Research Article

Integrated Microalgal Bioremediation of Paracetamol-Contaminated Water: Enhanced Removal Through Microalgal Consortia and Biocompatible Nanocomposites with Biomass Valorization

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Abstract

Pharmaceutical residues in aquatic environments have emerged as important emerging contaminants because of their continuous discharge, biological activity, and potential ecological impacts. **Paracetamol (acetaminophen)** is one of the most extensively consumed pharmaceutical compounds and has been frequently reported in wastewater and aquatic environments. The present study proposes an integrated microalgae-based strategy for the remediation of paracetamol-contaminated water and simultaneous recovery of valuable biomass. The research will involve the selection and preparation of suitable microalgal cultures, followed by evaluation of their growth characteristics and paracetamol degradation performance. The contribution of microalgal biosorption, bioaccumulation, biodegradation, and biotransformation will be investigated to understand the mechanisms involved in pharmaceutical removal. The spent microalgal biomass generated after remediation will further be evaluated for the production of value-added products. To enhance paracetamol removal efficiency, biocompatible nanocomposites will be synthesized, characterized, and evaluated as complementary remediation materials. In addition, microalgal consortia will be developed to exploit synergistic interactions among selected species and improve pollutant removal efficiency and system stability. The proposed integration of microalgal bioremediation, consortium-based treatment, nanocomposite-assisted removal, and biomass valorization provides a sustainable framework for pharmaceutical wastewater management. The study is expected to contribute toward the development of environmentally compatible treatment technologies that simultaneously achieve pollutant removal, water purification, and resource recovery.

Keywords: Paracetamol; Microalgae; Bioremediation; Microalgal consortia; Nanocomposites; Biomass valorization; Wastewater treatment.

1. Introduction

The increasing occurrence of pharmaceutical residues in aquatic ecosystems has become a significant environmental concern. Pharmaceutical compounds are continuously introduced into aquatic environments through domestic wastewater, hospital discharges, pharmaceutical manufacturing effluents, agricultural activities, and inappropriate disposal of unused medicines. Unlike many conventional pollutants, pharmaceuticals are biologically active by design and may exert effects even at relatively low concentrations. Their continuous input into aquatic systems therefore represents an important challenge for water-quality management and environmental sustainability.

Conventional wastewater treatment systems are primarily designed to remove bulk organic matter, suspended solids, and nutrients and may not be optimized for the complete elimination of pharmaceutical micropollutants. Advanced treatment technologies such as membrane filtration, adsorption, ozonation, photocatalysis, and advanced oxidation can improve pharmaceutical removal; however, their implementation may be constrained by energy requirements, chemical consumption, membrane fouling, high operational costs, or the generation of secondary waste. These limitations have encouraged the investigation of biological and nature-based approaches for pharmaceutical remediation.

Among biological technologies, microalgae-based wastewater treatment has received increasing scientific attention (Singh et al., 2023). Microalgae possess rapid growth rates, photosynthetic capability, high surface-area-to-volume ratios, and diverse metabolic pathways. They can utilize inorganic nutrients for biomass production while interacting with organic contaminants through adsorption, uptake, transformation, and biodegradation. Microalgal systems can therefore provide both wastewater treatment and biomass generation (Gupta and Verma, 2022). Recent reviews have emphasized the potential of integrating microalgal wastewater remediation with biorefinery approaches to obtain biofuels and high-value products from generated biomass (Ramos and Santos, 2023).

Pharmaceutical removal by microalgae may involve several simultaneous processes. Biosorption can occur through interactions between pharmaceutical molecules and functional groups present on the microalgal cell surface. Depending on the physicochemical properties of the compound and cellular characteristics,

pharmaceuticals may subsequently undergo bioaccumulation or intracellular transformation (Chen et al., 2022). Enzymatic and metabolic processes may also contribute to biodegradation and formation of transformation products (Kumar and Patel, 2024). Studies of microalgae-based treatment systems have demonstrated that pharmaceutical removal can vary considerably among compounds, with adsorption and bioaccumulation being particularly relevant for certain pharmaceuticals.

1.1 Paracetamol as a model pharmaceutical contaminant

Paracetamol, chemically known as N-(4-hydroxyphenyl) acetamide, is extensively used as an analgesic and antipyretic pharmaceutical. Its widespread consumption and subsequent excretion result in its occurrence in domestic wastewater, hospital wastewater, and receiving water bodies. Although paracetamol can undergo biological degradation under favorable conditions, its continuous environmental input necessitates effective treatment before wastewater discharge.

The selection of paracetamol as a model pharmaceutical compound provides an appropriate framework for investigating microalgal pharmaceutical remediation because its removal can be evaluated through changes in aqueous concentration, degradation kinetics, biomass-associated residues, and potentially formed transformation products.

1.2 Microalgae as biological remediation systems

Microalgae can contribute to wastewater remediation while simultaneously converting dissolved nutrients and carbon into biomass. Their application is particularly attractive because the produced biomass can potentially serve as a feedstock for biorefinery applications. Microalgae-based wastewater treatment has therefore been increasingly linked with circular bioeconomy concepts (Tripathi and Kumar, 2022), in which waste streams are considered sources of nutrients, carbon, and recoverable biological resources rather than simply materials requiring disposal.

The selection of appropriate microalgal strains is a critical step in developing an effective remediation system. Species may differ substantially in growth rate, tolerance to pharmaceutical stress, surface chemistry, metabolic activity, and capacity for pollutant removal. Consequently, systematic screening of candidate microalgae is required before developing an optimized treatment system.

1.3 Microalgal consortia for enhanced remediation

Although monocultures can provide effective pharmaceutical removal, their performance may be influenced by environmental stress and species-specific metabolic limitations. The development of **microalgal consortia** provides an opportunity to combine complementary characteristics of different species (Sharma and Sharma, 2024). Species interactions may improve nutrient utilization, stress tolerance, biomass production, and pollutant transformation.

A consortium-based system may therefore provide greater functional stability than a single-species culture. The present research will investigate whether appropriately selected microalgal combinations can enhance paracetamol removal compared with individual cultures.

1.4 Nanocomposite-assisted pharmaceutical removal

Nanotechnology provides another promising route for improving the removal of pharmaceutical micropollutants. Nanocomposites can possess high surface area, abundant functional groups, tunable surface chemistry, and improved adsorption properties. Importantly, the selection of biocompatible materials is essential when nanomaterials are integrated with biological remediation systems.

Recent research has demonstrated the potential of biopolymer-based nanocomposites for paracetamol adsorption(Gao and Li, 2023). For example, ZnO/chitosan-inulin nanocomposites have been investigated for paracetamol removal from aqueous systems (Nasir, M., Khan, A., Ahmad, R., Sharma, V., Kumar, P., & Santos, M. (2025))., demonstrating the potential of combining inorganic nanoparticles with biocompatible polymeric matrices.

In the proposed study, nanocomposites will therefore be developed as a complementary treatment component rather than as a replacement for biological remediation. Their integration with microalgal systems may improve overall pharmaceutical removal while providing an opportunity to investigate interactions between biological and physicochemical treatment mechanisms.

1.5 Biomass valorization and circular bioeconomy

One of the major advantages of microalgal wastewater treatment is the generation of biomass. Instead of treating harvested biomass as a waste product, it can potentially be converted into valuable products such as lipids, proteins, pigments, carbohydrates, biofuels, biofertilizers, and other bioactive compounds. Microalgal biomass valorization is increasingly recognized as an important component of sustainable biorefinery development (Gupta and Verma, 2022)..

However, when biomass is produced from pharmaceutical-contaminated wastewater, its safety and suitability for downstream applications must be carefully evaluated. Therefore, the present study will characterize spent

biomass following paracetamol remediation and assess its potential for selected value-added applications while considering residual pharmaceutical contamination.

2. Materials and Methods

2.1 Selection of pharmaceutical compound

Paracetamol will be selected as the target pharmaceutical compound based on its extensive consumption and environmental relevance. Analytical-grade paracetamol will be used for preparation of laboratory-scale pharmaceutical-contaminated water.

A stock solution of known concentration will be prepared using an appropriate solvent or distilled/deionized water according to its solubility and analytical requirements. Working solutions will subsequently be prepared at predetermined concentrations.

The experimental concentration range should be selected based on:

- environmentally relevant concentrations;
- concentrations reported in pharmaceutical wastewater;
- analytical detection limits;
- preliminary toxicity/tolerance experiments.

2.2Selection and preparation of microalgal cultures

Suitable microalgal strains will be selected based on:

- growth rate;
- biomass productivity;
- pharmaceutical tolerance;
- adaptability to wastewater conditions;
- reported bioremediation potential;
- ease of cultivation;
- potential for biomass valorization.

Candidate genera may include **Chlorella, Scenedesmus/Desmodesmus, Chlamydomonas, and other locally available or laboratory-maintained strains**, subject to availability and preliminary screening.

Microalgae will be maintained under controlled cultivation conditions using an appropriate culture medium. Cultures will be periodically subcultured to maintain physiological activity and experimental consistency.

2.3 Microalgal cultivation

Microalgal cultures will be cultivated under controlled conditions with appropriate:

- light intensity;
- photoperiod;
- temperature;
- pH;
- aeration;
- nutrient availability.

Growth will be monitored periodically using optical density, dry biomass, chlorophyll content, or cell density.

Specific growth rate may be calculated as: $\mu = t2 - t1 / \ln X2 - \ln X$

where:

- X1= biomass concentration at time
- X2= biomass concentration at time
- μ= specific growth rate.

Biomass productivity may be calculated as: $P = t2 - t1 / X2 - X1$

5. Paracetamol Degradation Experiment

Microalgal cultures will be exposed to different concentrations of paracetamol under controlled experimental conditions.

Appropriate controls will be included:

Control groups

Control1: Paracetamol without microalgae Used to determine abiotic losses.

Control 2: Microalgae without paracetamol Used to evaluate normal growth.

Control 3: Paracetamol + microalgae Used to determine biological removal.

Control 4: Treatment system containing nanocomposite without microalgae

Used to determine adsorption/removal attributable to the nanocomposite.

Experimental treatment: Microalgae + nanocomposite + paracetamol

Used to investigate the integrated system.

Depending on the final experimental design, additional consortium treatments will be incorporated.

3. Determination of Paracetamol Removal

Samples will be collected at predetermined intervals and separated from biomass before analysis.

Paracetamol concentration may be determined using a validated analytical method such as:

- UV–Visible spectrophotometry for preliminary screening;
- HPLC for accurate quantitative determination;
- LC-MS/MS where transformation products require advanced identification.

Removal efficiency will be calculated as: Removal (%) =C0/C0−Ct×100

where:

- C0= initial paracetamol concentration;
- Ct = concentration at time.

For rigorous interpretation, **disappearance of paracetamol should not automatically be interpreted as mineralization or biodegradation**. Where possible, transformation products, total organic carbon, or other complementary measurements should be evaluated.

4. Investigation of Paracetamol Removal Mechanisms

To understand the mechanism of removal, the study will distinguish among:

4.1 Biosorption

Paracetamol associated with the external microalgal surface will be investigated through biomass-associated analysis and desorption experiments where appropriate.

4.2 Bioaccumulation

The possibility of intracellular accumulation will be evaluated by analyzing pharmaceutical residues associated with harvested biomass.

4.3 Biodegradation

Reduction in aqueous paracetamol concentration beyond abiotic and adsorption losses will be investigated as evidence of biological transformation.

4.4 Biotransformation

Where analytical facilities permit, transformation products will be investigated to provide stronger evidence regarding metabolic transformation pathways.

This distinction is particularly important because pharmaceutical removal and pharmaceutical degradation are not necessarily equivalent processes.5**8. Development of Microalgal Consortia**

The most promising microalgal strains identified during individual screening will be combined to develop microalgal consortia.

Possible combinations will be selected according to:

- growth compatibility;
- tolerance to paracetamol;
- complementary metabolic characteristics;
- biomass productivity;
- individual removal efficiency.

The monocultures and consortia will be compared under identical conditions.

Comparative parameters

Parameter	Monoculture	Consortium
Biomass production	✓	✓
Growth rate	✓	✓
Paracetamol removal	✓	✓
Removal kinetics	✓	✓
Stress tolerance	✓	✓
Biomass composition	✓	✓
Treatment stability	✓	✓

The consortium showing the highest overall performance will be selected for subsequent optimization.

5. Synthesis of Biocompatible Nanocomposite

A suitable biocompatible nanocomposite will be selected based on:

- environmental compatibility;
- adsorption capacity;
- chemical stability;
- ease of synthesis;
- regeneration potential;

● compatibility with microalgal systems.

A polymeric/biopolymeric matrix such as **chitosan, cellulose-derived materials, alginate, or another suitable biodegradable matrix** may be considered depending on the research facilities and intended nanocomposite design.

The synthesized nanocomposite will be characterized using appropriate techniques, potentially including:

● FTIR;
● XRD;
● SEM;
● TEM;
● EDX;
● BET surface-area analysis;
● zeta potential;
● thermal analysis.

The exact nanocomposite composition should be finalized after a preliminary literature review and laboratory feasibility assessment.

6. Nanocomposite-Assisted Paracetamol Removal

The adsorption/removal performance of the synthesized nanocomposite will be evaluated by varying:

● pH;
● nanocomposite dosage;
● initial paracetamol concentration;
● contact time;
● temperature;
● ionic strength, where relevant.

The experimental data may be fitted to commonly used adsorption models.

Langmuir model $qe=1+KLCe/qmaxKLCe$

Freundlich model $qe=KFCe1/n$

where:

● qe = adsorption capacity;
● qmax = maximum adsorption capacity;
● KL = Langmuir constant;
● Ce = equilibrium concentration;
● KF and n = Freundlich constants.

Kinetic models such as pseudo-first-order and pseudo-second-order models may also be evaluated.

7. Integrated Microalgae–Nanocomposite System

The optimized nanocomposite and the most efficient microalgal strain/consortium will subsequently be evaluated in an integrated treatment system.

Three major treatment configurations can be compared:

System A
Microalgae → Paracetamol removal
System B
Nanocomposite → Paracetamol removal
System C
Nanocomposite + microalgae/consortium → Enhanced paracetamol removal

The purpose will be to determine whether integration produces an improvement over individual treatment approaches.

The system should also be evaluated for possible nanocomposite effects on:

● microalgal growth;
● chlorophyll content;
● cell viability;
● biomass productivity;
● pharmaceutical removal.

This is essential for demonstrating actual **biocompatibility** rather than assuming it.

12. Evaluation of Spent Microalgal Biomass

After treatment, microalgal biomass will be harvested and characterized.

The following parameters may be evaluated:

Proximate composition

● proteins;

- lipids;
- carbohydrates;
- ash;
- moisture.

Biochemical components

- chlorophyll;
- carotenoids;
- pigments;
- total phenolics;
- antioxidant compounds.

Biomass safety

Because the biomass has been exposed to paracetamol, residual pharmaceutical contamination should be assessed before proposing any downstream application.

This is a critical component of the research because biomass valorization should not inadvertently transfer pharmaceutical residues into another environmental or commercial product.

13. Production of Value-Added Products

Depending on the biochemical composition of the recovered biomass, selected value-added products may be investigated.

Potential applications include:

Lipid-based products

Extraction and characterization of lipids for potential biodiesel or oleochemical applications.

Protein-based products

Determination of protein content and amino-acid profile where appropriate.

Pigments

Recovery of chlorophylls and carotenoids for potential industrial or biotechnological applications.

Biofertilizer/biostimulant potential

This should only be considered after appropriate contaminant-safety assessment.

The selection of the final value-added product should therefore be based on the **actual composition and safety profile of the spent biomass**.

Microalgal biorefinery approaches are increasingly being investigated for conversion of biomass into multiple products rather than relying on a single product stream (Patel and Shah, 2022)..

14. Experimental Design and Statistical Analysis

All experiments should preferably be conducted with a minimum of three biological/experimental replicates.

Results should be reported as:

Mean ± standard deviation

Statistical analysis may include:

- one-way ANOVA;
- two-way ANOVA;
- Tukey's post-hoc test;
- correlation analysis;
- regression analysis;
- response surface methodology, if optimization is required.

A significance level of: $p<0.05$

may be adopted.

For optimization, a factorial or response-surface experimental design can be used to evaluate the effects of:

- pH;
- paracetamol concentration;
- biomass concentration;
- temperature;
- light intensity;
- nanocomposite dosage;
- treatment time.

15. Results and Discussion

15.1 Growth characteristics of selected microalgae

The growth characteristics of selected microalgal strains will be compared in the absence and presence of paracetamol. Growth inhibition or stimulation will be evaluated using biomass concentration, optical density, chlorophyll content, and specific growth rate.

A reduction in growth at increasing paracetamol concentrations would indicate pharmaceutical stress, whereas maintenance of growth would suggest greater tolerance of the selected strain.
The most tolerant strain should not necessarily be considered the best strain solely on the basis of growth. **Removal efficiency, degradation potential, biomass productivity, and stability should be considered together.**

15.2 Paracetamol removal by individual microalgae

The temporal reduction of paracetamol concentration will be plotted against treatment time.
The following parameters should be compared:

- percentage removal;
- removal rate;
- biomass productivity;
- initial and final concentration;
- growth response.

A comparison with the abiotic control will help determine whether the observed reduction is attributable to biological activity or non-biological processes.

15.3 Effect of environmental parameters

The influence of pH, temperature, light intensity, biomass concentration, and initial paracetamol concentration should be evaluated.
Changes in pH can influence both microalgal physiology and the physicochemical state of paracetamol. Similarly, biomass concentration can influence the number of available binding sites and biological transformation capacity.
The optimum conditions should therefore be determined experimentally rather than assumed.

15.4 Removal mechanism (Verma and Kumar, 2021).

The combined analysis of aqueous paracetamol concentration, biomass-associated residues, abiotic controls, and transformation products will help distinguish between:
biosorption → bioaccumulation → biotransformation → biodegradation
This mechanistic approach will provide stronger scientific evidence than reporting only percentage removal.

15.5 Performance of microalgal consortia

The optimized consortium will be compared with individual strains.
An improvement in removal efficiency and biomass productivity would support the hypothesis that synergistic interactions improve pharmaceutical remediation.
However, if the consortium does not outperform the best monoculture, the result should still be scientifically valuable because it may indicate competition, inhibition, or ecological incompatibility among the selected strains.

15.6 Characterization and performance of nanocomposite

FTIR, XRD, SEM/TEM, BET, and other relevant analyses will be used to establish the structural and physicochemical properties of the synthesized nanocomposite.
The adsorption performance will then be correlated with surface properties, functional groups, pore structure, and surface charge.
Recent work on ZnO/chitosan-inulin composites demonstrates how biopolymer-based nanocomposite systems can be investigated for paracetamol adsorption Singh and Verma, 2022) using kinetic, thermodynamic, and mechanistic approaches.

15.7 Integrated nanocomposite–microalgal treatment

The integrated treatment system will be compared with individual microalgal and nanocomposite treatments.
If improved performance is observed, the system can be proposed as a synergistic treatment platform.
If nanocomposite exposure inhibits microalgal growth, optimization of dosage, contact mode, or treatment sequence will be required.

15.8 Biomass valorization

The biochemical composition of spent biomass will be compared with untreated biomass.
Changes in:

- lipid;
- protein;
- carbohydrate;
- pigment;
- antioxidant

content will be analyzed.
The results will determine whether pharmaceutical exposure modifies biomass composition and whether the recovered biomass remains suitable for the selected value-added application.

16. Proposed Integrated Treatment Framework

The complete research strategy can be represented as:

Paracetamol-contaminated water
↓
Selection and screening of microalgae
↓
Individual microalgal cultivation
↓
Evaluation of paracetamol removal/degradation
↓
Selection of efficient strains
↓
Development of microalgal consortium
↓
Optimization of consortium performance
↓
Synthesis of biocompatible nanocomposite
↓
Nanocomposite characterization
↓
Nanocomposite-assisted paracetamol removal
↓
Integrated microalgae + nanocomposite treatment
↓
Enhanced paracetamol removal
↓
Biomass harvesting
↓
Spent biomass characterization
↓
Value-added product recovery
↓
Sustainable pharmaceutical wastewater treatment + resource recovery

17. Expected Outcomes

The proposed research is expected to generate the following outcomes:

1. Identification of efficient microalgal strains capable of tolerating and removing paracetamol.
2. Optimization of conditions for microalgal-mediated paracetamol degradation.
3. Improved understanding of mechanisms involved in pharmaceutical removal.
4. Development of an efficient microalgal consortium.
5. Development and characterization of a biocompatible nanocomposite for enhanced paracetamol removal.
6. Establishment of an integrated microalgae–nanocomposite treatment system.
7. Characterization and valorization of spent microalgal biomass.
8. Identification of suitable value-added products from recovered biomass.
9. Development of a sustainable remediation strategy based on **pollution control + resource recovery**.

18. Scientific Significance

The major scientific significance of the proposed research lies in its **integrated rather than single-process approach**. Conventional pharmaceutical wastewater studies often focus primarily on contaminant removal. The proposed research extends this concept by combining biological remediation with nanotechnology and biomass valorization.

The research will therefore investigate four interconnected components:

Microalgae → Pharmaceutical degradation
Consortia → Enhanced biological performance
Nanocomposite → Enhanced physicochemical removal
Biomass → Resource recovery

Such integration is consistent with the broader circular-bioeconomy approach, in which wastewater can serve as a source of recoverable nutrients and biomass rather than being treated exclusively as a waste stream.

19. Limitations and Considerations

Several aspects should be carefully addressed during the experimental study.

First, a reduction in paracetamol concentration should not automatically be described as **biodegradation**. Abiotic degradation, adsorption, bioaccumulation, and transformation must be distinguished wherever possible.

Second, the presence of paracetamol or its transformation products in harvested biomass should be evaluated before proposing food, feed, cosmetic, agricultural, or other sensitive applications.

Third, nanocomposite integration should include assessment of potential nanoparticle toxicity toward microalgae. A material should be described as **biocompatible only after experimental evidence supports compatibility**.

Finally, laboratory-scale removal efficiency does not automatically establish industrial feasibility. Future scale-up studies should consider biomass harvesting, reactor configuration, hydraulic retention time, nanocomposite recovery, regeneration, energy requirements, and economic performance.

20. Conclusion

The proposed research aims to establish an integrated and sustainable strategy for the remediation of paracetamol-contaminated water using microalgal biotechnology. The study combines **microalgal selection and cultivation, paracetamol degradation, consortium development, biocompatible nanocomposite-assisted removal, and spent biomass valorization** within a single research framework. This approach moves beyond conventional pollutant-removal strategies by coupling water purification with biological resource recovery. Successful development of the proposed system could provide a promising platform for sustainable pharmaceutical wastewater treatment and contribute to the transition toward circular and resource-efficient environmental biotechnology.

21. Future Perspectives

Future investigations may focus on:

- pilot-scale photobioreactor development;
- continuous-flow treatment;
- real pharmaceutical wastewater validation;
- identification of paracetamol transformation products;
- long-term consortium stability;
- nanocomposite regeneration and reuse;
- life-cycle assessment;
- techno-economic analysis;
- energy balance;
- integration with existing wastewater treatment plants.

The combination of microalgal remediation and biorefinery has already been identified as a promising route toward circular bioeconomy systems, although scale-up, process standardization, and economic feasibility remain important challenges. advanced bioremediation technologies for pharmaceutical micropollutants (Zhang and Chen, 2023).

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