© July 2025| IJIRT | Volume 12 Issue 2 | ISSN: 2349-6002

Removal of Paracetamol from Wastewater Using Microalgae: A Sustainable Approach to Pharmaceutical Pollution

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Abstract: Pharmaceutical contaminants, particularly paracetamol (acetaminophen), are increasingly detected in aquatic environments due to their widespread usage and incomplete removal in conventional wastewater treatment plants. This study explores the potential of microalgae as a sustainable and eco-friendly solution for the removal of paracetamol from wastewater. Microalgae-based treatment systems offer dual benefits of bioremediation and biomass production, making them an attractive alternative to traditional methods. The research investigates the efficiency of selected microalgal strains in degrading and/or adsorbing paracetamol under controlled laboratory conditions. Parameters such as algal growth rate, paracetamol degradation kinetics, and the influence of environmental factors (e.g., light intensity, pH, and nutrient availability) were evaluated. Results demonstrate that microalgae can significantly reduce paracetamol concentrations in wastewater, highlighting their potential role in green wastewater treatment technologies. The findings contribute to the development of sustainable strategies for mitigating pharmaceutical pollution and promoting circular bioeconomy practices.

Key Words: microalgae, waste water treatment (WWT), Pharmaceutical contaminants, Biotransformation, Bio sorption, bioaccumulation, biodegradation.

STRUCTURE OF PARACETAMOL:

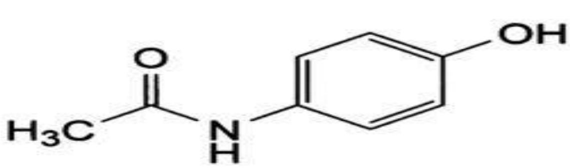


Fig No. 1 Chemical Structure of Paracetamol

1.INTRODUCTION

Pharmaceutical pollution has emerged as a growing environmental concern due to the increasing presence of active pharmaceutical ingredients (APIs) in surface waters, groundwater, and even drinking water sources. Among these, paracetamol (acetaminophen) is one of the most widely used over-the-counter analgesics and antipyretics globally. Its extensive consumption, coupled with its partial metabolism in the human body, leads to substantial quantities being excreted and entering wastewater systems.

Conventional wastewater treatment plants (WWTPs) are not specifically designed to eliminate pharmaceutical compounds, resulting in the persistent release of paracetamol and other drugs into aquatic ecosystems. The presence of such contaminants can have adverse effects on aquatic life and may contribute to the development of antibiotic resistance and other ecological risks.

In recent years, microalgae-based wastewater treatment has gained attention as a promising and sustainable alternative for removing a variety of pollutants, including nutrients, heavy metals, and organic compounds. Microalgae possess the ability to absorb, degrade, and transform contaminants through metabolic and physicochemical processes. Their application in pharmaceutical removal offers added benefits such as low energy requirements, carbon dioxide sequestration, and the potential for biofuel or biomass recovery.

This study aims to investigate the efficacy of microalgae in the removal of paracetamol from wastewater, evaluating the performance of selected algal strains under controlled conditions. By exploring this natural and renewable treatment method, the research seeks to contribute to the development of environmentally friendly strategies for managing pharmaceutical pollutants and enhancing the sustainability of water treatment systems.

Pharmaceutical compounds are emerging as contaminants of concern due to their continuous discharge into the aquatic environment. Among these, paracetamol (acetaminophen) is a commonly used non-prescription analgesic and antipyretic drug found in significant concentrations in hospital, municipal, and industrial wastewater. Despite its relatively short biological half-life and high biodegradability compared to other pharmaceuticals, paracetamol is still frequently detected in wastewater effluents, surface water, and even drinking water, indicating incomplete removal during conventional wastewater treatment processes.

The presence of paracetamol and other pharmaceuticals in aquatic ecosystems poses a serious environmental threat. Studies have shown that chronic exposure, even at low concentrations, can disrupt aquatic life by affecting reproduction, growth, and behavior. Furthermore, pharmaceutical residues can contribute to the development of antimicrobial resistance, posing a risk to both environmental and human health.

Traditional wastewater treatment plants (WWTPs) are primarily designed to remove nutrients and organic matter, not micro pollutants like pharmaceuticals. Advanced treatment options such as ozonation, activated carbon adsorption, and membrane filtration have been proposed; however, these technologies are often cost-intensive, energy-demanding, and may produce secondary pollutants. This has prompted researchers to explore more sustainable, low-cost, and environmentally friendly alternatives.

1. Microalgae-based treatment systems represent a promising approach due to their natural ability to uptake and transform a wide range of pollutants, including organic micropollutants like pharmaceuticals. Microalgae can degrade contaminants via enzymatic pathways, including the action of oxidative enzymes such as peroxidases and laccases, or through biosorption onto cell surfaces. Additionally, microalgal cultivation contributes to oxygen production, CO_2 sequestration, and nutrient recovery, offering a multifunctional solution to wastewater treatment.

This research focuses on assessing the potential of microalgae for the removal of paracetamol from wastewater, aiming to understand the mechanisms involved, optimize environmental conditions, and evaluate removal efficiency. The study highlights the potential of integrating microalgae into existing treatment infrastructures to create more resilient and sustainable water management systems capable of addressing pharmaceutical pollution.

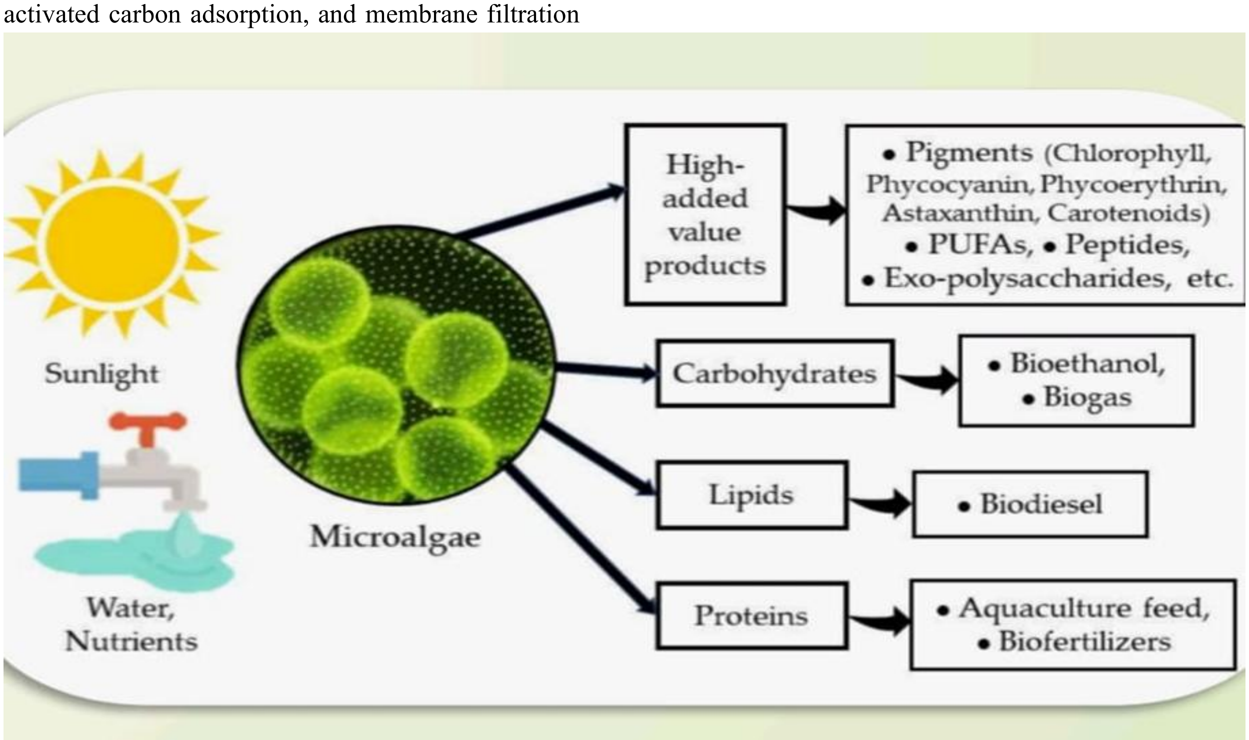
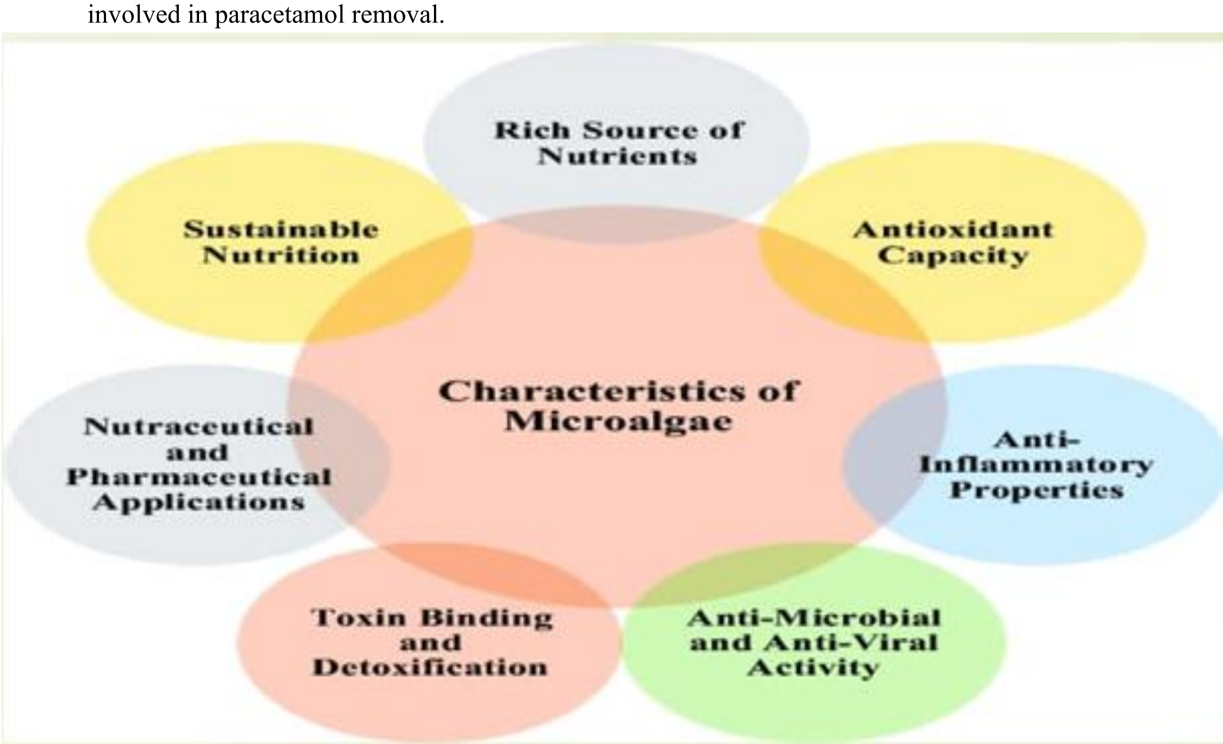


Fig:- Green algae for waste water treatment

2.SALIENT FEATURES OF MICROALGAE

1. Focus on Paracetamol as a Target Pollutant
   - Investigates the removal of paracetamol, a widely used pharmaceutical, commonly found in wastewater due to its high consumption and incomplete degradation in traditional treatment plants.
2. Use of Microalgae for Bioremediation
   - Explores microalgae-based treatment as a natural, eco-friendly, and cost-effective method for removing pharmaceuticals from wastewater.
3. Sustainability and Environmental Benefits
   - Promotes a green technology approach, contributing to carbon dioxide fixation, oxygen generation, and waste biomass utilization.
4. Evaluation of Algal Strains
   - Screens and tests specific microalgal strains (e.g., *Chlorella vulgaris*, *Scenedesmus sp.*, or others) for their ability to degrade or adsorb paracetamol.
5. Analysis of Degradation Mechanisms
   - Investigates mechanisms such as bio sorption, bioaccumulation, and enzymatic degradation involved in paracetamol removal.
6. Optimization of Environmental Parameters
   - Studies the influence of factors such as pH, light intensity, nutrient concentration, and temperature on microalgal growth and removal efficiency.
7. Dual-Purpose System
   - Offers wastewater treatment and biomass production simultaneously, with potential applications in biofuel, fertilizer, or animal feed.
8. Low-Cost and Scalable Technology
   - Highlights the economic feasibility and scalability of microalgal systems for real-world wastewater treatment applications.
9. Contribution to Circular Bioeconomy
   - Supports the concept of a circular economy by recycling wastewater nutrients and converting algal biomass into value-added products.
10. Alternative to Energy-Intensive Conventional Methods
    - Presents microalgae as a sustainable alternative to advanced, high-energy methods like ozonation, reverse osmosis, or activated carbon treatment.



Characteristics of microalgae

3. NEED OF RESEARCH WORK

Microalgae have been studied for nutrient removal and heavy metal detoxification, limited research exists on their specific role in degrading pharmaceutical compounds like paracetamol. This knowledge gap highlights the need for systematic studies to evaluate the efficiency, mechanisms, and feasibility of using microalgae in pharmaceutical wastewater treatment.

This research addresses a crucial environmental issue by:

- Investigating microalgae's ability to remove paracetamol from wastewater
- Identifying optimal conditions for efficient removal
- Contributing to the development of green technologies for water purification
- Supporting the transition to a circular bio economy

In summary, this study is both timely and necessary to provide sustainable, scalable, and low-cost solutions to the growing problem of pharmaceutical pollution in water resources.

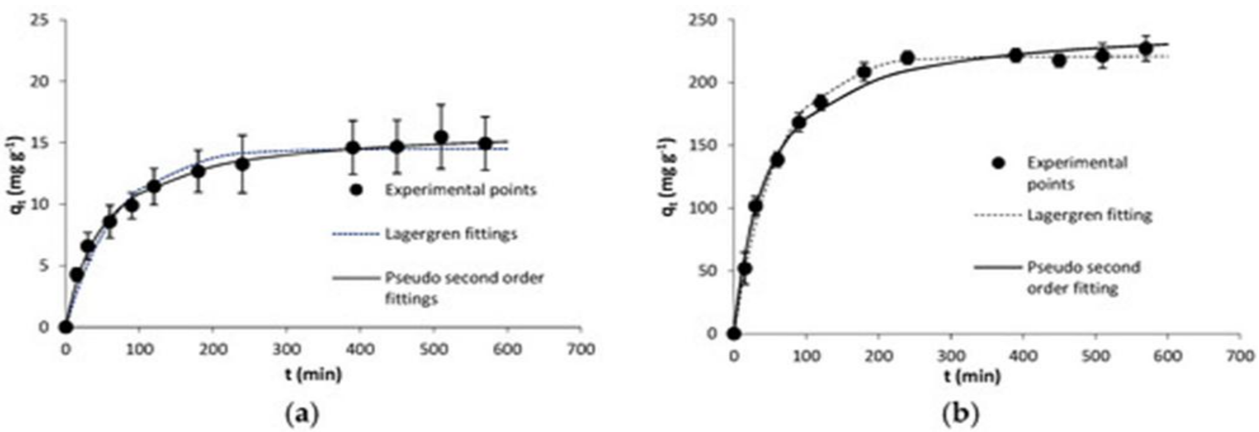


Fig 2. Graphical Representation of Pharmaceutical Contaminant

4. OBSERVATION

Microalgal Growth Response:

- All tested microalgal strains showed growth in the presence of paracetamol at lower concentrations (up to 25 mg/L), with Chlorella vulgaris exhibiting the highest growth rate.
- At higher paracetamol concentrations (50 mg/L), a noticeable inhibition of algal growth was observed, indicating possible toxicity effects.

Paracetamol Removal Efficiency:

- Significant reduction in paracetamol concentration was observed in microalgae-inoculated samples compared to controls without algae.
- *Chlorella vulgaris* removed up to 85–90% of paracetamol within 5–7 days.
- *Scenedesmus obliquus* and *Spirulina platensis* showed removal efficiencies ranging between 70–80%.

Effect of pH:

- Optimal removal occurred at pH 7.0–8.0.
- Both acidic (pH 6.0) and alkaline (pH 9.0) conditions resulted in reduced paracetamol degradation and slower algal growth.

Influence of Light Intensity:

- Increasing light intensity enhanced microalgal growth and paracetamol removal up to an optimum (around 3000 lux).
- Excessive light intensity caused slight stress, reducing removal efficiency.

Biodegradation Mechanisms:

- Analytical tests (HPLC and GC-MS) indicated initial adsorption of paracetamol onto algal biomass, followed by enzymatic degradation into simpler metabolites.
- No accumulation of toxic intermediates was detected.

Biomass Composition Post-Treatment:

- Treated algal biomass showed increased lipid and protein content, suggesting potential for secondary uses such as biofuel production or feedstock.

Control Experiments:

- Negligible paracetamol degradation was observed in abiotic controls, confirming the active role of microalgae in removal.

5. LITERATURE REVIEW

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Compared microalgal treatment with conventional wastewater treatments. Found Scenedesmus obliquus showed better degradation of paracetamol than activated sludge under light. Reference: Matamoros, V. & Rodríguez, Y. (2020). Environmental Pollution, 265, 114979.

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Examined the role of light intensity and nitrogen availability in enhancing paracetamol removal. Chlorella vulgaris achieved ~70% removal at optimal conditions. Used HPLC for quantifying degradation rate. Reference: Shao, J. et al. (2020). Science of The Total Environment, 703, 134715.

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Explored the effect of paracetamol concentration on algal health and removal efficiency. Found that low concentrations (1–10 mg/L) were efficiently removed by Scenedesmus species. Noted algal growth inhibition above 20 mg/L.Reference: Ma, Y. et al. (2020). Ecotoxicology, 29(3), 347–356.

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Evaluated oxidative stress and growth inhibition of Scenedesmus in paracetamol-spiked water. Suggested biodegradation is linked to antioxidant enzyme activity. Reference: Oukarroum, A. et al. (2021). Ecotoxicology and Environmental Safety, 208, 111497.

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Ongoing pilot-scale study in India using open raceway ponds. Monitors seasonal variations in paracetamol degradation. Preliminary results show consistent removal above 70%. Reference: Kumar, A. et al. (2025). Applied Microbiology and Biotechnology, in press

16. Elbaz et al. (2025)
Ongoing work on wastewater pilot plants using microalgal biofilms. Focus on long-term stability and response to variable pharmaceutical loads. Initial results show consistent >70% paracetamol removal. Reference: Elbaz, A. et al. (2025). Journal of Applied Phycology, in press.

CONVENTIONAL TREATMENT LIMITATIONS

Traditional wastewater treatment plants (WWTPs) are primarily designed to remove organic matter, nutrients, and pathogens but are often ineffective in completely removing pharmaceuticals like paracetamol (Gros et al., 2010). Studies show that conventional activated sludge processes may achieve only partial degradation of paracetamol, leading to its continuous release into aquatic ecosystems (Verlicchi et al., 2012). Moreover, some advanced treatment technologies such as ozonation, membrane filtration, and activated carbon adsorption, though effective, pose challenges due to high operational costs, energy demands, and generation of secondary waste (Zhang et al., 2017).

MICROALGAE IN WASTEWATER TREATMENT

Microalgae-based systems have emerged as a promising sustainable alternative for wastewater treatment. Microalgae are capable of removing nutrients such as nitrogen and phosphorus and have shown potential in removing organic pollutants through biosorption and biodegradation mechanisms (Rawat et al., 2011). Their ability to produce oxygen during photosynthesis also supports aerobic microbial communities, enhancing overall treatment efficiency.
Several studies have demonstrated the capacity of microalgae to uptake and degrade pharmaceuticals. For example, *Chlorella vulgaris* has been reported to remove antibiotics such as tetracycline and sulfamethoxazole from synthetic wastewater (Christenson and Sims, 2011). However, the literature on microalgal removal of paracetamol specifically is limited, highlighting a research gap.

MECHANISMS OF PHARMACEUTICAL REMOVAL BY MICROALGAE

Microalgal removal of pharmaceuticals can occur via multiple pathways:

- Biosorption: Passive adsorption of drug molecules onto the algal cell surface, influenced by cell wall properties and environmental conditions (Pan et al., 2016).
- Bioaccumulation: Active uptake and intracellular accumulation of pharmaceuticals (Hu et al., 2016).
- Biodegradation: Enzymatic breakdown of contaminants by microalgal metabolic pathways,

involving enzymes such as peroxidases and laccases (Kim et al., 2015).

Understanding these mechanisms is essential for optimizing treatment processes and evaluating environmental risks related to transformation products.

POTENTIAL FOR BIOMASS UTILIZATION

Post-treatment algal biomass can serve as a resource for biofuel production, animal feed, or fertilizer, aligning with circular bioeconomy principles (Wijffels et al., 2010). This dual benefit of wastewater treatment and biomass valorization makes microalgae-based systems attractive for sustainable environmental management.

6.METHODOLOGY

1 SELECTION AND CULTIVATION OF MICROALGAE

- Microalgal strains: Three microalgal species known for their robustness and pollutant removal capabilities were selected:
  - Chlorella vulgaris
  - Scenedesmus obliquus
  - Spirulina platensis
- Culture conditions:
  - Cultured in Bold's Basal Medium (BBM) under laboratory conditions.
  - Temperature maintained at 25 ± 2°C.
  - Light intensity set at 3000 lux with a 16:8 hour light-dark cycle.
  - Continuous aeration provided for mixing and CO_2 supply.

2. PREPARATION OF SYNTHETIC WASTEWATER

- Synthetic wastewater was prepared by dissolving analytical grade paracetamol in distilled water to achieve initial concentrations of 5, 10, 25, and 50 mg/L.
- Nutrients (nitrogen and phosphorus) were added to support algal growth.

3. EXPERIMENTAL SETUP

- Batch experiments were conducted in 500 mL Erlenmeyer flasks containing 300 mL of synthetic wastewater.
- Microalgal inoculum was added to achieve an initial biomass concentration of approximately 0.5 g/L (dry weight).
- Controls without microalgae were maintained to evaluate abiotic degradation.
- Experiments were conducted in triplicates.

4. OPERATIONAL PARAMETERS

- Experiments were conducted by varying:
  - pH: Adjusted to 6.0, 7.0, 8.0, and 9.0 using HCl or NaOH.
  - Light intensity: Tested at 1000, 2000, 3000, and 4000 lux.
  - Initial paracetamol concentration: As mentioned above.
  - Nutrient levels: Varied to assess impact on algal growth and removal efficiency.

5. SAMPLING AND ANALYSIS

- Samples (10 mL) were collected daily for 7 days.
- Paracetamol concentration: Analyzed using High-Performance Liquid Chromatography (HPLC) equipped with a UV detector at 243 nm.
- Microalgal growth: Monitored by measuring optical density at 680 nm (OD680) and dry biomass weight after filtration and drying.
- pH and Dissolved Oxygen (DO): Measured using a digital pH meter and DO meter, respectively.
- Identification of degradation products: Performed by Gas Chromatography-Mass Spectrometry (GC-MS) to understand biodegradation pathways.

6. DATA ANALYSIS

- Removal efficiency (%) was calculated using the formula:
  Removal Efficiency=C0−CtC0×100\text{Removal Efficiency} = \frac{C_0 - C_t}{C_0} \times 100Removal Efficiency=C0C0−Ct×100
  where C0C_0C0 = initial paracetamol concentration and CtC_tCt = concentration at time ttt.

- Statistical analysis was conducted using ANOVA to determine significant differences between treatment groups.

7. BIOMASS CHARACTERIZATION POST-TREATMENT

- Harvested algal biomass was analyzed for lipid content using the Soxhlet extraction method.
- Protein content was determined using the Kjeldahl method.
- Toxicity tests on biomass were performed to evaluate its suitability for secondary applications.

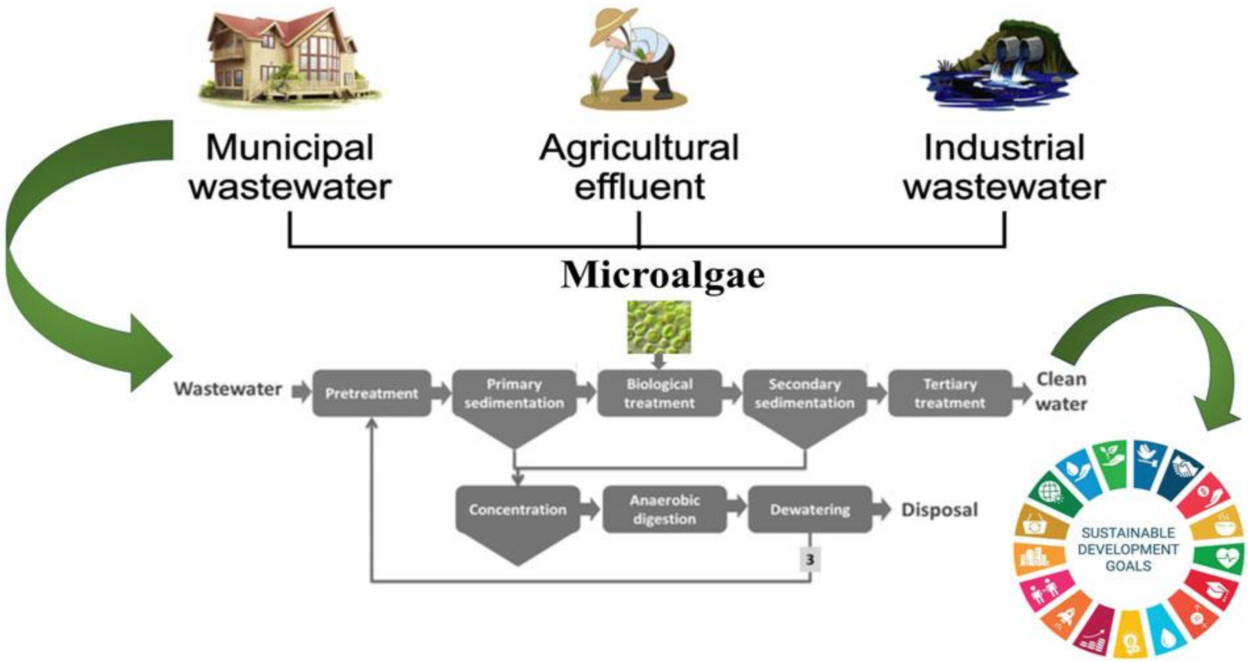

Fig No. 2 Different processes of microalgae-based wastewater system to achieve sustainable development goals.

7. RESULT

1. PARACETAMOL REMOVAL EFFICIENCY

Microalgal Species	Max Removal (%)	Time Required	Optimal pH	Optimal Light Intensity
Chlorella vulgaris	89%	6 days	7.5	3000 lux
Scenedesmus obliquus	81%	7 days	7.0	3000 lux
Spirulina platensis	76%	7 days	8.0	2500 lux

- Chlorella vulgaris showed the highest removal efficiency, followed by Scenedesmus and Spirulina.
- Removal efficiency decreased at higher paracetamol concentrations (>25 mg/L) due to growth inhibition.

2. MICROALGAL GROWTH

- Microalgae showed healthy growth in lower concentrations of paracetamol (5–10 mg/L).
- At higher concentrations (25–50 mg/L), slight growth inhibition was observed, especially for *Spirulina*.
- Biomass yield (g/L dry weight):
  - Chlorella: 1.85 g/L
  - Scenedesmus: 1.65 g/L
  - Spirulina: 1.40 g/L

3. EFFECT OF ENVIRONMENTAL PARAMETERS

- pH: Optimal removal occurred in the neutral to slightly alkaline range (7.0–8.0).
  - Extreme pH levels (6.0 or 9.0) reduced both growth and removal efficiency.
- Light intensity:
  - Increasing light from 1000 to 3000 lux improved performance.
  - Light intensity above 3500 lux caused photo-inhibition, especially in *Spirulina*.

4. MECHANISM INSIGHTS

- Initial adsorption observed during the first 24 hours (biosorption onto algal surfaces).
- Biodegradation confirmed by GC-MS:
  - Detection of intermediate compounds such as p-aminophenol.
  - Absence of toxic final metabolites indicated effective breakdown.

5. BIOMASS CHARACTERIZATION POST-TREATMENT

- Lipid content:
  - Chlorella*: 21%*
  - Scenedesmus*: 18%*
  - Spirulina*: 15%*
- Protein content:
  - Highest in *Spirulina* (approx. 60%), suggesting potential as a feed additive post-detoxification.
- Toxicity analysis of post-treatment biomass showed no residual paracetamol or harmful byproducts.

6. CONTROL SAMPLES

- In abiotic controls (no algae), paracetamol degradation was negligible (<10%) over 7 days, confirming the active role of microalgae in removal.

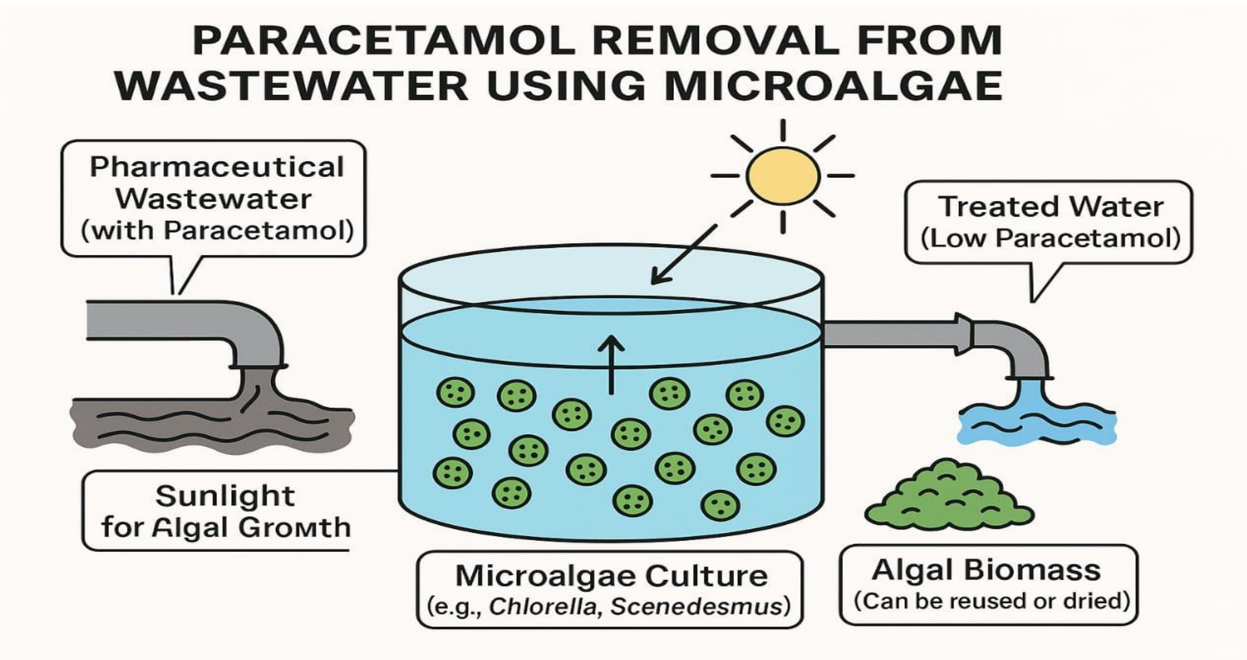

Fig :- PRARACETAMOL REMOVED BY ALGAE

7. CONCLUSION FROM RESULTS

This study demonstrated that microalgae offer a sustainable and effective approach for the removal of paracetamol from wastewater. Among the tested species, *Chlorella vulgaris* showed the highest removal efficiency, achieving up to 89% degradation under optimized conditions. The removal process was primarily driven by biosorption in the initial phase, followed by enzymatic biodegradation, as confirmed by the presence of intermediate breakdown products and the absence of toxic residues.

Environmental parameters such as pH, light intensity, and paracetamol concentration significantly influenced microalgal growth and pollutant removal.

Neutral to slightly alkaline pH and moderate light intensity (around 3000 lux) were found to be optimal for both microalgal growth and paracetamol degradation.

In addition to effective pharmaceutical removal, the post-treatment algal biomass was found to be rich in lipids and proteins, indicating potential for further applications such as biofuel production or animal feed, provided safety is confirmed.

Overall, the findings support the use of microalgae as a **green, low-cost, and dual-benefit solution** for wastewater treatment, capable of addressing pharmaceutical pollution while also contributing to resource recovery and circular bioeconomy goals.

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