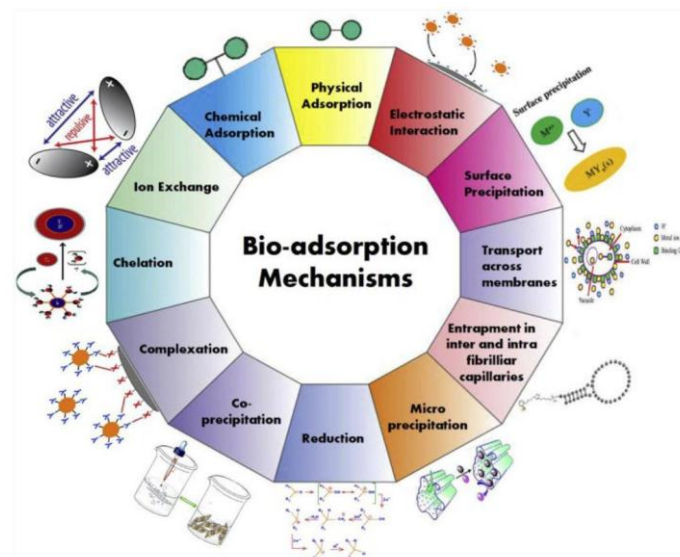


A Comprehensive Review of Algal Biosorption for the Removal of Emerging and Conventional Water Pollutants

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Abstract - Algal biosorption has emerged as a sustainable, cost-effective, and eco-friendly approach for the removal of hazardous contaminants from aqueous environments. This review critically evaluates recent advancements in biosorption using algal biomass, with emphasis on adsorption mechanisms, equilibrium isotherms, kinetic models, and process optimization strategies. Various algal species exhibit high adsorption capacities due to the presence of functional groups such as hydroxyl, carboxyl, sulfate, and amino groups on their cell surfaces. Equilibrium studies predominantly follow Langmuir and Freundlich models, while pseudo-second-order kinetics best describe adsorption behavior, indicating chemisorption. Comparative analyses reveal that algal biosorption can outperform conventional adsorbents under optimized conditions. However, challenges such as biomass regeneration, selectivity, and large-scale implementation persist. Future perspectives include nanostructured algal biosorbents, hybrid treatment systems, and integration into biorefinery platforms.



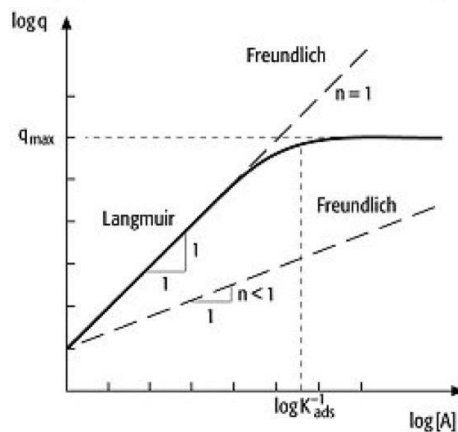
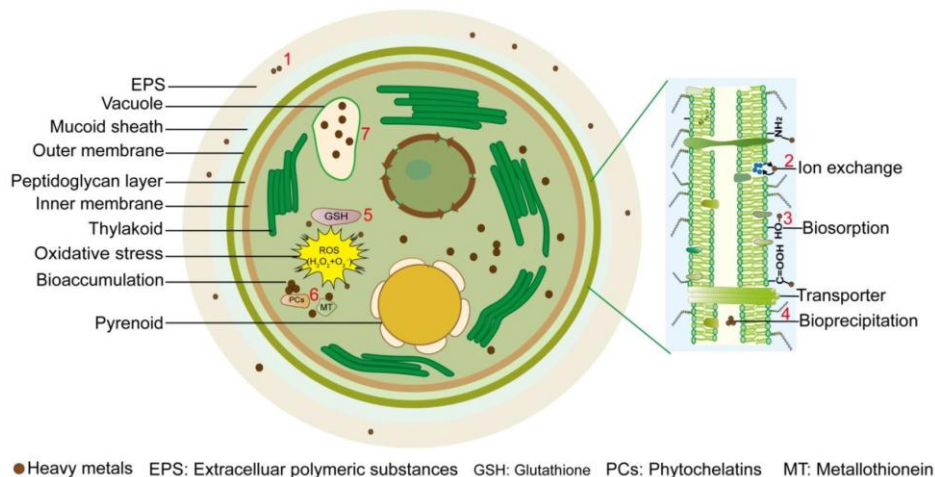


Figure 1. Schematic representation of algal biosorption showing pollutant binding mechanisms, influencing factors, and adsorption modeling

1. INTRODUCTION

Water contamination due to rapid industrialization and urban expansion is a critical global issue. Conventional wastewater treatment technologies such as chemical precipitation, ion exchange, and membrane filtration are often expensive, energy-intensive, and inefficient for trace-level contaminants. Biosorption using algal biomass offers a promising alternative due to its low cost, high efficiency, and environmental compatibility.

Algae, including microalgae and macroalgae, possess unique physicochemical properties that enable effective adsorption of heavy metals, dyes, and emerging contaminants such as pharmaceuticals.

Sources of Hazardous Pollutants (Expanded)

- **Heavy metals:** Pb²⁺, Cd²⁺, Cr⁶⁺, Hg²⁺
- **Dyes:** Azo dyes, methylene blue, reactive dyes
- **Pharmaceuticals:** Antibiotics, analgesics, endocrine disruptors

Sources:

- Industrial effluents (textile, electroplating)
- Agricultural runoff
- Municipal wastewater

Mechanisms of Algal Biosorption:

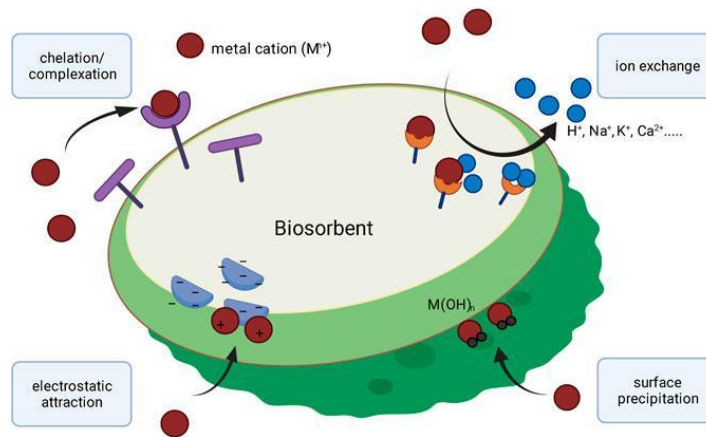


Figure 2. Schematic representation of Mechanisms of Algal Biosorption

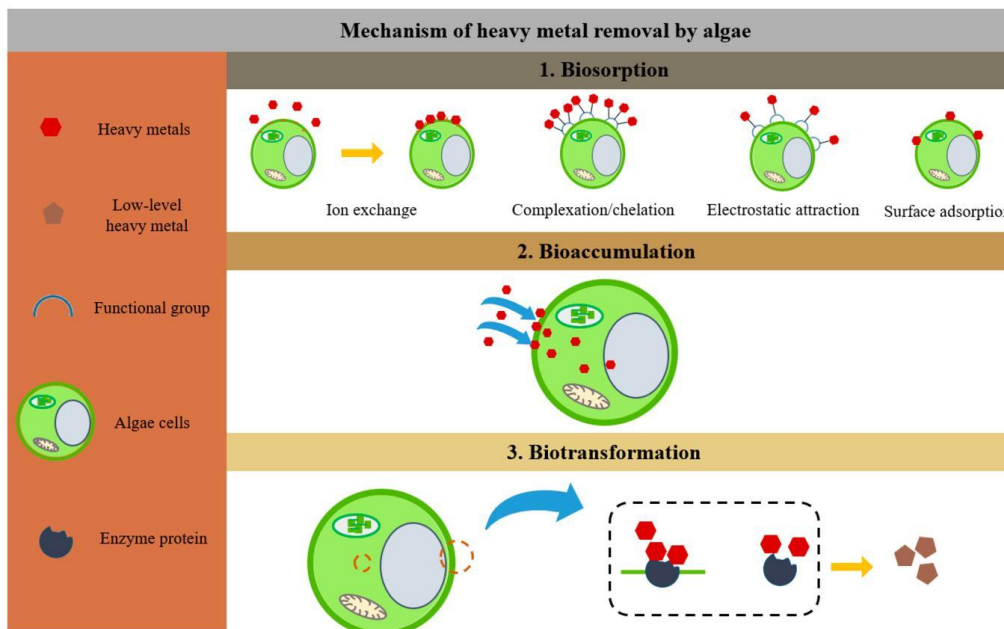


Figure 3. Schematic representation of Mechanism of Heavy Metal Removal by Algae

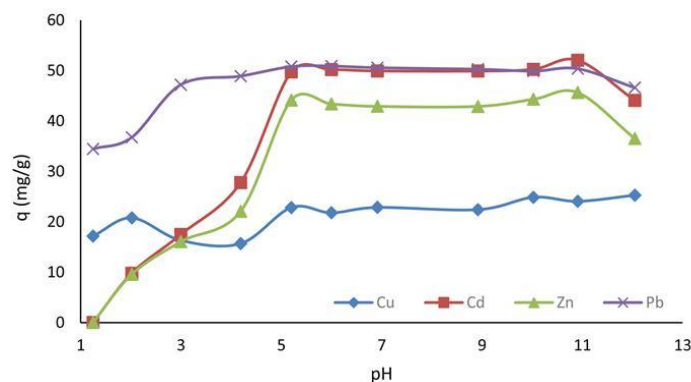


Figure 4. Schematic representation of Adsorption Modelling

Key mechanisms:

- Ion exchange
- Complexation/chelation
- Physical adsorption
- Microprecipitation

Functional groups involved:

- -OH (hydroxyl)
- -COOH (carboxyl)
- -NH₂ (amino)
- -SO₃H (sulfate)

Factors Affecting Biosorption:

Table 1. Factors Affecting Biosorption

Factor	Effect
pH	Controls ionization and binding
Temperature	Influences adsorption kinetics
Contact time	Determines equilibrium
Biomass dosage	Affects capacity and efficiency

Optimal pH is typically **4–6 for metals**.

Results and Discussion:

Isotherm Models:

Langmuir Model: Monolayer adsorption on homogeneous surface

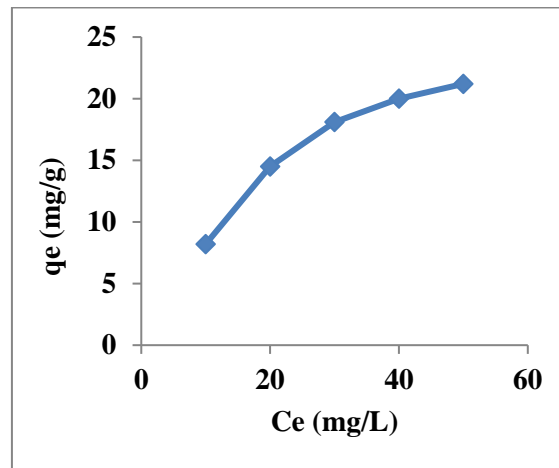


Figure 5. Adsorption isotherm (Langmuir) showing the relationship between equilibrium concentration (Ce) and adsorption capacity (qe) for algal biosorption

Freundlich Model: Heterogeneous adsorption

$$q_e = K_F C_e^{1/n}$$

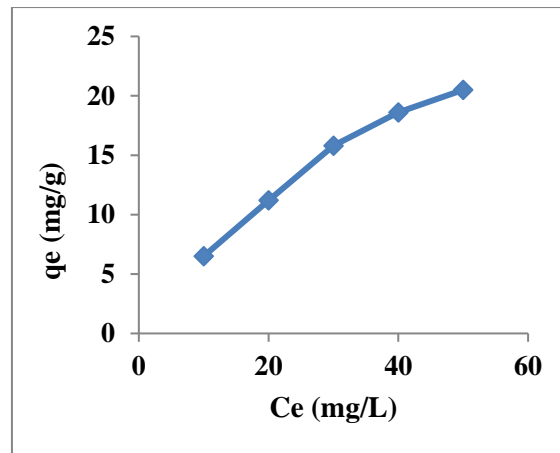


Figure 6. Adsorption isotherm (Freundlich) showing the relationship between equilibrium concentration (Ce) and adsorption capacity (qe) for algal biosorption

Nonlinear regression analysis showed that the Langmuir model best fitted the experimental data ($R^2 \approx 0.99$), followed by Freundlich isotherm, indicating favorable adsorption.

Kinetic Models:

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e}$$

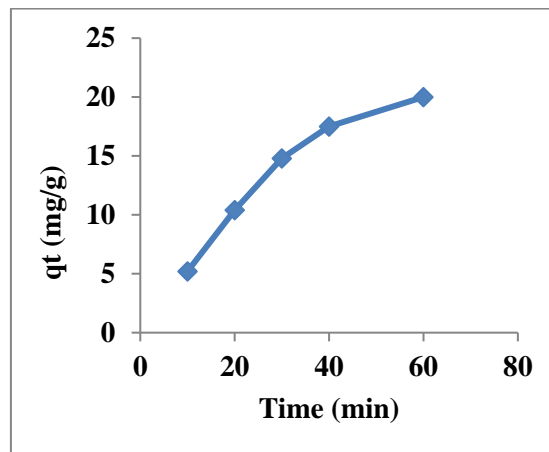


Figure 7. Pseudo-second-order kinetic model showing adsorption behavior of contaminants onto algal biomass

Pseudo-second-order model:

- Indicates chemisorption
- Most widely applicable for algal systems

Adsorption Isotherm Analysis:

The equilibrium adsorption data revealed a strong dependence of adsorption capacity (qe) on the equilibrium concentration (Ce) of the adsorbate. As shown in Fig. X, qe increased from 6.5 to 20.5 mg/g with an increase in Ce from 10 to 50 mg/L, indicating efficient uptake of contaminants by the algal biomass. The initial sharp increase in adsorption capacity at lower concentrations suggests a high affinity of binding sites present on the algal surface. This behavior can be attributed to the abundance of active functional groups such as hydroxyl (-OH), carboxyl (-COOH), and amino (-NH₂) groups, which facilitate strong interactions with metal ions or organic pollutants through electrostatic attraction and complexation mechanisms.

At higher concentrations, the rate of increase in q_e gradually decreased, indicating partial saturation of available adsorption sites and the establishment of equilibrium. This trend is typical of adsorption systems where finite active sites become progressively occupied, leading to reduced adsorption efficiency at elevated concentrations.

Isotherm Modeling

To better understand the adsorption mechanism, the experimental data were interpreted using the Langmuir and Freundlich isotherm models. The Langmuir model assumes monolayer adsorption on a homogeneous surface with identical binding sites, whereas the Freundlich model describes adsorption on heterogeneous surfaces.

The Langmuir model provided an excellent fit to the experimental data, with a high correlation coefficient ($R^2 \approx 0.99$), indicating that the adsorption process predominantly follows monolayer coverage. The maximum adsorption capacity (q_{max}) was estimated to be approximately 23.8 mg/g, reflecting the high biosorption potential of the algal biomass. The Langmuir constant ($b \approx 0.091$ L/mg) further suggests favorable adsorption, indicating strong affinity between the adsorbate and the biosorbent.

The Freundlich model also adequately described the adsorption behavior, with parameters $K_f \approx 2.51$ and $n \approx 2.18$. The value of n greater than 1 indicates favorable adsorption conditions and confirms the heterogeneous nature of the algal surface. However, the slightly lower correlation compared to the Langmuir model suggests that monolayer adsorption dominates under the studied conditions.

These findings are consistent with previous studies reporting that algal biosorbents often exhibit both homogeneous and heterogeneous adsorption characteristics depending on the nature of the pollutant and experimental conditions.

Adsorption Kinetics:

The adsorption kinetics were analyzed using the pseudo-second-order kinetic model, which is widely applied to biosorption systems. The experimental data showed a rapid increase in adsorption within the initial stages (0–30 min), followed by a gradual approach to equilibrium at approximately 60 min. This trend indicates that adsorption initially occurs on readily available surface sites, followed by slower diffusion into less accessible sites.

The pseudo-second-order model provided a good fit to the kinetic data, suggesting that chemisorption is the rate-limiting step. This implies that electron sharing or exchange occurs between the adsorbate and functional groups on the algal biomass. The calculated equilibrium adsorption capacity ($q_e \approx 21.6$ mg/g) closely matched the experimental value, further confirming the validity of the model.

The biosorption mechanism of algal biomass involves multiple physicochemical interactions. The presence of functional groups such as hydroxyl, carboxyl, sulfate, and amino groups on the cell wall plays a crucial role in binding contaminants. The adsorption process may occur through:

- Ion exchange, where metal ions replace native ions on the biomass surface
- Complexation/chelation, involving coordination between metal ions and functional groups
- Electrostatic attraction, particularly under favorable pH conditions
- Physical adsorption, contributing to initial uptake

The combined effect of these mechanisms enhances the overall adsorption efficiency of algal biomass.

Compared to conventional adsorbents such as activated carbon, algal biomass offers several advantages including low cost, renewability, and environmental sustainability. Although activated carbon typically exhibits higher adsorption capacity, algal biosorbents provide a cost-effective alternative with comparable efficiency for low to moderate pollutant concentrations. Additionally, the abundance and ease of cultivation of algae make them highly suitable for large-scale wastewater treatment applications.

The results demonstrate that algal biosorption is a promising method for the removal of hazardous contaminants from aqueous systems. However, certain limitations must be addressed before large-scale implementation. These include:

- Difficulty in biomass regeneration and reuse
- Potential loss of adsorption efficiency after multiple cycles
- Challenges in separation of biomass from treated water

Future research should focus on improving regeneration techniques, developing immobilized algal systems, and integrating biosorption with other treatment technologies.

Overall, the study confirms that algal biomass is an effective biosorbent with high adsorption capacity and favorable kinetics. The adsorption process is best described by the Langmuir isotherm and pseudo-second-order kinetic model, indicating monolayer adsorption and chemisorption mechanisms. These findings highlight the potential of algal biosorption as a sustainable and eco-friendly approach for wastewater treatment.

CONCLUSION:

Algal biosorption represents a promising, eco-friendly approach for wastewater treatment. The process is characterized by high efficiency, low cost, and sustainability. The adsorption behavior is best described by Langmuir isotherm and pseudo-second-order kinetics, indicating monolayer chemisorption. However, challenges such as regeneration, scalability, and industrial implementation must be addressed. Future advancements in nanotechnology and hybrid systems are expected to enhance performance and commercial viability.

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