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Optimization of Algal–Bacterial Biomass for Sustainable Treatment of Textile Industry Wastewater

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Abstract

Textile wastewater represents a major environmental challenge due to its high organic load, salinity, suspended solids, and resistance to conventional physico-chemical treatment processes, which are often energy-intensive and generate excessive secondary sludge. Integrated algal–bacterial consortia offer a sustainable alternative by coupling bacterial biodegradation with algal nutrient uptake and photosynthetic oxygen production. In this study, the treatment performance of algal, bacterial, and integrated algal–bacterial sludge systems was evaluated using real textile wastewater collected from the inlet of the effluent treatment plant at Quetta Textile Mills, Pakistan. Indigenous microalgal strains (Chlorella vulgaris and Scenedesmus) and a bacterial strain (Bacillus subtilis) were cultivated and applied under controlled laboratory conditions. Treatment efficiency was assessed at hydraulic retention times of 2, 4, 6, and 8 h by monitoring pH, chemical oxygen demand (COD), biological oxygen demand (BOD), total dissolved solids (TDS), and total suspended solids (TSS). Among all tested systems, the Chlorella vulgaris–Bacillus subtilis consortium exhibited the highest treatment efficiency, achieving approximately 95% overall pollutant removal within 8 h. COD and BOD were reduced from 1486 to 90 mg L^{-1} and 800 to 45 mg L^{-1}, respectively, while TDS and TSS decreased from 9000 to 1033 mg L^{-1} and 720 to 60 mg L^{-1}. The integrated system also demonstrated excellent sludge settleability, with a sludge volume index (SVI) of 30–35 mL g^{-1}, indicating efficient solid–liquid separation. The superior performance of the algal–bacterial consortium was attributed to synergistic interactions, where algal oxygen production enhanced aerobic bacterial degradation, while bacterial metabolism supplied CO_2 and nutrients to support algal growth. These findings highlight the potential of algal–bacterial sludge systems as an eco-friendly, energy-efficient, and rapid treatment strategy for high-strength textile wastewater, with strong applicability for industrial-scale wastewater management, reuse, and integration into circular bioeconomy frameworks.

Keywords: Textile wastewater, Scenedesmus, Bacillus subtilis, COD removal, BOD reduction, TDS and TSS removal.

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1. Introduction

The textile industry is one of the largest and most economically significant industrial sectors in Pakistan, contributing substantially to employment generation, export revenue, and overall economic development. Despite its socioeconomic importance, the textile sector is widely recognized as a major source of environmental pollution due to extensive water consumption and the intensive use of chemicals during processing operations. Textile manufacturing processes, including scouring, bleaching, dyeing, printing, and finishing, generate large volumes of wastewater characterized by complex and hazardous chemical compositions. It has been reported that textile processing units in Pakistan collectively discharge approximately 114,411.67 m^3 of wastewater per day, much of which remains untreated or inadequately treated before disposal (Nowruzi et al., 2023).

In many developing regions, including Pakistan, insufficient wastewater treatment infrastructure and weak enforcement of environmental regulations have resulted in the widespread discharge of untreated or partially treated textile effluents into natural water bodies or their reuse for irrigation in peri-urban agricultural areas. Such practices pose serious environmental and public health risks, as textile wastewater typically exhibits high biological oxygen demand (BOD), chemical oxygen demand (COD), total dissolved solids (TDS), total suspended solids (TSS), and elevated concentrations of toxic organic and inorganic contaminants (Pancha, 2023). Water pollution arising from industrial discharges alters the physical, chemical, and biological properties of aquatic systems, leading to ecosystem degradation, loss of biodiversity, and increased risks to human health (Fidiastuti et al., 2020; Wang et al., 2025).

Anthropogenic activities, particularly the discharge of untreated domestic sewage and industrial effluents, represent one of the primary drivers of water quality deterioration in developing countries. While domestic wastewater introduces pathogens, nutrients, and organic matter, industrial effluents—especially from textile operations—contain complex mixtures of dyes, surfactants, salts, heavy metals, and oxidizing and reducing agents that severely compromise water quality (Liu & Hong, 2021; Calijuri et al., 2025). Globally, nearly 70% of dyes used in the textile industry belong to azo and anthraquinone classes, which are known for their chemical stability, high toxicity, and resistance to biodegradation (Xu et al., 2024). The presence of heavy metals as dye-fixing or solubilizing agents further exacerbates the toxicity of textile effluents (El-Sheekh et al., 2025).

Conventional wastewater treatment technologies, including physico-chemical methods and activated sludge systems, are commonly employed to treat textile effluents. However, these methods suffer from several limitations, such as high operational and energy costs, excessive chemical consumption, generation of large quantities of secondary sludge, and vulnerability to shock loads of toxic compounds. In activated sludge systems, aeration alone accounts for approximately 50–75% of total energy consumption, making these processes economically and environmentally unsustainable for high-strength industrial effluents (Kumar et al., 2023). Moreover, operational instability and inconsistent treatment efficiency under variable wastewater compositions further limit their effectiveness (Hasanath et al., 2025). These constraints highlight the urgent need for alternative treatment strategies that are both energy-efficient and environmentally sustainable (Zabochnicka, 2022).

In recent years, microalgae-based wastewater treatment systems have gained increasing attention as a promising alternative to conventional technologies. In natural aquatic ecosystems, microalgae and bacteria coexist in symbiotic relationships that enhance nutrient cycling and organic matter degradation (Sathinathan et al., 2023). Engineered algal–bacterial consortia exploit this natural synergy by integrating bacterial biodegradation of organic pollutants with algal nutrient uptake and photosynthetic oxygen production. This interaction reduces the need for external aeration while simultaneously improving treatment efficiency (Sátiro et al., 2022). High-rate algal ponds (HRAPs) and algal sludge systems have been proposed as scalable, low-energy solutions capable of removing organic matter, nutrients, and suspended solids from industrial wastewater streams (Malik et al., 2022).

Beyond wastewater remediation, microalgal biomass generated during treatment offers additional benefits, including potential utilization for biofuels, biofertilizers, and other value-added products, thereby supporting circular bioeconomy and resource recovery frameworks (Kusmayadi et al., 2020; Ummalyma et al., 2021). However, challenges associated with biomass harvesting, particularly high energy demands and low separation efficiency, remain significant barriers to large-scale implementation (Nagi et al., 2020). To address these limitations, alternative strategies such as bioflocculation, algal–bacterial aggregation, and sludge-based systems have been proposed to enhance biomass settleability and reduce harvesting costs (Xu et al., 2024).

Despite the growing body of research on microalgae-based wastewater treatment, limited studies have systematically evaluated integrated algal–bacterial sludge systems for the treatment of real textile wastewater under controlled laboratory conditions, particularly in developing country contexts. Moreover, comparative assessments of individual algal, bacterial, and combined consortia across short hydraulic retention times, along with evaluations of sludge settleability and system stability, remain insufficiently explored.

Therefore, the present study was designed to develop and evaluate an integrated algal–bacterial sludge system for the sustainable treatment of high-strength textile wastewater. The specific objectives were to:

1. Isolate and cultivate indigenous microalgal (Chlorella vulgaris and Scenedesmus) and bacterial (Bacillus subtilis) strains;
2. Evaluate the treatment performance of individual and combined sludge systems across key physicochemical parameters (pH, COD, BOD, TDS, and TSS) at different hydraulic retention times; and
3. Assess sludge settling characteristics and system efficiency to determine the feasibility of algal–bacterial consortia as an eco-friendly, energy-efficient alternative for industrial textile wastewater treatment.

2. Materials and Methods

2.1 Study Area

All laboratory experiments were conducted at the Balochistan University of Information Technology, Engineering and Management Sciences (BUITEMS), Airport Road, Quetta, Balochistan, Pakistan.

2.2 Algae Collection

Algal samples were collected from Quetta Textile Mills, located in the provincial capital of Balochistan, Pakistan. The samples were transported to the laboratory and stored at temperatures below 4 °C to prevent changes in their chemical and biological characteristics. The stored samples were subsequently used for isolation, cultivation, and experimental analysis.

2.3 Collection of Wastewater Sample

Wastewater samples were collected from the equalization tank of Quetta Textile Mills Limited, Quetta. Sample collection was carried out with the assistance of staff from the Environmental Protection Agency (EPA). The collected samples were transported to the laboratory under controlled conditions and subjected to physicochemical analysis before treatment experiments.

2.4 Analytical Procedures

Wastewater samples were analyzed for colour, pH, electrical conductivity (EC), biological oxygen demand (BOD), chemical oxygen demand (COD), total dissolved solids (TDS), and total suspended solids (TSS). Standard laboratory procedures were followed for all analyses.

2.4.1 pH

The pH of wastewater samples was measured using a calibrated digital pH meter. Calibration was performed using standard buffer solutions of pH 4, 7, and 10. The electrode was rinsed with distilled water, immersed in the sample, and the pH value was recorded after stabilization.

2.4.2 Electrical Conductivity

Electrical conductivity was measured using a conductivity meter (Jenvey EC Meter, Model-4070). Readings were recorded at 25 °C and expressed as dS m^{-1}, equivalent to mmhos cm^{-1}.

2.4.3 Biological Oxygen Demand (BOD)

BOD was determined by measuring dissolved oxygen (DO) concentrations before and after incubation at 20 °C for 5 days. Samples were diluted with distilled water, and pH was adjusted to neutrality (6.5–7.5). Nutrient solutions ($CaCl_2$, $FeCl_3$, buffer solution, and sulphate) were added at 1 mL L^{-1}. Two sets of 300 mL BOD bottles were prepared. One set was analyzed immediately for initial DO (D_0), while the other was incubated for five days to measure final DO (D_5). BOD was calculated using the following equation:

$$\mathrm{BOD5(mg\ L-1)} = (\mathrm{D0} - \mathrm{D5}) \times \text{Dilution factor}$$

Where;

D_0=Initial dissolved oxygen (mg L^{-1})

D_5 = Dissolved oxygen after 5 days (mg L^{-1})

2.4.4 Chemical Oxygen Demand (COD)

COD was determined using the dichromate reflux method. A 20 mL wastewater sample was mixed with 10 mL potassium dichromate solution, followed by the addition of silver sulphate and mercuric sulphate. Sulfuric acid (30 mL) was added, and the mixture was refluxed using a Liebig condenser. After cooling, the solution was titrated with ferrous ammonium sulphate using ferroin indicator until the colour changed from blue-green to reddish-brown. A blank was run using distilled water. COD was calculated as:

$$\mathrm{COD(mg\ L-1)} = \mathrm{(mL)(B - T)} \times \mathrm{N} \times 1000 \times 8/\text{Sample volume}$$

Where;

B = Titrant volume for blank (mL)

T = Titrant volume for sample (mL)

N = Normality of titrant

2.4.5 Total Dissolved Solids (TDS)

TDS was measured by filtering a well-mixed wastewater sample through a pre-weighed glass fibre filter. The filtrate was evaporated to dryness at 180 °C, and the residue was weighed. TDS was calculated using:

$$TDS(mg\ L-1) = (TDSa - TDSb) \times 1000/\ \text{Sample volume (mL)}$$

Where;

TDS_a = Weight of dish + residue (mg)

TDS_β = Weight of empty dish (mg)

2.4.6 Total Suspended Solids (TSS)

TSS was determined by drying a pre-weighed filter paper and aluminum dish at 105 °C until a constant weight was achieved. A measured volume of wastewater was filtered, and the retained solids were dried and weighed. TSS was calculated using:

$$TSS(mg\ L-1) = (TSSA - TSSB) \times 1000/\ \text{Sample volume (mL)}$$

Where;

TSS_a = Weight of dish + filter + residue (mg)

TSS_β = Weight of dish + filter (mg)

2.5 Isolation and Microscopic Identification of Algal Strains

Isolation of Chlorella spp. was carried out using serial dilution techniques. Following 3-4 successive dilutions, morphologically similar cells were inoculated into flasks. Cell density was monitored using a hemocytometer. Identification was performed based on microscopic examination. Enriched cultures were transferred to 10 L containers for further growth, and cell counts were recorded daily.

2.6 Culture Medium for Algal Production

Algal cultures were grown using BG-11 medium, prepared from stock solutions according to standard formulation. Stock solution 1 was added at 100 mL L^{-1}, stock solutions 2–8 at 10 mL L^{-1} each, and stock solution 9 at 1 mL L^{-1}. For 5 L of working medium, the appropriate volumes of stock solutions were mixed and adjusted to the final volume with distilled water.

2.7 Algal Growth in Plastic Cans

Growth performance of Chlorella vulgaris was evaluated at four pH levels (6.5, 7.0, 7.8, and 8.0). Cell counts were performed every 24 hours using a microscope at 100× magnification. After 23–26 days, stable biomass was harvested through centrifugation, washed with double-distilled water, sun-dried for 72 hours, and stored for further use. Continuous aeration and illumination were provided using an aquarium pump and LED lights.

2.8 Retention Time of Sludge

Treatment efficiency of algal sludge, bacterial sludge, and combined algal–bacterial sludge was evaluated at retention times of 2, 4, 6, and 8 hours. Parameters including pH, COD, BOD, TDS, and TSS were analyzed at each interval.

2.9 Sludge Preparation

Nitrogen and phosphate fertilizers were added at concentrations of 100 mg L^{-1} and 50 mg L^{-1}, respectively, to promote sludge development. Sludge formation occurred over 15 days with a settling period of 30 minutes. Aeration was continuously supplied, and dissolved oxygen levels were monitored at 8-hour intervals.

2.10 Sludge Volume Index (SVI)

SVI was used to assess sludge settling characteristics. It was calculated as the volume (mL) occupied by 1 g of sludge after 30 minutes of settling:

$$SVI = \text{Settled sludge volume } (mL\ L-1) \times 1000/\ MLSS\ (mg\ L-1)$$

2.11 Statistical Analysis

All experimental results were statistically analyzed using MINITAB software to evaluate data variability and treatment performance.

3. Results

3.1 Initial Characteristics of Textile Wastewater

The untreated textile wastewater collected from the equalization tank of

Quetta Textile Mills (Pvt) Ltd., Quetta, exhibited poor physicochemical quality, indicating severe pollution potential. The effluent was strongly alkaline with an initial pH of 8.7, reflecting the extensive use of alkaline chemicals during scouring, bleaching, and dyeing processes.

The biological oxygen demand (BOD) and chemical oxygen demand (COD) were high, measured at 680 mg L^{-1} and 1409 mg L^{-1}, respectively, indicating the presence of substantial biodegradable and non-biodegradable organic compounds. The total dissolved solids (TDS) and total suspended solids (TSS) were also elevated at 4500 mg L^{-1} and 9000 mg L^{-1}, reflecting the high content of salts, dyes, fibres, and particulate matter.

All measured parameters exceeded the Balochistan Environmental Protection Agency (BEPA) discharge limits. These results emphasize that direct disposal of untreated wastewater would have serious environmental impacts, including oxygen depletion in receiving waters, soil salinization, and toxicity to aquatic organisms. Therefore, effective treatment is required before discharge or reuse.

3.2 Algal Strains Growth Behaviour at various pH levels.

The growth of Chlorella vulgaris was measured using the concluding absorbance value of the suspension at 685nm mentioned earlier in the report.

3.2.1. Growth Response of Chlorella vulgaris

The growth of Chlorella vulgaris was monitored using absorbance at 685 nm. pH strongly influenced growth performance.

At acidic to near-neutral pH (6.5 and 7.0), algal growth was minimal, with cell densities stabilizing at ~13 × 10^4 cells mL^{-1}, indicating suboptimal metabolic activity. Conversely, mildly alkaline conditions promoted rapid exponential growth. At pH 7.8, cell density increased from 15 × 10^4 to 28 × 10^4 cells mL^{-1} by day 23, followed by a stationary phase likely due to nutrient limitation and self-shading. At pH 8.0, the growth pattern was similar, but the maximum cell density was slightly lower than at pH 7.8. Overall, pH 7.8 was determined to be optimal for maximum biomass production and stability.

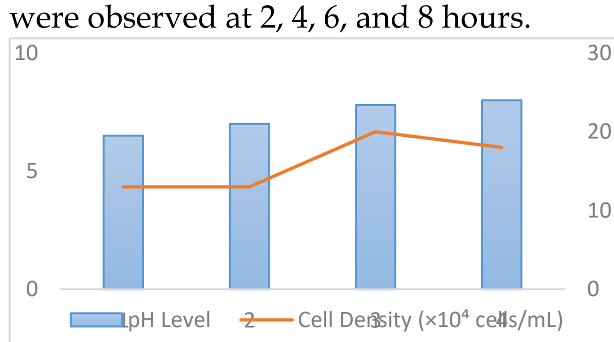
3.2.2 Growth Response of Scenedesmus

Scenedesmus exhibited a similar growth trend over six weeks. Growth was limited at pH 6.5 and 7.0 (~13 × 10^4 cells mL^{-1}), while significant exponential growth occurred at pH 7.8 and 8.0. The maximum biomass was recorded at pH 7.8, reaching 20 × 10^4 cells mL^{-1} on day 26, after which growth plateaued. Although Scenedesmus reached lower maximum cell densities than Chlorella vulgaris, it demonstrated effective growth under slightly alkaline conditions, aligning with the natural pH of textile wastewater.

3.3 Performance of Individual Sludge Systems

3.3.1 Treatment Efficiency of Bacillus subtilis Activated Sludge

Treatment efficiency increased with hydraulic retention time. Progressive decreases in pH, COD, BOD, TDS, and TSS were observed at 2, 4, 6, and 8 hours.



1. At 2 and 4 hours, pollutant removal was moderate, reflecting the initial microbial acclimation.
2. At 6 hours, the removal efficiency increased significantly.

3. Maximum performance was achieved at 8 hours, with effluent parameters approaching NEQS discharge limits, demonstrating effective biodegradation and pollutant uptake by Bacillus subtilis.

3.3.2 Treatment Efficiency of Chlorella vulgaris Activated Sludge

The Chlorella vulgaris sludge system also demonstrated effective pollutant removal.

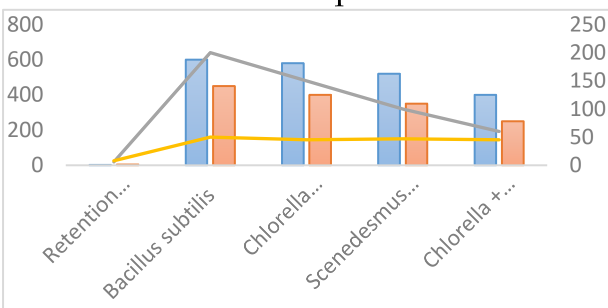


Figure 3.3.1: COD Reduction by Different Sludge Systems

1. Initial reductions at 2–4 hours were mainly due to nutrient uptake and biosorption.
2. Significant decreases in BOD, COD, TDS, and TSS were observed at 6 and 8 hours, attributed to active nutrient assimilation, bioflocculation, and sedimentation.
3. After 8 hours, effluent quality improved considerably, confirming the ability of Chlorella vulgaris to treat high-strength textile wastewater under controlled conditions, even without bacterial augmentation.

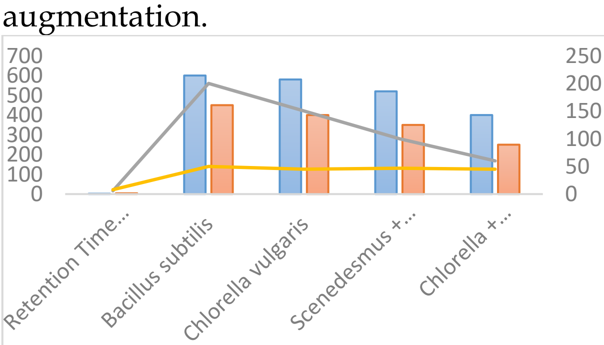


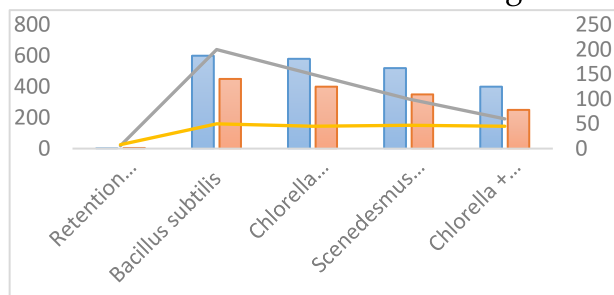
Figure 3.3.2: BOD Reduction by Different Sludge Systems

3.4 Performance of Algal–Bacterial Consortia

3.4.1 Scenedesmus + Bacillus subtilis

The algal-bacterial consortium of Scenedesmus and Bacillus subtilis performed better than the individual systems.

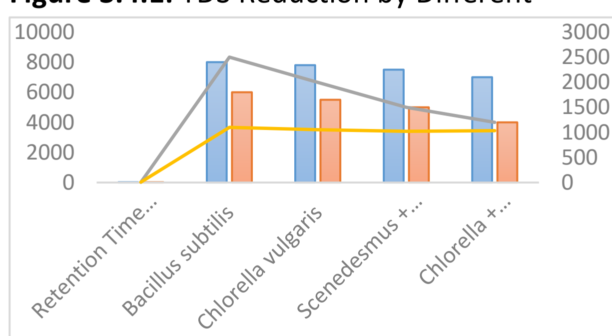
1. Substantial reductions in pH, BOD, COD, TDS, and TSS were recorded, with the 8-hour treated effluent meeting BEPA discharge standards.



2. Synergistic interactions were observed: algal photosynthetic oxygen enhanced bacterial aerobic degradation, while bacterial respiration supplied CO_2 and nutrients to algae, promoting mutual metabolic activity.

3.4.2 Chlorella vulgaris + Bacillus subtilis

Figure 3.4.1: TDS Reduction by Different Sludge Systems



Among all systems tested, the Chlorella vulgaris + Bacillus subtilis consortium exhibited the highest treatment efficiency.

1. Overall pollutant removal reached ~95% after 8 hours.
2. COD decreased from 1486 to 90 mg L^{-1}, BOD from 800 to 45 mg L^{-1}, TDS from 9000

to 1033 mg L^{-1}, and TSS from 720 to 60 mg L^{-1}.

3. The system exhibited excellent sludge settling, with an SVI of 35–30 mL g^{-1}, indicating compact sludge formation and rapid solid–liquid separation.
4. These results confirm the technical viability and operational advantage of the Chlorella–Bacillus consortium for high-strength textile wastewater treatment.

4. Discussion

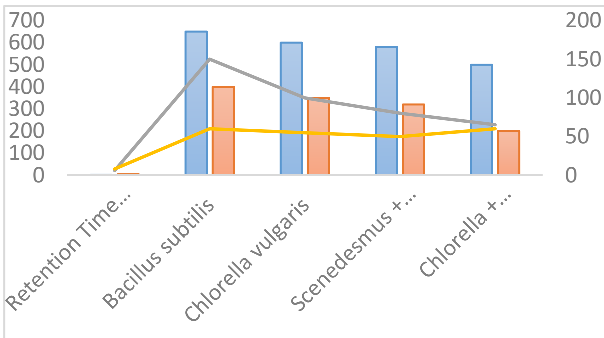


Figure 3.4.2: TSS Reduction by Different Sludge Systems

The results of this study demonstrate that the untreated textile wastewater from Quetta Textile Mills exhibited extremely poor physicochemical quality, with high BOD, COD, TDS, and TSS, reflecting severe pollution potential. Such high-strength effluents are consistent with previous reports highlighting the intensive use of alkaline chemicals, dyes, and other additives during textile processing (Pancha, 2023; Nowruzi et al., 2023). Direct discharge of such effluents can lead to oxygen depletion, soil salinization, and aquatic toxicity, underlining the urgent need for efficient treatment strategies (Wang et al., 2025; Fidiastuti et al., 2020).

4.1 Growth Behaviour of Algal Strains

The growth experiments revealed that Chlorella vulgaris and Scenedesmus exhibited optimal growth at slightly alkaline pH levels (7.8–8.0), which aligns closely with the natural pH of the textile effluent. Growth was limited at near-neutral or acidic conditions, likely due to reduced enzymatic activity and metabolic inhibition under suboptimal pH (Sathinathan et al., 2023). The superior growth of Chlorella vulgaris compared to Scenedesmus can be attributed to its higher photosynthetic efficiency and better adaptation to alkaline environments, which facilitated greater biomass accumulation. This finding confirms the potential of these strains to thrive in industrial effluents and provides a basis for their use in bioremediation.

4.2 Performance of Individual Sludge Systems

Bacillus subtilis activated sludge demonstrated progressive reduction of COD, BOD, TDS, and TSS with increasing retention time. Moderate reductions at shorter retention times (2–4 hours) indicate the initial microbial acclimatization and onset of metabolic activity, whereas significant removal at 6–8 hours reflects efficient biodegradation of both biodegradable and recalcitrant organic compounds. These observations align with the well-documented ability of Bacillus subtilis to secrete extracellular enzymes that degrade complex organics in wastewater (Kumar et al., 2023; Hasanath et al., 2025).

Similarly, the Chlorella vulgaris sludge system showed consistent pollutant reduction over time. Initial decreases in COD and BOD were likely due to biosorption and rapid uptake of soluble nutrients, while later reductions (6–8 hours) suggest active nutrient assimilation, bioflocculation, and sedimentation processes. These results reinforce the dual functionality of microalgae in both organic pollutant removal and biomass production, which can be further utilized in a circular bioeconomy context (Javed et al., 2023; Kusmayadi et al., 2020).

4.3 Performance of Algal–Bacterial Consortia

The combined algal–bacterial systems outperformed individual systems, demonstrating the synergistic potential of consortia in textile wastewater treatment. In the Scenedesmus + Bacillus subtilis system, enhanced reductions in all water quality parameters were observed, which can be attributed to mutual metabolic support: oxygen produced by algae facilitated aerobic bacterial degradation, while bacterial respiration released CO_2 and nutrients supporting algal growth (Sátiro et al., 2022).

The Chlorella vulgaris + Bacillus subtilis consortium exhibited the highest treatment efficiency, achieving approximately 95% overall pollutant removal within 8 hours, including COD reduction from 1486 to 90 mg/L, BOD from 800 to 45 mg/L, TDS from 9000 to 1033 mg/L, and TSS from 720 to 60 mg/L. The superior performance of this system can be explained by:

1. Enhanced biodegradation through complementary enzymatic activity of bacteria and algae
2. Bioflocculation and effective sludge settling, as evidenced by a low SVI (~35 mL/30 min), facilitating easy solid–liquid separation
3. Continuous nutrient recycling, where bacterial metabolism supplies CO_2 and micronutrients to algae, and algal photosynthesis maintains dissolved oxygen levels for bacterial activity (Malik et al., 2022; Sátiro et al., 2022).

These findings suggest that algal–bacterial consortia not only improve treatment efficiency but also reduce energy demands compared to conventional activated sludge systems, making them suitable for sustainable, large-scale industrial applications (Zabochnicka, 2022; Javed et al., 2023).

4.4 Implications for Industrial Wastewater Management

The study demonstrates that algal–bacterial sludge systems offer a viable and eco-friendly alternative to conventional physico-chemical treatments, with advantages including lower energy consumption, simultaneous removal of multiple pollutants, and potential biomass recovery for biofuels or fertilizers. The observed high retention-time efficiency (8 hours) and excellent sludge settling characteristics highlight the technical feasibility of scaling up this approach for industrial textile wastewater treatment.

Future studies should focus on optimization of inoculation ratios, reactor design, and continuous flow operation, along with molecular or enzymatic analyses to elucidate the specific pathways of pollutant degradation. Comparative cost–benefit analysis with chemical treatment methods would further strengthen the case for industrial adoption (Alam et al., 2023; Khan et al., 2022; Rashid et al., 2023).

5. Conclusion

This study demonstrated the effectiveness of algal, bacterial, and integrated algal–bacterial sludge systems for the biological treatment of high-strength textile wastewater under controlled laboratory conditions. The untreated wastewater exhibited extremely high pollution levels, including elevated COD, BOD, TDS, and TSS, confirming the necessity for efficient and sustainable treatment alternatives beyond conventional physico-chemical methods. Among all tested treatments, the integrated algal–bacterial consortia, particularly the Chlorella vulgaris–Bacillus subtilis system, showed superior performance. This system achieved up to 95% overall pollutant removal within an 8 h hydraulic retention time, with substantial reductions in COD, BOD, TDS, and TSS, bringing the effluent quality close to permissible discharge limits. In addition, the algal–bacterial sludge exhibited excellent settleability, as indicated by a low sludge volume index, highlighting its advantage in minimizing sludge handling and post-treatment separation challenges. The enhanced treatment efficiency of the algal–bacterial system can be attributed to synergistic interactions between microalgae and bacteria. Photosynthetic oxygen production by microalgae supported aerobic bacterial degradation of organic pollutants, while bacterial respiration supplied carbon dioxide and nutrients essential for algal growth. This mutualistic relationship improved organic matter removal, nutrient uptake, and sludge characteristics, making the integrated system more efficient than algal- or bacterial-only treatments. From a practical perspective, the findings suggest that algal–bacterial sludge systems offer a cost-effective, energy-efficient, and environmentally friendly solution for textile wastewater treatment, particularly in regions facing water scarcity and limited access to advanced treatment technologies. The rapid treatment time and reduced reliance on external aeration further enhance the feasibility of integrating this approach into existing effluent treatment plants. The study provides novel experimental evidence supporting the application of indigenous algal–bacterial consortia for sustainable textile wastewater management. Future research should focus on pilot-scale validation, long-term operational stability, and optimization under varying industrial conditions to facilitate large-scale implementation and contribution to circular bioeconomy-based wastewater reuse strategies.

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