GREEN CHEMISTRY STRATEGIES FOR NATURE-BASED REMOVAL OF EMERGING POLLUTANTS

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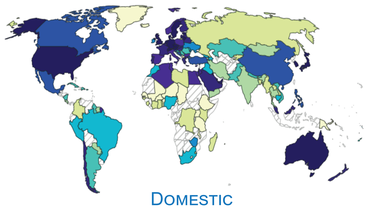
Introduction and aims

- Emerging pollutants (pesticides, dyes, heavy metals, pharmaceuticals) are increasingly detected in agricultural runoff and wastewater, posing ecological and health risks[1].
- Conventional treatment methods (chemical oxidation, adsorption, advanced filtration) are energy-intensive, expensive, and may generate toxic by-products[2,3].
- Microalgae-based bioremediation offers a nature-based, green chemistry strategy by coupling pollutant removal with biomass production[1,4].
- Microalgae possess unique metabolic pathways enabling bioaccumulation, degradation, or transformation of pollutants.
- Cultivation systems like raceway ponds and tubular photobioreactors provide scalable platforms for wastewater treatment.



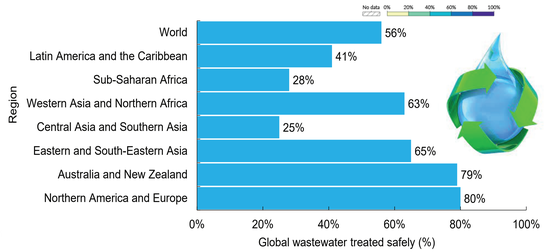


Fig 1: Global overview of wastewater treatment (WHO and UNICEF)[1].

Results and discussions

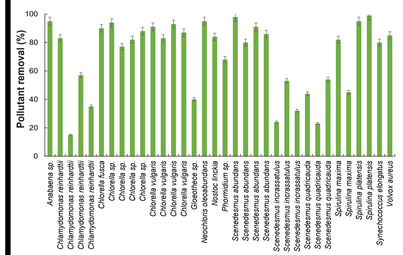


Fig 3: Microalgae strains isolated and overall pollutant removal (%)

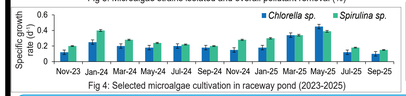


Fig 4: Selected microalgae cultivation in raceway pond (2023-2025)

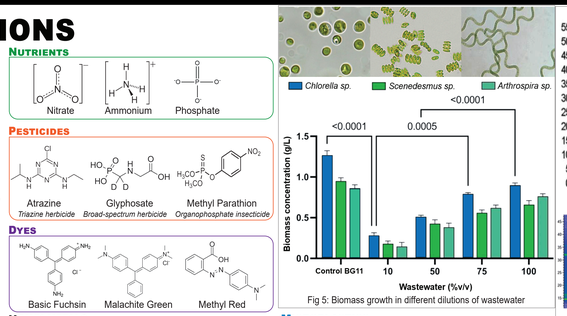


Fig 5: Biomass growth in different dilutions of wastewater

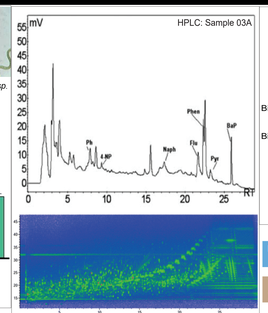


Fig 6: In-depth component analysis of wastewater

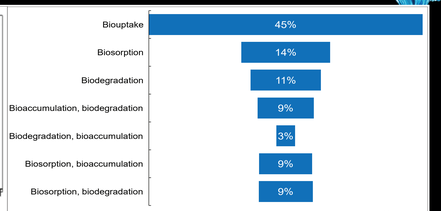
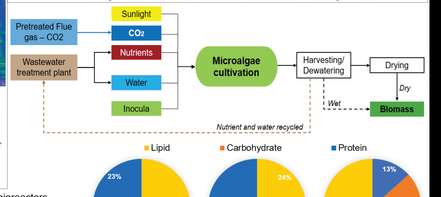
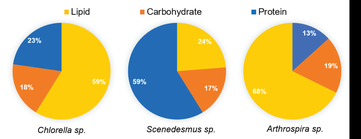


Fig 7: Assessment of bioremediation mechanisms in microlagae isolates[1,4]



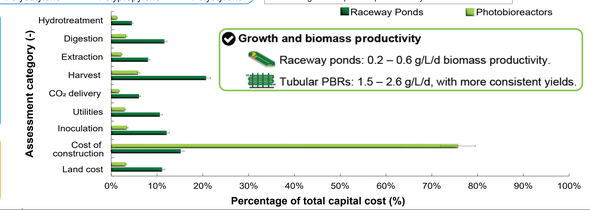


Pollutant removal efficiency

- **Nutrients:** Nitrate (70 – 90%), Phosphate (60 – 85%), Ammonium (65 – 80%).
- **Pesticides:** 65 – 85% removal (best with *Chlorella* and *Scenedesmus*).
- **Dyes:** Up to 83% removal in PBRs due to optimized light conditions.
- **Heavy metals:** 50 – 70% bioaccumulated; *Scenedesmus sp.* most effective.

System performance

- Raceway ponds performed better under nutrient-rich conditions with lower operational costs.
- PBRs achieved higher pollutant removal but required greater energy input.



Growth and biomass productivity

- Raceway ponds: 0.2 – 0.6 g/L/d biomass productivity.
- Tubular PBRs: 1.5 – 2.6 g/L/d, with more consistent yields.

Key points

- System trade-offs
- Strain specificity
- Circular bioeconomy potential
- Sustainability perspective

UN SDGs

3 Good health and well-being
6 Clean water and sanitation
12 Responsible consumption and production
13 Climate action
14 Life below water
15 Life on land

Methodology

Design of Experiments (DoE)

Cultivation systems

Raceway ponds: Open, paddlewheel-driven systems operated outdoors under natural light and temperature conditions.
Tubular photobioreactors: Closed, transparent tubular modules operated under controlled aeration and light–dark cycles.

Microalgae strain development: Isolated and screened from local water source and potent strains selected using high-throughput optimisation screening.

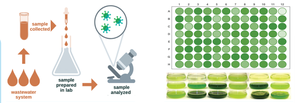
Water source: Agricultural runoff effluent, containing residual pesticides, synthetic dyes, and trace heavy metals, was used directly as growth medium (nutrients) with minimal pretreatment (ultrafiltration).

Analytical measurements

Growth and productivity: Measured via spectrophotometry, optical density (OD) at 750 nm and 680 nm, cell counts, and biomass dry weight.
Pollutant removal efficiency

- Pesticides: Quantified by High-Performance Liquid Chromatography (HPLC)².
- Synthetic dyes: Assessed via UV-Vis absorbance reduction.
- Heavy metals: Measured using Inductively Coupled Plasma Mass Spectrometry (ICP-MS)³.

Comparative assessment: Removal efficiencies (%) and biomass productivities were compared between systems. Data normalized to account for differences in cultivation volume and operational parameters.



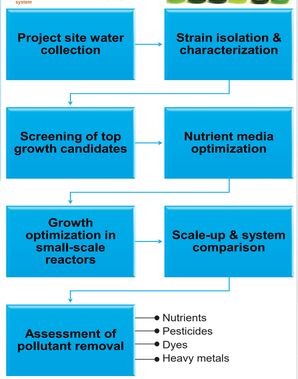
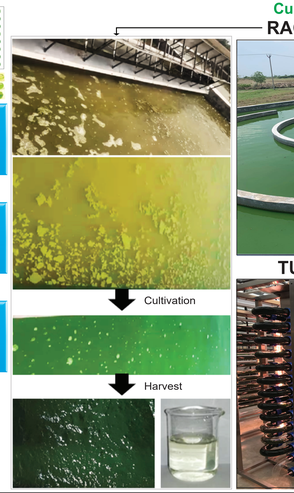


Fig 2: Process workflow



Merits
Low CapEx and OpEx
Large-scale feasibility
Sunlight-driven
Natural mixing and aeration
Co-cultivation friendly

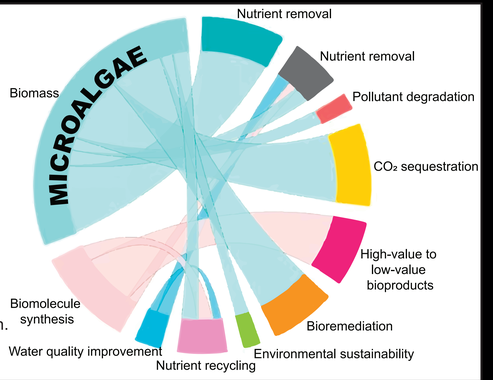
Demerits
Lower biomass productivity
Contamination risks
Evaporation losses
Light limitation
Seasonal variability

Merits
High remediation efficiency
Higher biomass productivity
Low contamination risk
Efficient CO_2 utilization
Precise control

Demerits
High CapEx and OpEx
Fouling issues
Scaling constrains
Limited scalability
Complex operation

Conclusions

- Microalgae efficiently removed pesticides, dyes, heavy metals, and nutrients from agricultural runoff.
- Raceway ponds: cost-effective and scalable.
  Tubular PBRs: higher removal efficiency and productivity.
- Demonstrates a green chemistry approach coupling wastewater remediation with biomass valorization.



Future directions

- Optimize strain-pollutant specificity for targeted remediation.
- Scale up hybrid systems combining open ponds and PBRs for efficiency and cost-effectiveness.
- Integrate with biorefineries for value-added products.
- Conduct long-term field trials using diverse effluent sources to validate industrial applicability.
- Explore microalgae-based nanoparticles for advanced pollutant removal.

References

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3. Stephan, S., Hippler, J., Köhler, T., Deeb, A.A., Schmidt, T.C. and Schmitz, O.J., 2016. Contaminant screening of wastewater with HPLC-IM-qTOF-MS and LC+ LC-IM-qTOF-MS using a CCS database. Analytical and bioanalytical chemistry, 408(24), pp.6545-6555.
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"From waste to worth, clean water, clean conscience. Clean water starts with clean choices, industry included."

A green path to sustainable sanitation.