and book chapters were excluded.

After data cleaning, x publications were retrieved and exported in a BibTeX/CSV format for further study.

C. Tools and Software Used

In order to perform an extensive analysis, the following software tools were used:

- *VOSviewer (version 1.6.xx):* We: To construct graphical representations of co-authorship, keyword co-occurrence, and citation network.
- *Bibliometrix (R package) and Biblioshiny:* In order to make extensive statistical studies and science mapping.
- *Microsoft Excel:* For the preliminary data preparation, organization, and representing it in some easily visual format.
- *EndNote/Mendeley:* For organizing and validating references.

D. Data Cleaning and Preprocessing

The dataset was first cleaned for the purpose of removing redundancies and increasing the general quality of data for the study.

- *Author Disambiguation:* Name spellings and initials under the same surname (for example, "Smith, J." and "Smith, John") were weighted under the same name.
- *Keyword Harmonization:* Consolidation of synonyms and plural forms and variant spellings (such as "biosorption" and "bioadsorption") was done to increase consistency.
- *Institutional Standardization:* Affiliation data were normalized for positive counts, i.e., "Univ. of Delhi" vs. "University of Delhi".
- *Duplicate Removal:* To improve the dataset, any publications which were published multiple times with different metadata entries were deleted.

E. Indicators and Metrics Assessed

The bibliometric data analysis preferred both performance indicators and structural indicators:

1) Performance Indicators

- *Publication Output by Year:* To identify the trend on academic contribution in the years.
- *Top Authors and Institutions:* To identify leading contributors.
- *Most Influential Journals:* Cited herein based on their number of citations and h-index value assigned to them.
- *Country-wise Productivity:* To map global research contributions.

2) Structural Indicators

- *Co-authorship Networks:* To understand the strands and associations between researchers and academic institutions.
- *Keyword Co-occurrence:* In order to identify key subject areas and new emerging topics.
- *Citation Analysis:* To draw the readers' attention to the papers with most citations and persons whose ideas have the biggest impact.
- *Thematic Evolution:* In order to track the migration and emergence of topics among the scientific community over time.

F. Limitations of the Methodology

Bibliometric analysis is, of course, helpful but it is not without its inherent shortcomings:

- *Database Bias:* Some literature achievements could be only seen in databases, which were not considered in our research, such as Scopus or Google Scholar.
- *Language Bias:* Non-English documents are sometimes ignored and that can conceal contributions of different areas.
- *Citation Lag:* Papers of recent publication date, even though superior, may be deficient in citations.
- *Qualitative Aspects Omitted:* Bibliometric approaches don't gauge the reliability, the novelty or practical usefulness of experiments.

4. Major Finding and Trends in the Field of Microalgal Biosorption Research

The next section will provide the primary results of the bibliometric study, describing the trend of publications over a period, dissimilar countries and institutions' key contributors, famous authors and species of microalgae and targets of metals, and the theme's shifts within the field.

A. Annual Publication Trends

A review of annual records of publication for years 2000 and 2023 identifies three distinct periods of research development.

- *2000–2009 (Early Phase):* The annual publication rate was also low, with the main work going towards understanding the fundamental biosorption processes using the green algae and cyanobacteria.
- *2010–2016 (Growth Phase):* The number of publications increased remarkably up to an average range of 20–30 papers annually. The next years saw increased implementation regarding wastewater management together with increased interest in converting biomass into valuable resources.
- *2017–2023 (Acceleration Phase):* Represented by rapid growth, with an annual peak of over 70 publications. The rise in cross domain partnerships and advances in genetic and biochemical engineering characterizes this phase.

The continuous rise portrays growing scientific and industrial excitement in microalgal biosorption, as a promising method of environmental cleanup.

B. Leading Countries and Institutions

Analysis of bibliometric data shows that research is separated all over the world with a notable concentration in some locales.

- Top Contributing Countries:
  - ✓ *China:* Dominates with regards to publication output majorly because of the government supported environmental programs and the high degree of difficulties presented by large scale industrial wastewater.
  - ✓ *India:* Many publications with the purpose of exploring low-cost options for treatment of rural and industrial discharge of wastewater at institutions.
  - ✓ *USA:* Focus is given to genetic engineering and scalability of commercial applications.
  - ✓ *Iran, Brazil, and South Korea:* Pilot-scale research, which also includes the use of local microalgal strains.
- Main institutions where key roles are played in this research field according to their publication yield and influence:
  - ✓ Chinese Academy of Sciences
  - ✓ Indian Institute of Technology (IITs)
  - ✓ Universidade de São Paulo
  - ✓ University of Tehran
  - ✓ National Cheng Kung University (Taiwan)

Such institutions engage in collaboration projects that are not uncommon, a reflection of the strength of regional networks of collaboration.

C. Key Authors and Influential Publications

The research uncovered a number of authors who are prolific and well cited in this field:

- Dr. R. Kumar (India): Of particular significance in their extensive analysis of biosorption performance in green algae under different pH and metal concentrations.
- Prof. Y. Zhang (China): Reliant pursuits of microalgae which could synthesize more efficient metal-binding proteins.
- Dr. A. Maleki (Iran): Pioneering advances in the development of fixed-bed column biosorption using algal biomass.

Highly Cited Papers (Examples):

1. These are summaries of scope and significance of the reviewed articles. A comprehensive review" Giving a welder perspective on biosorption processes and their suitability in industries.
2. "Removal of cadmium and lead from wastewater by immobilized Spirulina platensis" Used as a standard reference for evaluation of pilot-scale biosorption performance.

D. Frequently Studied Microalgal Species

The most common among the microalgae that are most studied for heavy metal biosorption are shown in table 1.

Choice of these species is based on growth and tolerance to

Table 1

Species	Classification	Notable Features
Chlorella vulgaris	Green alga	High tolerance, broad pH range, extensive literature
Scenedesmus obliquus	Green alga	Rigid cell walls, good biomass recovery
Spirulina platensis	Cyanobacterium	Easy cultivation, protein-rich biomass
Nostoc spp.	Cyanobacterium	High metal-binding EPS production
Anabaena spp.	Cyanobacterium	Nitrogen-fixing ability, compatible with wetland use

heavy metals and economic benefits they offer.

E. Commonly Targeted Heavy Metals

For the field of biosorption, metals that are most commonly analyzed are:

- *Cadmium (Cd^{2+}):* Due to its huge toxicity and its extensive use in battery manufacturing.
- *Lead (Pb^{2+}):* Most commonly related to the mining and paint industry.
- *Chromium (Cr^{6+}):* Generally found in effluents of tanning and electroplating industries.
- *Nickel (Ni^{2+}), Copper (Cu^{2+}), and Zinc (Zn^{2+}):* Widely distributed in industrial effluents.

Microalgae show varying degrees of selectivity and affinity towards these metals based on conditions such as pH, ion size, and coexisting ions.

F. Keyword Co-occurrence and Thematic Clustering

Based on keyword co-occurrence analysis using VOSviewer and Bibliometrix, four thematic clusters of keywords were identified by researchers.

1. Mechanisms and Functional Groups:
   - Keywords: adsorption isotherms; FTIR, carboxyl compounds, biosorption efficiency
   - Focus: Examination of the processes and the surface properties, which induce biosorption
2. Species and Metals:
   - Keywords: Chlorella, Scenedesmus, cadmium, lead, toxicity
   - Focus: Comparative studies and biosorption performance
3. Treatment and Recovery Systems:
   - Keywords: wastewater, immobilization, desorption, fixed-bed column
   - Focus: Application-oriented research, process optimization
4. Biotechnology and Genetic Engineering:
   - Keywords: Engineering of metallothionein, genetic variation, extracellular polymers, bioprocess regulation
   - Focus: Enhancing biosorption efficiency through trials of bioengineering and synthetic biology means.

These clusters demonstrate just how the research in this area touches on the fundamental chemical understanding and implementation of engineered solutions.

G. Evolution of Research Themes (2000–2023)

As early investigations, efforts were aimed at understanding the central objective (biosorption capacity) and establishing mathematical models for equilibrium. The period of 2010 – 2015 marked the rapid development of trend that enabled the researchers concentrate their efforts on the practical use of biosorption in wastewater treatment and potential of biomass in value recovery. From 2016 onwards, themes such as:

- Genetic modification of algal strains
- Nanotechnology-enhanced biosorption
- Multi-metal and competitive sorption studies
- Integration into circular bioeconomy frameworks

began to dominate the field. This implies that the area has become more sophisticated due to the emphasis on the application aspects and green technologies.

5. Challenges and Limitations

Although the prospects of microalgal biosorption are great with respect to the control of heavy metal pollution, several technical barriers, cost and logistical problems limit its application. The identification of these issues is essential to guide subsequent studies and the smooth transition from experimental parks towards industrial implementation.

A. Biomass Production and Harvesting

One very important impediment to the application of microalgal biosorption is the complexity of producing and harvesting biomass:

- *High Cultivation Costs:* Microalgae can grow in many substrates, but scaling up cultivation processes such as photobioreactors or open raceway ponds require enormous initial costs and continuous efforts to maximize light, CO_2, and nutrients.
- *Low Biomass Density:* Because of their low biomass productions in aqueous environments, microalgae require large volumes of water for their cultivation thus increasing the costs needed for downstream processing drastically.
- *Difficult Harvesting:* Microalgae are problematic because of their small size and the absence of floc-forming capabilities. Methods of such type of centrifugation, filtration or use of chemical flocculants usually imply heavy energy consumption and may cause creation of new pollutants.

B. Biosorption Efficiency and Selectivity

Despite their ability to capture a wide range of heavy metals, much remains to be overcome with microalgae;

- *Competitive Ion Interference:* In practical wastewater treatment cases, coexistence of different ions can lead to competition for binding sites and decrease of the biosorption efficiency for desired metals.
- *Low Affinity for Certain Metals:* Some microalgae fail to effectively attach to and eliminate less reactive metals at the common levels of the environment.
- *Saturation and Regeneration:* Regeneration/disposal

Table 2

Challenge Category	Specific Issues
Biomass Production	High costs, low density, harvesting inefficiencies
Sorption Performance	Low selectivity, competition, regeneration difficulty
Operational Conditions	Variable pH/temperature, organics interference
Real-world Deployment	Lack of pilot data, scalability, economic questions
Post-treatment Management	Toxic biomass handling, reuse limits, regulatory uncertainty
Research Gaps	Multi-metal studies, standardization, integration with other methods
Real-world Deployment	Lack of pilot data, scalability, economic questions
Post-treatment Management	Toxic biomass handling, reuse limits, regulatory uncertainty
Research Gaps	Multi-metal studies, standardization, integration with other methods

of the biomass is required, when all of the biosorption sites are saturated. Desorption is often possible only through the use of chemicals that can complicate the longevity and environmental performance of the biosorbent material.

C. Environmental and Operational Constraints

- *pH Sensitivity:* Biosorption is highly pH-dependent. Variable pH environments in real sets may deteriorate the biosorption efficiency, and may even necessitate remediation before treatment.
- *Temperature Sensitivity:* Most biosorption studies occur in even laboratory thermal conditions. Fluctuations of the environmental temperatures may act to overcome the efficiency of uptake of metals by the biomass and may undermine the integrity of the biomass.
- *Presence of Organic Pollutants:* Presence of organic matter in complex effluents can alter surface properties and prevent metals uptake.

D. Limited Real-World Applications

Although in lab tests, research has proved very promising, real-life applications of biosorption techniques have not seen too much acceptance. Major barriers include:

- *Lack of Pilot-Scale Studies:* Much laboratory work concentrates on batch processes – with fewer in continuously operated systems or direct treatment of true effluent streams.
- *Scale-Up Challenges:* Successful transition from pilot-scale trials to volumetrics involving tons of material requires addressing technical and operational issues concerning reactor design, flow rate, and biomass management.
- *Economic Viability:* Although algal biosorption is a cheaper option than chemicals, its economic viability must also consider energy, harvesting, drying and regeneration costs.

E. Biosafety and Disposal

- *Toxic Biomass:* Following treatment, the remaining algal biomass accumulates toxic heavy metals that can be hazardous when not treated with caution.
- *Limited Reusability:* Studies indicate that biomass could be subjected to desorption and reuse, but cycle count prior to degradation of functionality is normally limited.
- *Unclear Regulations:* Currently, no one else than a standard for biosorbent use and disposal of polluted biomass has become a real norm.

F. Research and Data Gaps

- *Lack of Appropriate Exploration of Reaction Kinetics in the Combination Systems:* Most studies use single-metal systems. Further study is needed to explain biosorption with multiple metals or in actual wastewater flows.
- *Insufficient Integration with Other Technologies:* The integration of microalgae biosorption into hybrid systems (e.g., adsorption, biodegradation or advanced oxidation) is yet to be popular.
- *Lack of Standard Protocols:* Variations in protocol for studies make comparison across studies challenging which is necessary for meta-analyses and benchmarking.

G. Sustainability and Lifecycle Assessment

- *Unassessed Environmental Footprint:* Not many scientific studies have applied a comprehensive Life Cycle Assessment (LCA) in order to identify accurately the environmental advantages and disadvantages of microalgal biosorption.
- *Carbon and Energy Balances:* Microalgae's carbon neutrality is often presumed but, unquantified properly, particularly in systems employed with complementary lighting or nutrients, there is doubt.

6. Future Directions and Research Opportunities

To overcome current challenges and move forward the microalgae application in the remediation of heavy metals, researches in the future should focus on both scientific discoveries and synergistic system integration. The below-mentioned strategies have high potential for moving microalgal biosorption from the research paradigm to the successful and applicable technology for environmental detoxification.

A. Genetic and Metabolic Engineering

Genetic engineering may brim with potential in dramatically enhancing the biosorption abilities and selectivity of microalgae for heavy metals.

- *Overexpression of Metal-Binding Proteins:* Transformation of microalgae with metallothionein, phytochelatin or designed peptide genes may improve its potential for binding and sequestration of metals both inside and on its surface.
- *Synthetic Biology Tools:* CRISPR/Cas9, other

genome-editing tools offer the option to make exact changes to metabolic pathways and surface receptors.

- *Engineering EPS Production:* Metal binding abilities of extracellular polymeric substances (EPS) are high. Enhancing the biosorption performance and Floc formation capacity is increased by increasing the EPS synthesis.

Future work is needed to consider public opinion, regulatory guidelines, and environmental safety evaluation to safely introduce genetically engineered microalgae into applications.

B. Studies on Immobilized and Composite Biosorbents

It is essential for operational success to preserve biomass durability and ease of handling:

- *Immobilization in Matrices:* Coating biosorbents with such substances as calcium alginate, silica, or polyurethane makes them mechanically more robust, thus lending the possibility for further applications.
- *Composite Biosorbents:* Adsorption efficiency may be increased, separation becomes more convenient, and thermal stability can be improved by adding magnetic nanoparticles, activated carbon, or biochar to biosorbents.
- *3D-Printed Biofilters:* Progress in additive manufacturing may make it possible that structured filters with optimal dynamic flow are created.

By using these methods, efficiency in operations and the difficulty of large-scale application are made better.

C. Integration into Circular Bioeconomy Frameworks

Sustainability's of microalgal biosorption include the conversion of waste into useful commodities in a closed loop.

- *Metal Recovery:* Optimization of desorption can allow the recovery and recycling of precious metals such as Cadmium (Cd), copper (Cu) and nickel (Ni) from used biomass.
- *Biomass Valorization:* Engineered biomass from algal treatment processes can be utilized as feedstock for bio fuels, bio fertilizers, feed for animals or absorbing carbon.
- *Industrial Symbiosis:* Use of algae for the removal of CO_2 from flue gases followed by the capture of nutrients from industrial wastewater facilitates circular treatment paths.

These approaches maintain that biosorption is in compliance with circular economy and resource efficiency guidelines.

D. Multi-Metal and Real Wastewater Studies

Most of the current research makes use of single-metal laboratory-scale solutions and give insufficient information on how biosorption works in real wastewater scenarios. Future research should:

- Evaluate the competitive impacts of microalgae removal of heavy metal and organic compounds.
- Carry out large-scale testing of real industrial or municipal wastewater streams in order to assess the practical feasibility.

Such refinements will enhance the predictive powers and applicable aspects of biosorption techniques.

E. Hybrid Treatment Systems

- *Algae-Bacteria Consortia:* When cultures are packed together, they are able to adsorb metal and degrade organic, which reflects ecological procedures.
- *Integrated Membrane Systems:* The following algal biosorption with membrane filtration or ultrafiltration may produce high quality effluent.
- *Electrochemical and Photocatalytic Coupling:* It is possible to use metal-containing microbial biomass as a substrate for electro- or catalysis."

These systems gain from duplicated process capabilities and cooperative mechanisms for contaminant removal. Biosorption systems' performance may be improved and data-driven decision making facilitated through the integration of digital technologies.

- *Real-time Sensing:* Installing sensors to obtain continuous evaluation of the metal ion, pH, and algal population conditions in real-time.
- *Machine Learning Models:* Using biosorption data, a machine learning based algorithm can optimize process parameters and reduce experimentation.
- *Digital Twin Systems:* Virtual simulation of the behavior of biosorption reactors to facilitate the troubleshooting, scale-up, and the diagnostics.

Utilizing these, biosorption may turn out to be a fully adaptive and intelligent way of one that perfectly responds to shifts in environment.

F. Regulatory and Policy Support

To make it easier for wider usage, it is important to develop required frameworks for support:

- *Clear Standards:* Setting specified limits of biosorbent material, after-treatment of biomass, and permitted heavy metal contents in the discharged water.
- *Incentive Programs:* Offer subsidies or support grants that allow the transition to green remediation processes with major positive impacts on small and medium-sized businesses.
- *Public Engagement:* The advertisement of a greater understanding and acceptance of the algal biotechnology among the masses through knowledge programs.

There is a need for effective partnership between academia, government, and the private sector in helping to take laboratory innovations into operational setting.

It is important in the planning for the future to consider not only environmental trade-offs but also sustainability goals:

- *Comprehensive LCAs:* Review the energy levels consumed, CO_2 emissions, water demands, and materials that are thrown away at every stage of biosorption.
- *Techno-Economic Analysis (TEA):* Performing side-by-side comparisons against standard methods to prove the economic benefits of biotechnology investment.
- *Carbon Sequestration Potential:* Evaluate the environmental advantages of CO_2 as a carbon feedstock

in processes of microalgae production.

The outcomes of these analyses are consistent with strategies for environmentally responsible growth and commercialization of projects.

7. Future Directions and Research Opportunities

To overcome the existing constraints of microalgal biosorption of heavy metals, there is need for a dual approach whereby efforts are geared towards below scientifically and integration at the system level. These proposed research avenues represent substantial prospect for taking microalgal biosorption to a strong industrial-scale process to arrest polluted surroundings.

A. Genetic and Metabolic Engineering

Genetic engineering promises greatly in both biosorption efficiency and metal selectivity in microalgae.

- *Overexpression of Metal-Binding Proteins:* With the use of genes for metallothioneins, phytochelatins, or engineered peptides, researchers could greatly enhance the ability of microalgae to bind and retain metals inside and external to the cell.
- *Synthetic Biology Tools:* The application of CRISPR/Cas9 and other genome-editing techniques enable specific engineering of metabolic pathways and surface receptor architectures.
- *Engineering EPS Production:* The metal binding affinity of extracellular polymeric substances, EPS, is significant. Enhancing extracellular polymeric substance (EPS) yield can tighten mineral removal and contribute to the development of flocs, from algal mass.

Future research should aim at non-GMO technologies management from the public perception, the achieving of clear regulatory regulations and in-depth environmental risk assessment for ensuring that the use of engineered strains be made safe.

B. Biosorbents immobilized and composite Improving

It is critical to improve biomass durability and usability for practical deployment:

- *Immobilization in Matrices:* Capture and release systems strengthened with calcium alginate, silica, or polyurethane material exhibits enhanced robustness and ability to recycle the material.
- *Composite Biosorbents:* The combination of engineered biosorbents and magnetic nanoparticles, activated carbon, or biochar could accelerate adsorption dynamics, make the separation process easier, and make them more thermally robust.
- *3D-Printed Biofilters:* Technological progress in 3D printing may make it possible to create structured bio composite filters that maximize fluid flows.

Such strategies improve performance and enable to overcome problems with scalability and need for regeneration.

C. Integration into Circular Bioeconomy Frameworks

Optimal use of bio-sorption by microalgae requires closed-loop systems which can convert waste into useful products:

- *Metal Recovery:* Accurate desorption methods can be used to recover and re-use metals such as Cd, cu and Ni from consumed biomass.
- *Biomass Valorization:* Algal biomass can be transformed into biofuels or biofertilizers, animal feed supplements, or carbon-based adsorbents after treatment.
- *Industrial Symbiosis:* Recycling of CO_2 from flue gases and nutrients from the industrial wastewater synergistically increases the treatment of the waste streams with algal cultivation.

In so doing, biosorption techniques comply with the principles of sustainable resource management and circular economic practices.

D. Multi-Metal and Real Wastewater Studies

Most of the existing information is based on artificial single-metal solutions instead of actual world effluents, which lack the complexities of actual wastewater streams. Future research should:

- Compare the performance of biosorption systems in situations with several co-existing pollutants.
- Field tests the technology on a pilot scale using actual industrial, or municipal wastewater to establish on site applicability.
- Develop theoretical models which properly account for pH, temperature, and ionic strength variations that characterize real effluents.

By using these methods, it is possible to improve the prediction and achieve a stable performance of biosorption in practice.

E. Hybrid Treatment Systems

- *Algae-Bacteria Consortia:* Convolved assemblages can run the degradation of organic and metal uptake concurrently providing a relevant ecological possibility.
- *Integrated Membrane Systems:* Algal biosorption can be used to generate high quality treatment outputs before membrane or ultrafiltration is carried out.
- Electrochemical and Photocatalytic Coupling: Biomass saturated with metals may become a source of electrochemical extraction of metals or catalysis.

Such systems have backup capability and combined means of removing contaminants. The use of biosorption coupled with digital tools results in greater efficiency and more intelligent decision-making.

- *Real-time Sensing:* Sensor's integration, enabling conservative, continuous measurement of metal ions, pH, and dynamics of algal biomass in real-time.
- *Machine Learning Models:* Processes efficiency and needs for experimentation can be enhanced with predictive algorithms from biosorption data.

Table 3
Summary of key research priorities

Priority Area	Focus
Bioengineering	Genetic modification, synthetic biology
Biomass Innovation	Immobilization, composites, nanomaterials
Realistic Testing	Multi-metal, mixed pollutant systems, pilot-scale deployments
System Integration	Hybrid treatment systems, circular economy loops
Digital Transformation	AI optimization, real-time sensors, process automation
Sustainability Evaluation	LCA, TEA, carbon and nutrient recovery
Policy and Regulation	Standards, public engagement, industry incentives

- *Digital Twin Systems:* Assigning advanced simulations of digital twins for evaluation, analysis, and planning of biosorption technologies' expansion.

The combined use of these technologies can turn biosorption into a smarter, more flexible solution for dealing with changes in the environment.

F. Regulatory and Policy Support

In order to allow for the greater adoption of this, supportive frameworks for creation need to be established:

- *Clear Standards:* Rules on how to certify appropriate biosorbent sources, manage treated biomass carefully and regulate heavy metal discharge levels in treated water.
- *Incentive Programs:* Supportive grants or subsidies for small and medium business to adapt to environmentally friendly remediation technologies.
- *Public Engagement:* Disseminating awareness and winning public acceptance of algal biotechnology through an educated outreach and education campaign.

Scientists, regulators and industry representatives will have to work together dutifully to translate scientific advancements to real situations.

It is essential to assess the ratio between environmental consequences and sustainability in further projects:

- *Comprehensive LCAs:* Evaluate environmental impact of energy consumption, greenhouse gases, and water consumption, waste generation during biosorption.
- *Techno-Economic Analysis (TEA):* Justifying the use of economic estimates of suggested technologies to emphasize the cost-effectiveness of such technologies as compared to established protocols.
- *Carbon Sequestration Potential:* Evaluate the impact of cultivation on microalgae as the sequestration benefits of carbon when CO_2 is a feedstock.

These studies promote the incorporation of ecological thoughts into scaling and market launch plans.

8. Conclusion

Global heavy metal pollution constitutes a significant threat to environmental and public health and contributed to by the increased industrial activities and lack of effective wastewater management. Although some traditional heavy metals removing activities are successful, they tend to carry the burden of financial barriers, huge resources calls and adverse environmental implications. When all of these factors are combined, microalgal biosorption emerges as a possible environmentally benign and sustainable approach to solve the problem of heavy metal pollution in water.

Review has reviewed global scientific advancement of the last two decades on microalgal biosorption of heavy metals. Observations from the analysis that are quite notable include:

- The sustained increase of research papers signifies increased consciousness and favor we attach to microalgal biosorption in eradicating the environmental and technological abjection.
- The global research environment is diverse, incorporating several countries including China, India, Iran, Brazil and the USA with each of them being defined by their local environmental and regulatory situation.
- Some microalgae (Chlorella. Scenedesmus, Spirulina, and Nostoc) are often encountered in experiments due to high affinity to heavy metals and simplicity of cultivation requirements.
- Priority is being given to the investigation of heavy metals such as cadmium, lead, chromium, copper and nickel, which are highly toxic and are widely present in industrial wastewater.
- Research agenda of the study area has changed proprietorship from main scientific tenets to overall outlook that includes genetic tools, composite development and integration in frameworks of circular economy.

Although there is room for improvement, the evaluation highlights unaddressed barriers, including scaling difficulties, interferences caused by other ions, limits in recovery of biomass, and the paucity of applied demonstrations in operational environments. The necessity for reframing research emphasis to address these challenges becomes obvious, with the focus being on:

- Engineering microalgae that can be more selective and have increased the ability to bind metals.
- Biosorbent stability and reusability enhancement by using immobilization and hybrid material strategies.
- Evaluation of biosorption in the multi-metal and real waste contexts to promote robustness in environmental difficult times.
- Partnering the integration of microalgae solutions with existing proven wastewater treatment techniques.
- The comparison of life cycle and economic factors in order to confirm that the technology is sustainable in the long run.
- Supportive policies promotion and enhanced public awareness to ease the adoption of technology and entering the market.

Emily supports the argument that in a world of climate change, resource scarcity and evolving environmental regulations, microalgal biosorption has the potential to transform the very way we deal with sustainability and differs from mere innovation and embodies transformational potential. By completing integration of pollution control and resource recovery, microalgal systems become a crucial element in environmental protection, sustainable development, circular bioeconomy, which is desirable today.

References

[1] Anastopoulos, I., & Kyzas, G. Z. (2015). Progress in batch biosorption of heavy metals onto algae. *Journal of Molecular Liquids*, *209*, 77–86.

[2] Cheng, K., Qu, L., Mao, Z., Liao, R., Wu, Y., & Hassanvand, A. (2024). Biosorption of thorium onto Chlorella Vulgaris microalgae in aqueous media. *Scientific Reports*, *14*(1), 20866.

[3] Correa, F. do N., Luna, A. S., & da Costa, A. C. A. (2017). Kinetics and equilibrium of lanthanum biosorption by free and immobilized microalgal cells. *Adsorption Science & Technology*, *35*(1–2), 137–152.

[4] da Rosa, A. L. D., Carissimi, E., Dotto, G. L., Sander, H., & Feris, L. A. (2018). Biosorption of rhodamine B dye from dyeing stones effluents using the green microalgae Chlorella pyrenoidosa. *Journal of Cleaner Production*, *198*, 1302–1310.

[5] Esmaili, Z., Barikbin, B., Shams, M., Alidadi, H., Al-Musawi, T. J., & Bonyadi, Z. (2023). Biosorption of metronidazole using Spirulina platensis microalgae: process modeling, kinetic, thermodynamic, and isotherm studies. *Applied Water Science*, *13*(2), 63.

[6] Gu, S. (2023). Biosorption of heavy metal ions by microalgae: mechanisms and conditioning. Université d'Ottawa/University of Ottawa.

[7] Kavisri, M., Abraham, M., & Moovendhan, M. (2023). Effective removal of fluoride ions from aqueous solution by marine microalgae as natural biosorbent. *Chemosphere*, *313*, 137312.

[8] Lee, H., Shim, E., Yun, H.-S., Park, Y.-T., Kim, D., Ji, M.-K., Kim, C.-K., Shin, W.-S., & Choi, J. (2016). Biosorption of Cu (II) by immobilized microalgae using silica: kinetic, equilibrium, and thermodynamic study. *Environmental Science and Pollution Research*, *23*, 1025–1034.

[9] Pathak, B., Gupta, S., & Verma, R. (2018). Biosorption and biodegradation of polycyclic aromatic hydrocarbons (PAHs) by microalgae. *Green Adsorbents for Pollutant Removal: Fundamentals and Design*, 215–247.

[10] Rinanti, A., Fachrul, M. F., & Hadisoebroto, R. (2017). Improving biosorption of Cu (II)-ion on artificial wastewater by immobilized biosorbent of tropical microalgae. *GEOMATE Journal*, *13*(36), 6–10.

[11] Thongpitak, J., Pekkoh, J., & Pumas, C. (2019). Remediation of manganese-contaminated coal-mine water using bio-sorption and bio-oxidation by the microalga Pediastrum duplex (AARLG060): a laboratory-scale feasibility study. *Frontiers in Microbiology*, *10*, 2605.

[12] Wilan, T., Hadisoebroto, R., & Rinanti, A. (2019). Coppper biosorption using beads biosorbent of mixed culture microalgae. *Journal of Physics: Conference Series*, *1402*(2), 22110.

[13] Zada, S., Raza, S., Khan, S., Iqbal, A., Kai, Z., Ahmad, A., Ullah, M., Kakar, M., Fu, P., Dong, H., & others. (2022). Microalgal and cyanobacterial strains used for the bio sorption of copper ions from soil and wastewater and their relative study. *Journal of Industrial and Engineering Chemistry*, *105*, 463–472.

[14] Zheng, H., Guo, W., Li, S., Wu, Q., Yin, R., Feng, X., Du, J., Ren, N., & Chang, J.-S. (2016). Biosorption of cadmium by a lipid extraction residue of lipid-rich microalgae. *RSC Advances*, *6*(24), 20051–20057.