Original Research Paper

Integrated Nutrient Recovery and Decolorization from Textile Effluent in an Algal System: From Wastewater to Energy

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This study investigated continuous textile wastewater treatment using a mixed microalgal consortium (*Chlorella* sp., *Parachlorella* sp., *Coelastrella* sp., and *Scenedesmus* sp.) in a 10-L high-rate algal pond (HRAP) system. In contrast to earlier investigations that focused on the optimization of specific operating variables under either batch or semi-continuous conditions, the current investigation attempted to optimize the HRT, OLR, and SRT simultaneously in a continuous mode with genuine textile wastewater, while at the same time conducting a downstream evaluation of biomass utilization for energy production. Textile wastewater with an initial COD of 1520 mg/L, BOD_5 of 620 mg/L, and dye concentration measured at λ_{max}= 580 nm was treated under varying HRT conditions (3-10 days). Optimal performance was achieved at HRT of 5 days and SRT of 20 days, resulting in 72% COD removal, 80% BOD_5 removal, 88% TN removal, and 80% decolorization. All improvements in pollutant removal and biomass productivity at optimal HRT and SRT were statistically significant ($p < 0.05$, one-way ANOVA). Biomass productivity reached 56.3 mg/L.d with a balanced biochemical composition of 42.5% protein, 28.3% lipid, and 18.7% carbohydrate. Elemental analysis (C 47.2%, H 6.8%, N 8.1%, S 1%) supported theoretical energy estimates of 342 mL CH_4/g VS for biomethane and 83-98 mg bioethanol/g biomass. The integrated system demonstrates a viable pathway for the textile sector to transition toward a sustainable circular bioeconomy, coupling effective effluent treatment with energy-rich biomass production.

Keywords: Bioenergy, HRAP, Microalgae, Nutrient recovery

Introduction

The textile industry is one of the most water-intensive manufacturing sectors. It produces considerable amounts of wastewater that contains a substantial amount of different pollutants, such as synthetic dyes, heavy metals, and organic compounds dyes (El-Gawad et al., 2024). In Bangladesh, the textile industry is a major part of the economy, but it also

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causes plenty of environmental problems. It produces almost 2,820 MLD of textile wastewater (TW) and 1.14 kg of sludge for every cubic meter of TW treated (Anwar et al., 2018). Activated sludge processes, chemical coagulation, and membrane filtration are all examples of traditional treatment methods that often have problems with high energy use, chemical needs, and not completely removing stubborn compounds (Periyasamy, 2024).

Microalgae-based wastewater treatment (MBWT) has emerged as a promising biotechnological approach that combines pollutant removal with biomass production, aligning with circular economy principles (Abdel-Raouf et al., 2012; Aragaw & Asmare, 2018; Behera et al., 2025). MBWT offers a multifunctional platform that couples pollutant removal with value-added biomass generation, directly supporting circular-economy goals. Algal-bacterial consortia efficiently assimilate nitrogen and phosphorus, and biodegrade recalcitrant organics (Behera et al., 2026), including reactive dyes, and supply in situ oxygen for aerobic bacteria, thereby cutting aeration energy, for instance, by nearly 60 % compared with conventional activated sludge (Kadam et al., 2023). The harvested biomass can be routed to biogas, bioethanol, or bioplastic production, offsetting treatment costs and reducing sludge volume (Abdel-Raouf et al., 2012). Optimizing abiotic, biotic, and operational parameters for continuous MBWT enables robust, low-cost treatment of industrial effluents such as TW while producing an energy-rich algal feedstock, positioning MBWT as a scalable, eco-industrial solution for sustainable water management.

High-rate algal ponds (HRAP) are effective alternatives for wastewater treatment, offering sustainable biomass production through shallow depths (100-400 mm), length-to-width ratios ≥10:1, surface area-to-volume ratio 5-10 m^2/m^3, and paddlewheel mixing (0.15-0.30 m/s) (Acién Fernández et al., 2018). Previous research mainly examined batch or semi-continuous (fed-batch) cultivation systems for MBWT, highlighting scalability challenges due to operational instabilities related to hydraulic retention time (HRT), solids retention time (SRT), and organic loading rate (OLR) (Pham et al., 2021). For instance, Pham et al. (2021) achieved 77% COD and 80% TKN removal at an HRT of 4 d (SRT of 40 d) in an 80 L HRAP but noted low robustness and high human intervention. Park & Craggs, (2010) ran two pilot ponds (HRT 4 and 8 d, 1 % v/v CO_2 sparging) on municipal wastewater and achieved 75-85 % NH4-N removal and nearly 20 g/m^2.d algal biomass, yet they did not report SRT or recirculation, leaving solids management unresolved. In a study, García et al. (2000) showed that operating 0.3 m-deep HRAPs continuously with HRTs of 3 to 10 days could treat 70 to 80% of TN. Even though these removal rates are promising, their work did not find any correlation between OLR and biomass residence time. This outcome makes it hard to apply their results to larger scales. Sutherland et al. (2014) also explored system optimization at a deeper level, focusing on cultural factors affecting biomass productivity. Their comparison showed that deeper configurations (0.4 m) were much more productive than shallower ones (0.2 m) when HRT was held constant. This study was conducted under a limited range of hydraulic conditions and did not comprehensively assess the interaction between OLR and SRT. There is a significant knowledge gap because previous studies have examined only individual operational parameters. No one has ever considered how to optimize HRT, SRT, and OLR simultaneously in a continuous algal treatment system specifically designed to treat TW.

HRAP systems outperform closed photobioreactors due to various technical advantages. PBRs have higher volumetric productivities (1.5-1.6 g/L.d), but they cost 5 to 10 times more than HRAP systems and need ongoing maintenance for artificial lighting and temperature control (Novoveská et al., 2023). Membrane photobioreactors problems with fouling and require a lot of energy to filter, which makes them not cost-effective for treating large amounts of wastewater. HRAPs naturally boost the growth of microalgae by making it easier for CO_2 absorption from the air. This means that algal biomass can be produced in a way that doesn't require a lot of energy (de Godos et al., 2016). HRAP systems also make fair use of symbiotic interactions between algae and bacteria, which leads to better nutrient removal rates than closed bioreactor systems.

The uniqueness of this study resides in the systematic improvement of the continuous cultivation of a naturally occurring microalgae consortium in TW, utilizing a tabletop HRAP under regulated environmental conditions. This study investigates real TW treatment under steady-state conditions and at the same time examines at the possibility of biomass valorization. The study adds to scientific knowledge of MBWT systems by showing how operational parameters (HRT, SRT, and OLR) affect treatment performance in a measurable way. It additionally provides a comprehensive overview of how wastewater quality improves while biomass can be used to generate energy. Finally, the downstream valorization of harvested algal biomass is covered as well to make the process prone to a sustainable TW treatment system.

Materials and Methods

Wastewater Collection and Characterization

TW was collected from a textile manufacturing facility specializing in washing, desizing, dyeing, and finishing operations. The factory uses reactive dyes and generic chemical aids to process cotton and polyester fabrics. Wastewater was collected from the equalization tank, representing a mix of 24 h. This was performed to make sure that the samples were representative. Samples were transported in acid-washed polyethylene containers and stored at -18 °C until subsequent analysis and experimental treatments. Standard Methods for the Examination of Water and Wastewater manual was used to characterize the TW (APHA et al., 2017).

Dye Analysis and Quantification

This study utilized spectrophotometric (UV-Vis spectrophotometer by Thermo Fisher Scientific Genesys 10S) methods to analyze and quantify textile dye (TD) in wastewater samples. Representative samples were filtered through a 0.45 µm membrane filter and scanned visible range (400-700 nm) to determine the TD's peak absorbance. The wavelength (λ_{max}) at which maximum absorbance found was then used to monitor the dye removal. Fourier-transform infrared (FTIR) spectroscopy (PerkinElmer Spectrum Frontier) was also used to investigate at how the functional groups changed in both raw and treated TW samples. FTIR spectra were collected in the mid-infrared region (450-4000 /cm). Functional group modifications were assessed by comparing the characteristic peaks in the sample spectra.

Microalgal Strain and Inoculum Preparation

Microalgal consortia was sourced from an open freshwater reservoir (23°48′53″ N, 90°21′6″ E). Surface water were collected from a depth of 10 cm and filtered through a 100 µm mesh to remove large particulates, as most microalgae typically do not exceed this size (Yi et al., 2021). The phytoplankton community structure was assessed via light microscopy, confirming the predominance of *Chlorella* sp., *Scenedesmus* sp., *Coelastrella* sp., and *Parachlorella* sp. in the collected samples. The concentrated inoculum was enriched in BG-11 medium under controlled laboratory conditions with continuous illumination at approximately 100 µmol/m^2.s provided by LED panels, temperature of 30 ± 2 °C, and pH 7.0 ± 0.2. For inoculum preparation, exponentially growing cultures were harvested by centrifugation (3000 rpm, 10 minutes) and resuspended to achieve an initial biomass concentration of 0.1 g/L in the HRAP.

Fabrication of High-Rate Algal Pond and Operation

A custom-designed tabletop raceway pond reactor with a working volume of 10 L was constructed from fiber-reinforced plastic and is shown in Fig. 1(A). The reactor dimensions were 90 cm in length × 9 cm in width × 12 cm in depth. The reactor was constructed in a racetrack configuration consisting of two straight channels connected by semicircular curved sections. A paddle wheel system driven by a variable-speed motor (fabricated locally with a gear arrangement) provided continuous mixing at 10 rpm, generating a flow velocity of 0.15 m/s to prevent algal sedimentation while minimizing shear stress.

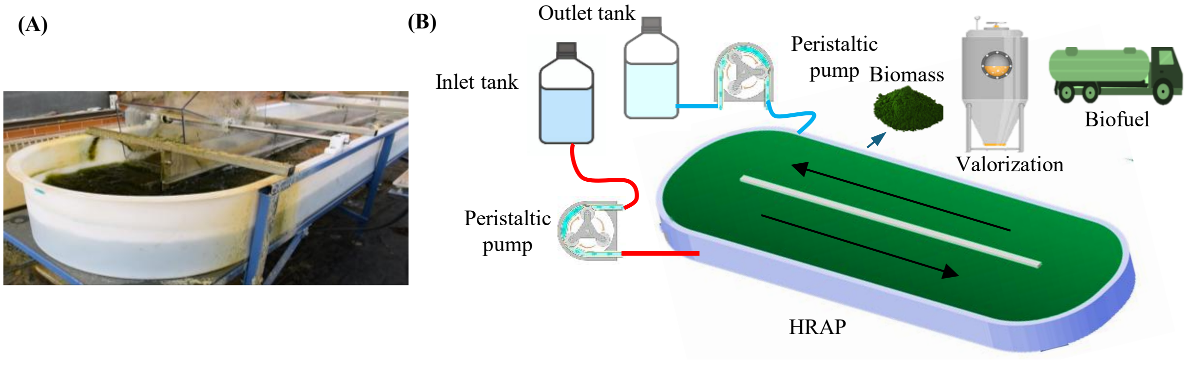

Fig. 1: Textile wastewater treatment in HRAP, (A) experimental setup, (B) schematic flow of the experiment

The reactor (HRAP) was covered with transparent film to minimize evaporation while allowing gas exchange through strategically placed ventilation holes (5 mm diameter, spaced 10 cm apart). Illumination was provided by natural light (outdoor conditions), delivering a photosynthetic photon flux density of 150-200 µmol/m^2.s. The temperature of the experimental zone was 28 ± 2 °C.

Continuous Operation and Parameter Control

The HRAP was operated in continuous mode with steady influent and effluent flow rates controlled by a peristaltic pump (Model: Miclins PP20 EX). Four different HRTs were investigated, such as 3, 5, 7, and 10 days, corresponding to flow rates of 3.33, 2.0, 1.43, and 1.0 L/d, respectively. SRT was controlled independently through biomass wasting, maintaining values of 15, 20, 25, and 30 days. The OLR was calculated based on COD input and reactor volume, ranging from 152 to 507 mg COD/L.d, depending on HRT conditions.

Growth and Treatment Efficiency Calculation

Influent and effluent samples were collected daily for water quality analysis following standard protocols. Biomass concentration was determined gravimetrically after filtration through pre-weighed 0.45 µm membrane filters and dried at 105 °C for 24 hours. Biomass productivity, specific growth rate, and doubling time were calculated as per Eqs. 1-3.

$$\text{Productivity (mg/L/d)} = \frac{X_2 - X_1}{t_2 - t_1} \quad \text{Eq. 1}$$

$$\text{Specific growth rate, } \mu \text{ (/d)} = \frac{\ln X_2 - \ln X_1}{t_2 - t_1} \quad \text{Eq. 2}$$

$$\text{Doubling time (d)} = \frac{\ln 2}{\mu} \quad \text{Eq. 3}$$

Where X_2 and X_1 are the biomass concentrations at times t_2 and t_1.

The textile wastewater treatment and decolorization efficiencies were calculated according to Eq. 4.

$$\text{Treatment efficiency (\%)} = \frac{C_{in} - C_{out}}{C_{in}} \times 100 \quad \text{Eq. 4}$$

Where C_{in} and C_{out} are the initial and final concentrations of nutrients or dye absorbance.

Biomass Characterization and Elemental Analysis

Harvested (4000 rpm for 10 minutes) biomass samples were freeze-dried and ground into powder for compositional analysis. The organic fraction composition, i.e., carbohydrate, protein, and lipid contents, was evaluated using Loewus's anthrone (Loewus, 1952), Lowry's Folin-phenol (Lowry et al., 1951), and Bligh and Dyer (Bligh & Dyer, 1959) Methods, respectively. Based on the organic fraction, theoretical bioethanol (Bio_{EtOH}) production was computed (Eq. 5).

The primary reaction for glucose (as a representative carbohydrate) is $C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$

$$\text{Theoretical } Bio_{EtOH} \text{ yield} = \frac{\text{Molar mass of } C_6H_{12}O_6}{\text{Molar mass of } 2C_2H_5OH} = \frac{92.14 \text{ g}}{180.16 \text{ g}} = \frac{0.511 \text{ g } Bio_{EtOH}}{\text{g carbohydrates}} \quad \text{Eq. 5}$$

Elemental analysis (C, H, N, S) was performed using a CHN elemental analyzer (Leco CHN-628) following standard protocols (Villanova et al., 2022). Oxygen content was calculated by difference. These data were used for theoretical calculations of biomethane potential using the Buswell equation and Bio_{EtOH} potential based on carbohydrate fermentation stoichiometry (Buswell & Mueller, 1952), as shown in Eq. 6.

$$C_aH_bO_cN_dS_e + \left(a - \frac{c}{2} - \frac{3d}{2} - 2e\right) H_2O \rightarrow \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8} - \frac{e}{4}\right) CH_4 + \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4} + \frac{3d}{8} + \frac{e}{4}\right) CO_2 + dNH_3 + eH_2S \quad \text{Eq. 6}$$

Where a, b, c, d, e are the number of moles for C, H, O, N, and S, respectively.

The theoretical higher heating values were evaluated as described by (Hasanath et al., 2026), as shown in Eq. 7.

$$T_{HHV}\ (MJ/kg) = (3.55C^2 - 232C - 2230H + 51.2CH + 131N + 20600)/1000 \quad \text{Eq. 7}$$

Where C, H, and N represent the content of carbon, hydrogen, and nitrogen, respectively.

Statistical Analysis

All experiments were performed in triplicate, and results were expressed as mean ± standard deviation. Statistical analysis was performed using one-way ANOVA (n=3) with significance defined at $p < 0.05$.

Results and Discussion

Initial Wastewater Characteristics

TW with a COD of 1520 ± 45 mg/L, BOD_5 of 620 ± 28 mg/L, and a BOD_5/COD ratio of 0.41, indicating moderate biodegradability. The TN concentration was 85 ± 4 mg/L, and the NH_3-N concentration was 45 ± 3 mg/L. This was enough nitrogen for microalgae to grow without putting them under stress conditions (Velásquez-Orta et al., 2024). The PO_4^{3-}-P level was 12 ± 1 mg/L, which kept the N:P ratio at about 7:1, which is favorable to sustained algal growth. The pH of 8.2 ± 0.1 was alkaline (due to usage of NaOH in textile dying process), which works for microalgal growth because most species like conditions that are slightly alkaline.

Treatment Performance Under Different HRT Conditions

The efficiency of COD removal showed a positive relationship with HRT, heading from 65.5 ± 2.1% at HRT 3 days to 72.4 ± 1.8% at HRT 5 days. It then improved to 75.8 ± 2.3% at HRT 7 days and 78.2 ± 1.9% at HRT 10 days (Table 1). The improvement in COD removal with longer HRTs was statistically significant ($p < 0.05$). This trend is consistent with earlier research indicating improved organic matter degradation with extended retention times in microalgae-based systems (Li et al., 2021; Velásquez-Orta et al., 2024). The better performance can be linked to the longer time that microorganisms and organic substrates are in contact with each other, which helps break down the organic compounds in TW more effectively.

Table 1: Treatment performance at different HRT conditions

Parameter	HRT 3 days	HRT 5 days	HRT 7 days	HRT 10 days
COD Removal (%)	65.5 ± 2.1	72.4 ± 1.8	75.8 ± 2.3	78.2 ± 1.9
BOD_5 Removal (%)	75.2 ± 2.8	80.0 ± 2.5	79.5 ± 2.1	78.8 ± 2.4
TN Removal (%)	81.8 ± 3.2	88.9 ± 2.1	86.4 ± 2.8	85.1 ± 3.1
NH_3-N Removal (%)	88.5 ± 2.4	94.8 ± 1.6	92.3 ± 2.2	90.7 ± 2.8
PO_4^{3-}-P Removal (%)	89.8 ± 2.1	95.0 ± 1.3	93.2 ± 1.8	91.5 ± 2.4

The efficiency of BOD_5 removal followed a similar pattern, reaching a maximum of 80 ± 2.5% at a HRT of 5 days and staying fairly stable at longer retention times. There were also statistically significant differences in BOD_5 removal at different HRTs ($p < 0.05$). The quick removal of BOD compared to COD shows that easily biodegradable organic matter breaks down faster, while harder-to-break-down compounds need longer treatment times (Velásquez-Orta et al., 2024). Bacteria break down complex organic matter and algae provide oxygen through photosynthesis in the raceway pond, which makes it easier for the algae-bacteria symbiosis to use organic matter (Mohammed et al., 2023).

TN removal showed optimal performance at a HRT of 5 days (88.9 ± 2.1%), attributed to the equilibrium regarding conditions facilitating both microalgal assimilation and bacterial nitrification-denitrification processes (Saha et al., 2022; Umetani et al., 2024; Velásquez-Orta et al., 2024). The removal of NH3-N was fair enough, reaching 94.8 ± 1.6% at HRT 5 days. This shows that mixed cultures quickly took it up for protein synthesis and growth (Velásquez-Orta et al., 2024). In spite of higher COD removal with longer HRT, 5-day HRT was the ideal operating condition because it was the best balance between treatment efficiency, biomass productivity, and reactor stability.

Decolorization

Fig. 2 shows that the full-spectrum analysis found the maximum absorbance peak (λ_{max} = 580 nm) that identified the primary textile dye chromophore. The decolorization efficiency of the mixed microalgal consortium was strongly influenced by operational parameters, with HRT having the most significant impact on dye removal. An extended HRT of 5 days led to the most significant decrease in absorbance ($\Delta\lambda_{580}$ = 0.82), which indicated that 80 ± 2.8% of the dye was removed. This occurred due to the microalgal-bacterial consortium was better at biosorption and breaking down the dye with enzymes. As HRT increased upwards, dye removal got better in a way that was statistically significant, especially between 3, 5, and 10 days ($p < 0.05$). On the other hand, a shorter HRT of 3 days culminated to a moderate decrease in absorbance ($\Delta\lambda_{580}$ = 0.40) and a dye removal rate of 71.2 ± 3.4%. This showed that there wasn't enough time for the chromophore to break down completely. The ideal OLR (200 mg COD/L.d) kept the pigment activity steady and the enzyme function functioning properly. On the contrary, higher OLRs (>400 mg COD/L.d) slowed down photodegradation because of metabolic stress and less light getting through, which made the process less efficient even at longer HRTs. However, the differences in dye removal between optimal and high OLRs were statistically significant ($p < 0.05$). At 20 days SRT, a high biomass concentration (1.35 ± 0.06 g/L) and peak enzyme expression allowed for the maximum dye removal (80 ± 3%). A shorter SRT (15 days) caused biomass washout and a lower removal rate (75%), while a longer SRT (30 days) triggered secondary metabolite formation. This was partially reabsorbed at 580 nm, lowering efficiency to 75 ± 4% even though biomass continued to be active.

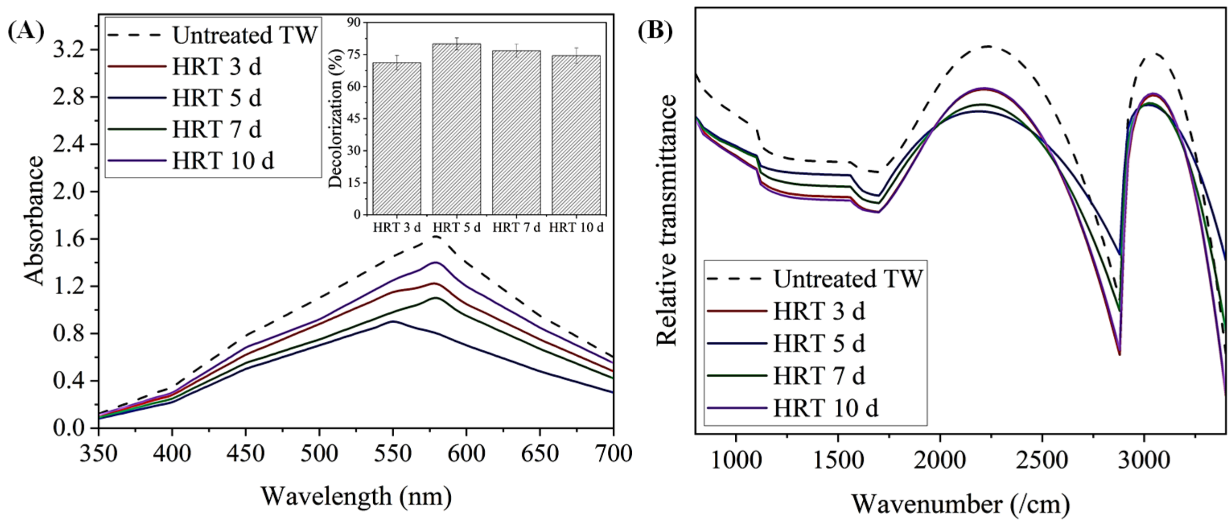

Fig 2: Decolorization of textile wastewater by the mixed microalgal consortium at varying HRTs: (A) UV-Vis absorbance spectra and (B) FTIR transmittance spectra

The FTIR spectra showed clear signs of molecular changes in the dye structures after continuous treatment with microalgae. For example, the azo (N=N) stretching band at about 1600 /cm became considerably weakened, and a new C=O stretching peak appeared near 1700 /cm. This suggests that oxidative cleavage of aromatic rings into carbonyl-containing intermediates occurred (Hasanath et al., 2021; Herrera & Moreno, 2022). These changes in the spectrum correspond to the UV-Vis decolorization data, which showed that HRT for 5 days results in the maximum drop in absorbance at λ_{max} = 580 nm ($\Delta\lambda_{580}$ = 0.82 ± 0.04; 80 ± 2.8% dye removal). This shows that chromophore breakdown is caused by chemical degradation and not just biosorption (Aragaw & Asmare, 2018; Uddin et al., 2022). In addition, there was noticeable skewing in the 2250/cm range, which was prompted by overtone and combination bands of N-H and C-H vibrations. This skewing got lesser and fewer over time, which shows that secondary bonds were breaking down during longer treatment. Also, the strong C-H stretching peak at about 2800 /cm showed a significant increase in transmittance after 5 days of HRT.

These FTIR observations have a strong connection to the UV-Vis decolorization metrics. At λ_{max} = 580 nm, HRT 5 days possessed a significant effect on absorbance reduction (80 ± 2.8% removal), which shows that chemical degradation is more effective than biosorption (Rani et al., 2023). FTIR peak changes were less noticeable with shorter (3 d) and longer (10 d) HRTs, and UV-Vis removal efficiencies were also lower (71.2 ± 3.4% and 74.5 ± 3.6%, respectively). This suggests that bond breakage or intermediate re-adsorption were not optimal under these conditions (Jadhav et al., 2025).

Biomass Growth and Productivity

The biomass concentration exhibited a clear HRT-dependent trend, peaking at 1.35 ± 0.06 g/L at a 5-day HRT, with productivity of 56.3 ± 3.2 mg/L.d (Fig. 3). Biomass productivity at HRT 5 days was statistically significant compared to other HRTs ($p < 0.05$). The analysis of the 3-day interval growth curve showed that there was a lag phase that lasted about 0 to 9 days, an exponential phase that lasted from 9 to 24 days, and then a transition to a quasi-steady state that lasted beyond 24 days for all HRTs. This means that the reactor stabilized and the substrate started to run out. The specific growth rate (μ) during the mid-exponential window (9-18 days) was calculated and observed at 0.18 ± 0.02 /d at HRT 5 days. In contrast, shorter and longer HRTs yielded slightly lower μ values of 0.16 ± 0.01 /d (HRT 3 days) and 0.14 ± 0.01 /d (HRT 10 days), with statistically significant differences between optimal and non-optimal HRTs ($p < 0.05$). Here, the 5-day HRT demonstrated superior performance due to its optimal balance between nutrient contact time and dilution rate, creating ideal conditions for microalgal metabolic processes, as evidenced by studies showing maximum acetate yield and enhanced carbon fixation at this specific retention time (Hasanath et al., 2020; Mohamadnia et al., 2023).

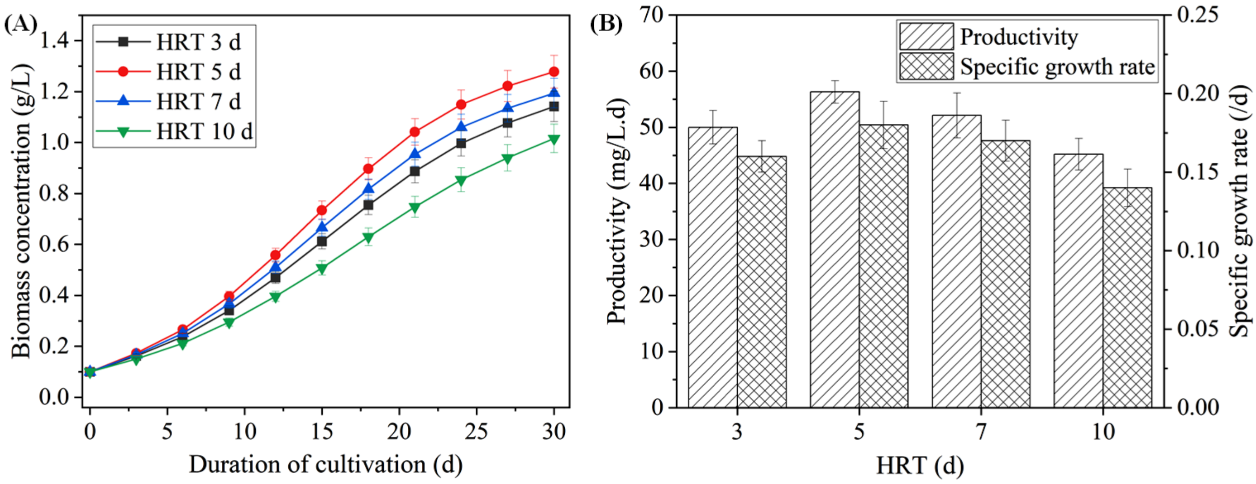

Fig. 3: Microalgal growth during textile wastewater treatment, (A) growth observation, (B) growth kinetics

As shown in Table 2, COD removal data plotted against biomass generation confirmed a yield coefficient of 0.42 ± 0.03 g biomass/g COD at HRT 5 days, consistent with the highest biomass yield observed and superior to yields at HRT 3 days (0.38 ± 0.02 g biomass/g $COD_{removed}$) and HRT 10 days (0.35 ± 0.02 g biomass/g $COD_{removed}$), demonstrating efficient substrate conversion under intermediate retention conditions. These findings underscore that an HRT of 5 days provides the balance between contact time, nutrient assimilation, and biomass productivity in continuous TW treatment systems employing mixed culture in MBWT.

Table 2: Biomass growth parameters under optimal conditions (HRT 5 days)

HRT (days)	Biomass Concentration (g/L)	Doubling Time (d)	Yield (g biomass / g $COD_{removed}$)
3	1.25	4.3	0.38
5	1.35	3.9	0.42
7	1.28	4.1	0.40
10	1.18	5.0	0.35

The high protein and lipid content observed in the microalgal biomass is particularly advantageous for downstream valorization. For example, proteins support bioproduct development and lipids serve as key precursors for biodiesel and other biofuels. Such balanced biochemical profiles enhance the feasibility of integrating microalgal cultivation into circular bioeconomy and biorefinery frameworks, maximizing both energy recovery and product diversification (Hasanath & Chatterjee, 2025; Suali & Sarbatly, 2012).

Effect of SRT on Biomass Characteristics

SRT significantly modified the biochemical profile of mixed microalgal biomass cultivated on TW. At SRT of 20 days, the culture reached a balanced state, with protein accounting for up 42.5 ± 2.1 % of dry weight (DW), lipid making up 28.3 ± 1.8 % of DW, and carbohydrate making up 18.7 ± 1.5 % of DW. This was linked to the highest nutrient absorption from dye-laden effluent streams and stable microalgal growth while the system was running continuously (Pandey et al., 2024). Lowering SRT to 15 days raised the protein content to 45.8 ± 2.3 % of DW because fast cell turnover assisted in creating nitrogen-rich biomass, but short residence time slowed down lipid biosynthesis pathways, lowering lipid yield to 24.1 ± 1.5 % of DW because not enough carbon was going into storage compounds (Pandey et al., 2024; Rahman et al., 2022).

Table 3: Biomass composition under different SRT conditions

Organic fraction	SRT 15 days	SRT 20 days	SRT 25 days	SRT 30 days
Protein (% DW)	45.8 ± 2.3	42.5 ± 2.1	40.1 ± 2.8	38.7 ± 3.1
Lipid (% DW)	24.1 ± 1.5	28.3 ± 1.8	29.8 ± 2.1	31.2 ± 2.4
Carbohydrates (% DW)	19.2 ± 1.8	18.7 ± 1.5	17.9 ± 1.9	16.8 ± 2.1

On the other hand, extending SRT to 30 days led to lipid accumulation of up to 31.2 ± 2.4 % DW due to prolonged nutrient limitation, which caused triacylglycerol synthesis. However, overall productivity dropped as older cultures experienced self-shading and resource exhaustion in the high-color, recalcitrant textile matrix (El-Sheekh et al., 2023; Hasanath et al., 2019). The carbohydrate content diminished from 19.2 ± 1.8% DW at 15 days to 16.8 ± 2.1% DW at 30 days, indicating a redirection of carbon towards lipogenesis under prolonged SRT stress conditions.

Elemental Composition and Energy Valorization

The higher heating value (HHV) was 19.9 ± 0.8 MJ/kg, which is comparable to lignocellulosic biomass and other algal feedstocks. This number shows that there is an ample amount of energy in it. The C/N ratio of 6.8 ± 0.3 is in the ideal range (6-8) for anaerobic digestion, which means that ammonia inhibition is kept to a minimum and methanogenesis is maximized (Moody et al., 2014). Using the Buswell stoichiometry: $C_{1.0}H_{1.72}O_{0.59}N_{0.15} + 0.39\ H_2O \rightarrow 0.51\ CH_4 + 0.49\ CO_2 + 0.15\ NH_3$, we can find the theoretical biomethane potential of 455.9 mL CH_4/g VS. Since microalgae usually have a conversion efficiency of 70-80%, it means that the actual biomethane potential is 341.9 mL CH_4/g VS. When combined with a biomass productivity of 56.3 mg/L.d, this yields 19.2 mL CH_4/L.d.

Table 4: Elemental analysis and energy characteristics of microalgal mixed culture

Parameter	Value	Unit
Carbon (C)	47.2	% DW
Hydrogen (H)	6.8	% DW
Nitrogen (N)	8.1 ± 0.4	% DW
Oxygen (O)	36.9 ± 1.5	% DW
Sulfur (S)	1.0 ± 0.1	% DW
Theoretical higher heating value	19.9	MJ/kg
Theoretical methane production	456	mL/g VS
Theoretical Bio_{EtOH} production	83-98	g/kg biomass

A biomethane study conducted by Hasanath and Chatterjee, (2025) reported a notable increase in methane yield, measuring 336 mL CH_4/g VS from the Scenedesmus obliquus strain cultivated in beverage wastewater, representing an 80% enhancement compared to cultivation in BG-11 media. The carbohydrate content of 16.8-19.2% also backs up the theoretical Bio_{EtOH} yields of 83-98 mg/g biomass (at 80% efficiency recovery relative to HHV), which adds 2.41 MJ/kg biomass (Hasanath & Chatterjee, 2025).

Integrated Biorefinery Approach

MBWT represents a paradigm shift toward sustainable water management by simultaneously addressing environmental pollution and resource recovery within a circular bioeconomy framework. The demonstrated high removal efficiencies for COD (72.4%), BOD (80%), nutrients (>88%), and dyes (80%) at an efficient HRT of 5 days highlight the exceptional bioremediation potential of microalgal systems compared to conventional treatment methods (Fazal et al., 2021). This approach transforms the linear "take-make-dispose" model into a regenerative cycle in which wastewater nutrients become valuable inputs for biomass production (1.35 g/L) with a balanced biochemical composition (42.5% protein, 28.3% lipid, 18.7% carbohydrate) (Hasanath & Chatterjee, 2025). The downstream valorization of microalgae biomass into various types of fuel, such as biodiesel, biomethane, and bioethanol, makes the process economically advantageous. Beyond economic benefits, this integrated system significantly reduces greenhouse gas emissions compared to conventional treatments and aligns with multiple UN Sustainable Development Goals, particularly SDG 6 (Clean Water), SDG 7 (Affordable Energy), SDG 12 (Responsible Consumption), and SDG 13 (Climate Action) (Olabi et al., 2023). The spectroscopic evidence of dye degradation pathways further validates the system's capacity to detoxify complex pollutants while generating value-added products, establishing a truly sustainable circular bioeconomy model for the textile industry (Fazal et al., 2021).

Conclusion

Integrating a microalgal consortium with HRAP for continuous textile wastewater treatment showed substantial pollutant removal ($p < 0.05$), with 72% COD and 80% dye decolorization at HRT of 5 days. Importantly, the 5-day HRT did not maximize every individual response: COD removal continued to increase at longer HRTs (up to 78.2% at 10 days), whereas biomass productivity, nutrient assimilation, and decolorization peaked at 5 days. The optimum therefore reflects a trade-off between substrate contact time and dilution rate rather than a single maximized variable, indicating that HRT alone is an insufficient design criterion for continuous algal treatment. The FTIR and UV-Vis spectrum analyses indicated that decolorization proceeded through chromophore degradation rather than biosorption alone, as evidenced by attenuation of the azo (N=N) band and the emergence of carbonyl (C=O). The elemental composition (C 47.2 ± 1.2 %, H 6.8 ± 0.3 %, N 8.1 ± 0.4 %) corresponded to a theoretical biomethane potential of up to 342 mL CH_4/g VS. The organic fraction, comprising 42.5% protein, 28.3% lipid, and 18.7% carbohydrate, supported a theoretical bioethanol yield of 86-98 mg per gram of biomass. This integration allows microalgae to combine effective wastewater treatment with bioenergy production, making HRAP systems energy-recovery systems with considerable prospective for a positive energy balance. The principal limitations are the laboratory scale, the controlled light and temperature regime, and the use of a single effluent source, which together constrain direct extrapolation to field conditions. Future study may consider a full techno-economic and life-cycle assessment. In addition, pilot-scale trials must evaluate real-world performance under fluctuating climatic conditions, including seasonal variations in light and temperature, to ensure long-term culture stability and progress towards commercial viability.

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Authors' Contributions

Md Abul Hasanath: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Validation, Resource, Writing - original draft; **Md Mostafizur Rahman**: Writing - review & editing; **Md Jahid Hasan:** Writing - review & editing; **Md Nashir Uddin**: Writing - Review & editing; **Monir Hossain**: Laboratory analysis, Writing - review & editing; **Md Nazmul Hasan**: Data curation, Validation; **Azahar M. Mishkat**: Formal analysis, Writing - review & editing; **Nahid Islam**: Formal analysis.

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