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Review Article

Microalgae: The Invisible Green Ghost Rewriting Our Future

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ABSTRACT

Microalgae carry out photosynthesis very efficiently, turning 8 to 10% of solar energy into biomass. They have ways to concentrate CO_2, which helps them outperform land-based crops. Because they can grow in different ways, they can produce valuable lipids, proteins, and pigments even when under stress. These qualities allow microalgae to serve two purposes in bioremediation: cleaning wastewater and capturing carbon. However, increasing production presents significant challenges. These challenges include contamination risks in open ponds, the high cost of photobioreactors, and the energy required for dewatering and harvesting. Just downstream processing takes up over 70% of the production energy. Future improvements will rely on engineered solutions:

- Genetic tools, like CRISPR strains, to increase yields
- Hybrid systems that combine algae and bacteria, along with AI-optimized reactors
- Circular integration for converting flue gas and wastewater into nutraceuticals or biofuels

In the short term, there are chances to develop premium products like astaxanthin and carbon credits. Long-term goals include projects like NASA's space bio-life-support systems and large-scale ocean carbon capture. Solving economic issues through policy changes and technological innovation will help unlock microalgae's potential as sustainable, living platforms.

INTRODUCTION

Microalgae are ancient single-celled organisms that use photosynthesis. They are at the cutting edge of sustainable biotechnology. They have remarkable photosynthetic efficiency, converting 8 to 10% of solar energy into biomass. This allows them to outperform land crops while using waste CO_2 and nutrients. Their ability to adapt lets them grow quickly in different environments, such as

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wastewater and seawater. They produce valuable compounds like proteins, omega-3 lipids, antioxidants such as astaxanthin, and biofuel precursors. As powerful agents of bioremediation and carbon sequestration, microalgae help clean ecosystems and fight climate change.

However, challenges in cultivation, such as contamination risks, energy-intensive harvesting, and high scaling costs, limit their industrial use. Breakthroughs in genetic engineering, particularly with CRISPR-enhanced strains, AI-driven photobioreactors, and circular bioeconomy frameworks like converting flue gas to feed, are making them more commercially viable. This article examines how microalgae, supported by innovative science and policy collaboration, are ready to transform food, energy, and environmental systems. They are moving from vital ecological players to essential components of a sustainable future.

Fig:01

MECHANISM, HOW IT WORKS:

1. Photosynthetic Powerhouse

Ultra-Efficient Light Harvesting: Microalgae use antenna complexes, such as phycobilisomes in cyanobacteria, to capture a wide range of light, including far-red and blue. They reach 8 to 10% solar-to-biomass efficiency, much higher than the 1 to 2% seen in crops.

CO_2 Fixation: Calvin cycle enzymes like Rubisco are concentrated in pyrenoids within chloroplasts, enabling rapid carbon fixation. Some species have CO_2-concentrating mechanisms (CCMs) to thrive in low CO_2 environments.

2. Metabolic Flexibility

Mixotrophy: Many microalgae, including Chlorella, combine photosynthesis with the uptake of organic carbon. This increases growth rates in varying light and nutrient conditions.

Lipid Triggers: Nutrient starvation, such as low nitrogen or phosphorus, or high salinity causes lipid accumulation, which can reach up to 70% of dry weight in Nannochloropsis.

Extremophile Adaptations: Halophiles, like Dunaliella, produce glycerol to deal with salt stress. Thermophiles, such as Synechococcus, create heat-shock proteins.

3. Bioremediation Mechanisms

Nutrient Uptake: Microalgae absorb nitrogen, phosphorus, and potassium from wastewater through active transport, including nitrate transporters and phosphate-binding proteins.

Heavy Metal Sequestration: They use biosorption, involving binding to cell walls, and bioaccumulation, which involves intracellular chelation through phytochelatins.

CO_2 Biofixation: Carbonic anhydrases convert CO_2 into HCO_3^- for storage. The carbon can then be stored as lipids or carbohydrates. [1][2][4][8]

PRODUCTION OF MICROALGAE

1. Cultivation

Microalgae are grown in two main systems:

Open Ponds (e.g., High-Rate Algal Ponds - HRAPs): These are large, shallow, raceway-shaped ponds mixed with paddlewheels.

- Advantages: Low cost, simple setup.
- Disadvantages: Risk of contamination, weather-dependent.

Closed Systems (Photobioreactors - PBRs): These consist of transparent tubes or panels that allow for better control over light, CO_2, and contamination.

- Advantages: Higher productivity, year-round operation.
- Disadvantages: High initial cost.

2. Nutrient and CO_2 Supply

Nutrients: Nitrogen, phosphorus, potassium, and trace elements are added to the growth medium.

CO_2 Supply: It is injected to boost photosynthesis and biomass production.

3. Growth Phase

Microalgae multiply quickly under ideal conditions, including light, temperature, and pH. Growth can be:

- **Photoautotrophic:** Using only light and CO_2.
- **Mixotrophic:** Using light and organic carbon sources.
- **Heterotrophic:** Using organic carbon in the dark.

4. Harvesting

Once enough biomass is produced, it is separated from the water using:

- **Flocculation:** Chemicals clump the algae for easy collection.
- **Centrifugation:** This spins the algae out of suspension.
- **Filtration:** Membranes filter out the cells.
- **Floatation:** Air bubbles lift the cells to the surface.

5. Drying and Processing

The wet biomass is dried using methods like solar drying or spray drying. It is then processed into:

- Biofuels (biodiesel, biogas)
- Nutraceuticals (omega-3, astaxanthin)
- Animal feed
- Fertilizers

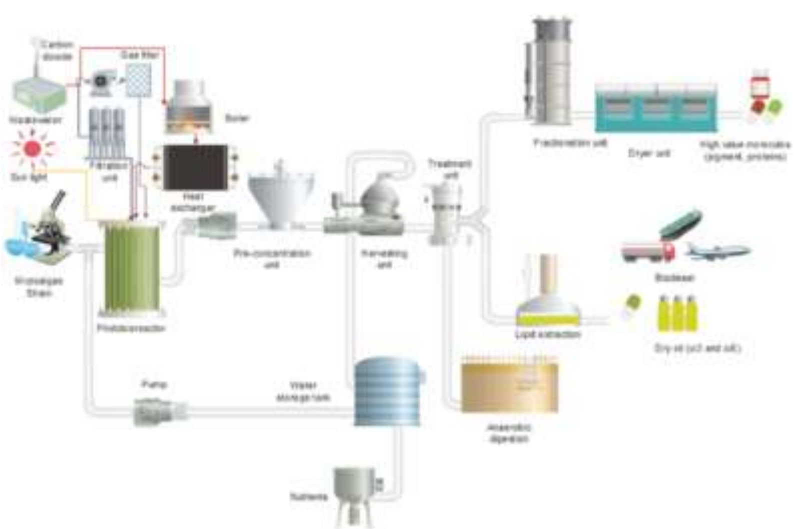

Fig:02

TREATMENT MECHANISMS:

Photosynthetic Oxygenation

1. **Microalgae release O_2 during photosynthesis:** $6CO_2 + 6H_2O + \text{light} \rightarrow C_6H_{12}O_6$ (glucose) + $6O_2$

Impact: This provides oxygen for aerobic bacteria to break down organic pollutants and reduce BOD. It also eliminates the need for mechanical aeration, saving 50 to 80% energy.

2. **Nutrient Assimilation (N & P Removal)**

Nitrogen: Absorbed as NH_4^+ (ammonium), NO_3^- (nitrate), or NO_2^- (nitrite) and converted into proteins or nucleic acids.

Removal efficiency: 80 to 95%. For example, Chlorella takes up 25 mg N per gram of biomass.

Phosphorus: Taken up as PO_4^{3-} (phosphate) and then used for ATP or phospholipids.

Removal efficiency: 70 to 90%, as shown by Scenedesmus, which removes 5 mg P per gram of biomass.

3. **Heavy Metal Biosorption/ Bioaccumulation**

Step 1: Passive biosorption happens on the cell wall. Carboxyl and amino groups bind to Cd^{2+}, Pb^{2+}, and Cu^{2+}.

Step 2: Active bioaccumulation occurs when metals are transported into cells and chelated by phytochelatins or metallothioneins.

Efficiency: 60 to 99% for Pb and Cd. For instance, Spirulina removes 85% Pb at 50 mg/L.

4. **Organic Pollutant Degradation**

Algal enzymes like laccases and cytochrome directly break down phenols and pesticides. Symbiotic bacteria indirectly mineralize organics using algal O_2.[3][6][5]

FLOW CHART OF ALGAL TREATMENT SYSTEM

REACTOR CONFIGURATIONS & OPERATIONAL PARAMETERS

1. **High-Rate Algal Ponds (HRAPs)** [6]

Design: Open raceway ponds, about 20 to 30 cm deep, with paddlewheel mixing.

Conditions:

- pH: 7 to 10 (rises due to CO_2 consumption)
- Temperature: 15 to 35°C (optimal at 25°C)
- Hydraulic Retention Time (HRT): 4 to 10 days

Performance:

- BOD removal: 90%
- N removal: 80%
- P removal: 75%

Pros: Low initial investment, $15 to $30 per square meter.

Cons: Depends on weather and evaporation losses.

2. Photobioreactors (PBRs)

Types: Tubular, flat-panel, bubble column (closed systems).

Conditions:

- Light intensity: 100 to 200 µmol photons per square meter per second
- CO_2 supplementation: 5 to 15% v/v (increases growth by 2 to 3 times)

Performance:

- Biomass productivity: 0.8 to 1.5 g/L/day compared to 0.1 to 0.3 g/L/day in HRAPs
- Pathogen removal: over 99% in a sterile environment

Pros: Controllable, operates year-round.

Cons: High initial investment, $100 to $500 per cubic meter; issues with biofilm fouling.

BIOMASS HARVESTING

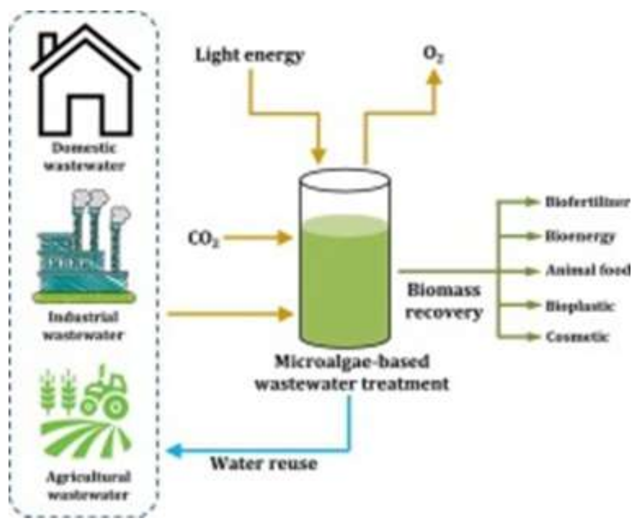

Fig:03

1. Flocculation:

- Add chitosan or alum at 10 to 50 mg/L to gather cells.
- Efficiency: 85 to 95% recovery. [9]

2. Floatation:

Use dissolved air floatation (DAF) to lift biomass with microbubbles.

3. Centrifugation:

Apply 5,000 to 10,000 × g for 95% recovery at a cost of $0.3 to $1 per kg of biomass. [3]

4. Filtration:

Use membrane microfiltration with a pore size of 0.1 to 0.8 µm for high-value products.[6]

CHALLENGES & OPTIMIZATION STRATEGIES [9][3][8]

- Challenge: Low winter productivity

Solution: Hybrid PBR-HRAP systems using mixotrophic strains

- Challenge: High harvesting cost

  Solution: Use auto-flocculating algae like Tetraselmis and electro-coagulation

- Challenge: Contamination in HRAPs

  Solution: Introduce algicidal bacteria and keep pH above 9.5

- Challenge: Metal toxicity

  Solution: Select strains like Dunaliella that tolerate 100 ppm Cu

FUTURE INNOVATIONS

- Biofilm Reactors: Algae grown on rotating discs make harvesting ten times easier. [13]
- Nanobubble Technology: Improves O_2/CO_2 transfer for 30% faster growth.[10]
- CRISPR-Edited Strains: Chlamydomonas with extra phytochelatins for double the metal uptake.[11]

CONCLUSION

Microalgae-based treatment systems represent a significant advancement in sustainable cleanup. They use natural photosynthesis to transform pollutants like nitrogen, phosphorus, heavy metals, and carbon dioxide into useful biomass. Their processes, which include oxygen production, nutrient uptake, and absorption, enable energy-positive wastewater treatment without chemical additives. High-Rate Algal Ponds (HRAPs) and photobioreactors (PBRs) effectively remove contaminants, achieving 80 to 95% removal for nitrogen and phosphorus and 60 to 99% for metals. However, scaling up these systems encounters hurdles due to the costs of harvesting and the difficulty of optimizing the systems. The future relies on integration:

- Hybrid systems that bring together algal and bacterial groups to improve degradation rates.
- Circular models that convert biomass into biofuels and fertilizers, such as Spain's All-Gas project.
- CRISPR-modified strains that increase resilience and metal absorption.

To fully unlock the potential of microalgae, we need to focus on low-energy harvesting methods like electro-coagulation and auto-flocculation, along with AI-based reactor management. As climate and water issues grow, these photosynthetic systems will move from niche solutions to standard, carbon-negative infrastructure, turning waste into resources and changing how we care for the environment.

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