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Advance Water Treatment Using Zeolite and Activated Carbon for The Removal of Iron and Manganese From Ground Water

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Abstract: *This study explores a sustainable wastewater treatment solution using microalgae species Chlorella vulgaris and Scenedesmus obliquus in an Inverse Fluidized Bed Reactor (IFBR). The system was designed to treat high-strength industrial effluent sourced from the Rourkela Steel Plant. Performance was assessed through BOD and COD reduction under both sterilized and non-sterilized conditions. Over a 7-day treatment cycle, the algae-IFBR system achieved up to 77.05% COD and 78.13% BOD removal in non-sterilized wastewater, indicating the synergistic potential of algae and native microbial communities. Microscopic analysis confirmed biofilm formation and species stability throughout the process. The findings validate the IFBR as a low-energy, scalable, and eco-efficient reactor configuration for decentralized industrial effluent treatment. The study contributes to circular economy goals through biomass valorization pathways including biofuel, fertilizer, and animal feed.*

Keywords*: Algae-based treatment, IFBR, Chlorella, Scenedesmus, COD, BOD, industrial effluent, biofilm, circular economy.*

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I. Introduction

The growing challenge of water pollution, driven by rapid industrialization, urban expansion, and population growth, has elevated the need for efficient and sustainable wastewater treatment solutions (Ghernaout, 2018). Industrial effluents, especially from steel, textile, and petrochemical sectors, are known for their high load of organic and inorganic pollutants, including heavy metals, nitrates, and phosphates, which severely degrade aquatic ecosystems if discharged untreated (Rawat et al., 2013). Conventional wastewater treatment technologies, such as activated sludge processes, trickling filters, and membrane bioreactors, have been widely adopted; however, these systems often suffer from limitations such as high energy consumption, excessive sludge production, and poor adaptability to fluctuating wastewater compositions (Christenson & Sims, 2011; Mehrabadi et al., 2016).

In response to these limitations, biological treatment methods using microalgae have gained prominence due to their ecological and economic advantages. Algae, particularly microalgae like *Chlorella vulgaris* and *Scenedesmus obliquus*, are photosynthetic microorganisms capable of uptaking nutrients such as nitrogen and phosphorus, reducing biochemical oxygen demand (BOD) and chemical oxygen demand (COD), and even sequestering heavy metals through mechanisms like biosorption and surface complexation (Prajapati et al., 2013; Khan et al., 2019). Moreover, algae produce oxygen through photosynthesis, enhancing aerobic degradation processes and reducing reliance on mechanical aeration (Kumar et al., 2010). Their cultivation also contributes to carbon dioxide fixation, biomass generation, and potential resource recovery in the form of biofuels, fertilizers, and animal feed—thus supporting the principles of the circular economy (Li et al., 2011; Rawat et al., 2013).

Despite their potential, conventional algal systems such as raceway ponds and photobioreactors encounter practical challenges including low biomass retention, susceptibility to contamination, light penetration issues, and harvesting difficulties (Christenson & Sims, 2011; Sengar et al., 2020). These constraints have prompted the exploration of alternative reactor configurations that facilitate better biomass retention, improved hydrodynamics, and enhanced light exposure. The Inverse Fluidized Bed Reactor (IFBR) emerges as an innovative solution in this context. In IFBRs, low-density polymeric media are fluidized downward against the upward flow of liquid, creating a stable and dynamic environment for biofilm development (Kumar & Trivedi, 2022). This unique hydrodynamic design minimizes biomass washout, increases contact time between biomass and wastewater, and supports continuous treatment under variable flow conditions.

Integrating microalgae with IFBR systems offers the combined benefits of enhanced pollutant removal and operational efficiency. Recent studies have demonstrated the potential of IFBRs in supporting stable biofilm formation, low energy consumption, and effective treatment of high-strength industrial wastewater (Jadhav & Ranade, 2023; Mishra et al., 2023). Additionally, the system allows for co-cultivation of different algal species, leveraging their synergistic capabilities to withstand environmental stress and improve pollutant degradation (Cheirsilp & Torpee, 2012; Gupta et al., 2021). However, comprehensive studies focusing on real industrial effluents, particularly from the steel industry, under both sterilized and non-sterilized conditions, remain limited.

This study addresses these research gaps by designing and evaluating an algae-based IFBR system for the treatment of effluent collected from the Rourkela Steel Plant. By employing *Chlorella vulgaris* and *Scenedesmus obliquus*, both individually and in combination, and assessing BOD and COD reduction across sterilized and non-sterilized wastewater, the study aims to investigate the practical viability and treatment efficiency of the proposed system. The integration of microalgal bioremediation with IFBR technology not only represents a sustainable alternative to energy-intensive conventional methods but also contributes to the global goals of water security, resource recovery, and environmental protection.

II. Materials and Methods

2.1 Algal Cultivation

The microalgal strains Chlorella vulgaris and Scenedesmus obliquus were selected for this study based on their demonstrated efficacy in nutrient uptake, adaptability to high-strength wastewater, and robust biofilm formation ability (Kumar et al., 2010; Gupta et al., 2021). The strains were initially cultured under controlled laboratory conditions in 250 mL Erlenmeyer flasks containing 100 mL of a synthetic nutrient medium.

The cultivation environment was optimized to support exponential algal growth and biofilm productivity. Cultures were incubated under a 14:10 hour light-dark photoperiod using white fluorescent lighting at an intensity of 3000–3500 lux, with temperature maintained at 27 ± 2°C. Aeration was provided through continuous bubbling using aquarium-grade air pumps, promoting gas exchange and preventing cell sedimentation.

The nutrient medium was prepared based on established protocols for freshwater microalgae (APHA, 2017), with macro- and micronutrients supporting algal metabolism, photosynthesis, and cell wall integrity. Table 1 outlines the complete composition of the medium used

Table 1: Composition of Nutrient Medium

Nutrient	Formula	Quantity (g/L)	Role
Urea	$CO(NH_2)_2$	0.50	Nitrogen source
KH_2PO_4	—	0.20	Phosphorus source
K_2HPO_4	—	0.20	Buffering & phosphorus
$MgSO_4 \cdot 7H_2O$	—	0.10	Chlorophyll formation
$CaCl_2$	—	0.05	Cell integrity
$FeCl_3$	—	0.01	Electron transport
$NaHCO_3$	—	0.20	Inorganic carbon source

The culture process lasted 30 days, and algal growth was monitored visually and through optical density (OD) at 680 nm. Microscopy was used periodically to ensure morphological integrity and absence of contamination. The culture was deemed ready for reactor inoculation when biomass concentration exceeded ~1.2 g/L dry weight. Figure 1 shows the algal growth progression from initial inoculation (a), through exponential phase (b), to dense biomass formation by Day 30 (c).

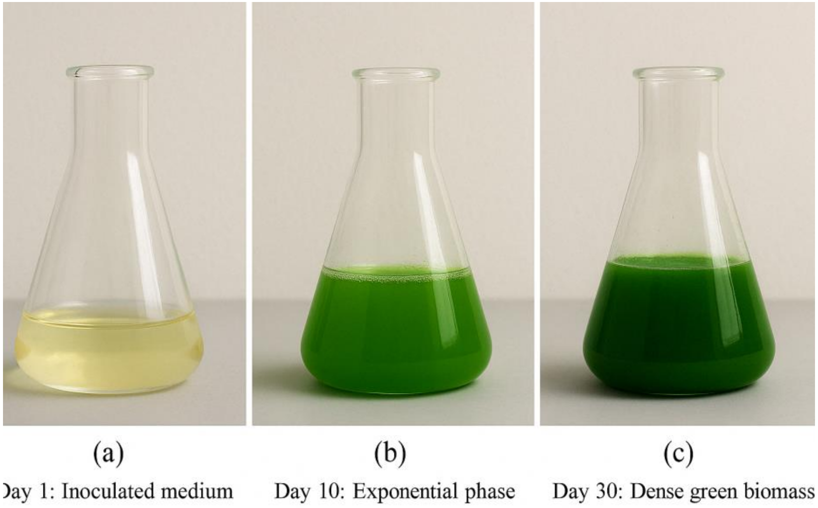

Figure 1: (a) Day 1: Inoculated medium, (b) Day 10: Exponential phase, (c) Day 30: Dense green biomass

2.2 Reactor Configuration

The Inverse Fluidized Bed Reactor (IFBR) used in this study was constructed using a transparent acrylic column measuring 45 cm in height and 8 cm in internal diameter to facilitate visual monitoring of flow behavior and biomass development. The reactor was packed with low-density polymer beads (specific gravity < 1 g/cm³), which served as carrier media for algal biofilm attachment and growth. These beads provided a large surface area and stable buoyancy to support inverse fluidization dynamics. Wastewater was introduced from the bottom and pumped upward using a peristaltic pump, creating an upward flow that fluidized the media in a downward motion—a distinct feature of inverse fluidization. A distributor plate ensured uniform flow across the column, and effluent was collected from the top outlet. The system operated in batch mode over a 7-day cycle, under continuous illumination and ambient temperature conditions, with provisions for sample collection at regular intervals to evaluate treatment performance.

2.3 Experimental Design

To evaluate the performance of the algae-based IFBR system, two experimental conditions were established using industrial wastewater collected from the Rourkela Steel Plant: one with sterilized effluent, in which indigenous microorganisms were eliminated through autoclaving, and the other with non-sterilized effluent, retaining the native microbial community. These two conditions were designed to compare treatment efficacy in controlled versus realistic microbial environments. Each wastewater condition was tested under three biological treatments: (i) monoculture of *Chlorella vulgaris*, (ii) monoculture of *Scenedesmus obliquus*, and (iii) a mixed culture of both species. This factorial design allowed for comparative analysis of species-specific and synergistic performance in pollutant removal. All experiments were conducted in triplicate, and key parameters including COD, BOD, and biofilm formation were monitored throughout the 7-day treatment period to assess the impact of culture type and microbial interaction on treatment efficiency.

2.4 Analytical Methods

BOD and COD were measured using APHA (2017) standard methods. Microscopy verified biofilm formation. COD was calculated via dichromate reflux titration using the formula:

$$\text{COD (mg/L)} = \frac{(A - B) \times N \times 8000}{V}$$

Where:

- A = FAS volume for blank
- B = FAS volume for sample
- N = Normality of FAS
- V = Sample volume (mL)

III. Results and Discussion

3.1 COD Reduction Performance

The efficiency of the Inverse Fluidized Bed Reactor (IFBR) system in reducing Chemical Oxygen Demand (COD) was assessed using non-sterilized industrial wastewater, which retained the native microbial community. The treatment was performed using a mixed culture of *Chlorella vulgaris* and *Scenedesmus obliquus*, and COD levels were monitored over a 7-day batch cycle. As shown in Table 2, the initial COD concentration of 610 mg/L progressively declined to 140 mg/L by the end of Day 7, representing a total reduction of 77.05%. This substantial decrease highlights the effective synergistic activity of the algal consortium in degrading both biodegradable and non-biodegradable organic compounds present in the effluent. Notably, the highest rate of COD reduction occurred between Day 1 and Day 3, indicating an active degradation phase supported by biofilm formation and photosynthetic oxygenation. The COD reduction trend is clearly visualized in Figure 2, which depicts a consistent downward trajectory, affirming the system's capability for continuous organic pollutant removal under realistic wastewater conditions.

Table 2: COD Removal in Non-Sterilized Wastewater

Day	COD (mg/L)	% Reduction
0	610	0%
1	490	19.67%
3	290	52.46%
5	185	69.67%
7	140	77.05%

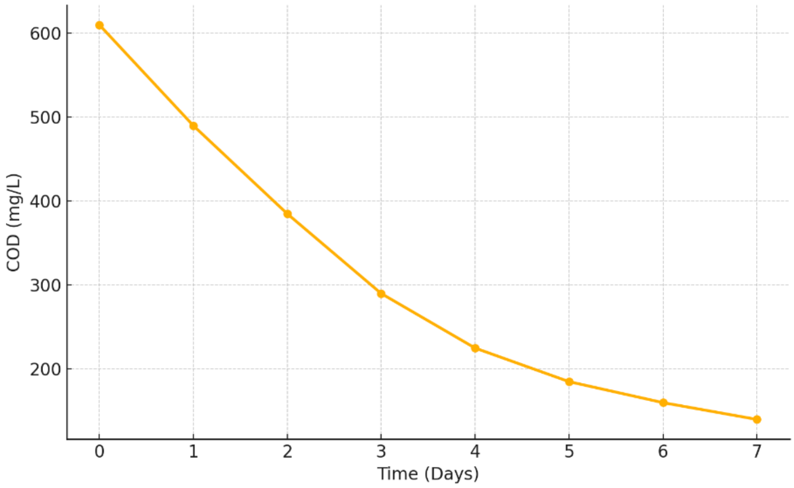

Figure 2: COD Reduction Over 7 Days

3.2 BOD Reduction Performance

Biochemical Oxygen Demand (BOD) serves as a critical indicator of the biodegradable organic load in wastewater. In this study, the algae-based IFBR system demonstrated significant BOD reduction, closely mirroring the COD removal trends. Starting with an initial BOD concentration of 320 mg/L, the system achieved a final value of 70 mg/L by the end of Day 7, corresponding to a total reduction of 78.13%. This high removal efficiency underscores the capacity of the mixed algal culture to effectively assimilate and metabolize biodegradable organics. The performance was particularly enhanced under non-sterilized conditions due to the collaborative metabolic activity between algae and indigenous bacteria. Among the treatments, the mixed culture consistently outperformed the individual monocultures of *Chlorella vulgaris* and *Scenedesmus obliquus*, indicating a synergistic interaction that facilitated superior pollutant degradation. These results validate the robustness of algal consortia in handling variable effluent characteristics and highlight their potential for large-scale application in decentralized wastewater treatment.

3.3 Microscopic Observation

Microscopic examination of the reactor media before and after the treatment period confirmed substantial biofilm formation by the algal cultures. The fluidized polymer beads provided a stable and expansive surface for algal colonization, which was visibly more pronounced in mixed culture treatments. Micrographs revealed densely packed, stable biofilms with healthy algal morphology, particularly in the non-sterilized effluent conditions. This suggests that the native microbial community may have complemented algal attachment and growth through beneficial interspecies interactions. The presence of a thick biofilm layer not only contributed to improved pollutant assimilation but also enhanced resistance against environmental fluctuations. Furthermore, the stability and coverage of the biofilm over the 7-day period ensured consistent treatment performance, reaffirming the suitability of IFBR systems for biofilm-based microalgal remediation strategies.

IV. Discussion

The results of this study clearly demonstrate the effectiveness of the algae-based Inverse Fluidized Bed Reactor (IFBR) system in treating high-strength industrial wastewater, with particular emphasis on Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD) reduction. The observed 77.05% reduction in COD and 78.13% reduction in BOD over a 7-day treatment cycle validate the reactor's capability to facilitate efficient organic pollutant removal under real-world conditions. These findings align with earlier studies by Khan et al. (2019) and Prajapati et al. (2013), which highlighted the capacity of microalgae to assimilate organic matter, support oxygen generation, and enhance biological degradation pathways.

One of the critical insights from this study is the superior performance of mixed algal cultures (*Chlorella vulgaris* and *Scenedesmus obliquus*) over monocultures. This is attributable to the complementary physiological traits of the species—*Chlorella* is efficient in nitrogen uptake and CO_2 fixation, while *Scenedesmus* excels in phosphate assimilation and structural stability under stress (Mehta et al., 2022; Gupta et al., 2021). The synergistic interaction between these species likely enhanced nutrient removal and biofilm robustness, a finding corroborated by Cheirsilp and Torpee (2012), who observed improved pollutant degradation in co-culture systems due to niche differentiation and mutualistic effects.

The successful application of the IFBR configuration also supports its viability as an innovative reactor design for biological wastewater treatment. Unlike traditional packed or suspended growth systems, the IFBR enables dynamic biofilm formation on low-density media, resulting in improved hydrodynamic control, reduced clogging, and stable biomass retention (Kumar & Trivedi, 2022). Furthermore, the fluidization behavior contributed to uniform light penetration and mass transfer—two critical factors influencing algal photosynthetic activity and pollutant assimilation (Grobbelaar, 2010). These operational advantages were particularly evident under non-sterilized conditions, where the presence of native microbial consortia did not inhibit algal performance, but rather enhanced it through possible microbial-algal symbiosis.

The comparative assessment between sterilized and non-sterilized setups highlighted the system’s robustness in real wastewater environments. Non-sterilized conditions yielded marginally higher pollutant removal efficiencies, likely due to additional enzymatic and metabolic pathways provided by indigenous heterotrophic bacteria (Zhou et al., 2018). This supports the notion that natural microbial communities, when paired with photoautotrophic algae, can create a resilient and diversified treatment consortium capable of degrading a broader spectrum of pollutants.

Microscopic analysis further confirmed stable biofilm attachment to the polymeric carriers throughout the experimental duration. Biofilm integrity is essential in IFBR systems to prevent biomass washout and ensure sustained pollutant removal (Wang et al., 2016). The visually dense and structured biofilms observed in mixed cultures substantiate the reactor’s operational stability and treatment reliability over time.

Overall, the study underscores the potential of algae-integrated IFBR systems as low-cost, energy-efficient, and environmentally friendly alternatives to conventional wastewater treatment methods. The integration of algae with inverse fluidization not only enhances treatment efficiency but also aligns with circular economy goals by enabling biomass valorization into biofuels, fertilizers, and other bioproducts (Li et al., 2011; Mehrabadi et al., 2016).

Despite the promising outcomes, the study also acknowledges certain limitations. The batch-mode operation and laboratory-scale setup may not fully replicate continuous flow and field-scale variability. Additionally, while COD and BOD were used as performance indicators, future studies should consider tracking nutrient profiles (N, P), heavy metals, and emerging contaminants for a more comprehensive treatment assessment.

V. Conclusion

This study successfully demonstrates the potential of an algae-based Inverse Fluidized Bed Reactor (IFBR) system as a sustainable and efficient technology for industrial wastewater treatment. The integration of *Chlorella vulgaris* and *Scenedesmus obliquus* into the IFBR configuration resulted in significant reductions of key pollution indicators—COD and BOD—achieving maximum removal efficiencies of 77.05% and 78.13%, respectively, within a 7-day treatment cycle. The mixed algal culture consistently outperformed individual monocultures, highlighting the benefits of species synergy in enhancing nutrient uptake and system resilience. The use of low-density polymer media enabled robust biofilm formation, ensuring stable biomass retention and continuous treatment performance. Moreover, the reactor operated effectively under both sterilized and non-sterilized conditions, demonstrating its adaptability to real-world wastewater scenarios. These findings affirm that algae-IFBR systems offer a low-energy, low-sludge, and resource-recoverable alternative to conventional treatment methods, making them particularly suitable for decentralized applications in industrial and resource-constrained regions. This research lays the foundation for future scale-up, techno-economic analysis, and integration with biomass valorization pathways, thereby contributing to the broader goals of environmental sustainability and circular economy.

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