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Research Article

Optimizing nutrient and light regimes for shrimp pond wastewater treatment by *Spirulina platensis* in high-rate algal ponds

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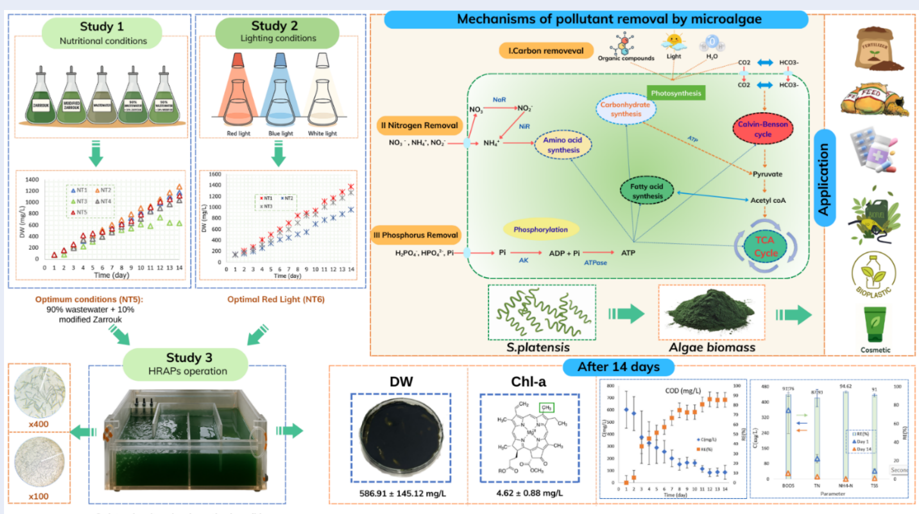
ABSTRACT

Wastewater pollution from shrimp aquaculture poses a significant environmental challenge, necessitating effective and sustainable treatment solutions. This study aimed to optimize the shrimp pond wastewater treatment capacity of *Spirulina platensis* (*S.platensis*) in High-Rate Algal Ponds (HRAPs) through the combined application of nutrient supplementation and light enhancement. The results demonstrated that the modified Zarrouk medium had yielded the highest growth performance, achieving a dry weight of *S.platensis* (DW) of 1123.43 ± 10.10 mg/L on day 14. Red light exceeded the performance of blue and white light, resulting in a DW of 1371.52 ± 15.76 mg/L, specific growth rate (SGR) of 0.18 ± 0.01 day^{-1}, doubling time (DT) of 3.93 ± 0.21 days, and biomass productivity (BP) of 94.87 ± 3.52 mg/L/day ($p < 0.05$). The HRAPs system, operated under red light and supplemented with modified Zarrouk medium, achieved removal efficiencies for chemical oxygen demand (COD) 85.44 ± 10.84%, biochemical oxygen demand (BOD_5) 91.76 ± 1.82%, total phosphorus (TP) 92.59 ± 6.43%, total nitrogen (TN) 89.10 ±8.31%, nitrate nitrogen (NO_3^--N) 87.93 ± 9.32%, ammonium (NH_4^+-N) 94.62 ± 1.12%, total suspended solids (TSS) 91.00 ± 1.77%, and Coliforms 99.99 %. The *S.platensis* biomass effectively absorbed nutrients in its growth from a culture medium combining shrimp pond waste and heterotrophic microbial community. Biomass production of *S.platensis* reached a DW of 586.91 ± 145.12 mg/L and chlorophyll a of 4.62 ± 0.88 mg/L after 14 days. The findings also suggest that The HRAPs system utilizing *S.platensis* not only provides high wastewater treatment efficiency but also promotes green technology, supporting a circular economy through the reuse of algal biomass for agricultural and energy purposes. The results confirm the potential of HRAPs under optimized conditions as a sustainable, environmentally friendly solution for aquaculture wastewater treatment, with prospects for large-scale implementation (Figure 1).

Graphical abstract (Source: Authors)



Key words: *Spirulina platensis*, algae biomass, dry weight, HRAPs, shrimp pond wastewater

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INTRODUCTION

The global shrimp aquaculture industry has emerged as a critical factor in meeting the increasing demand for seafood while playing a pivotal role in driving local economies and generating income for communities[1]. Vietnam is recognized as one of the world's leading shrimp producers[2]. Small-scale, household-based shrimp farming is a prevalent practice, particularly in the Mekong Delta, but it faces numerous challenges. Despite its potential to provide a stable income, small-scale shrimp farmers often encounter difficulties related to financial constraints, farming techniques, and managing excess wastewater generated from the production process. Shrimp pond wastewater contains high levels of nutrients and organic matter, primarily originating from feed and fertilizers used in the aquaculture environment. Approximately 18–27% of nitrogen and 6–11% of carbon is assimilated by farmed shrimp, with the remainder discharged into the environment[3]. Over time, the accumulation of these nutrients fosters the growth of pathogenic microorganisms, leading to eutrophication, water quality degradation, disruption of ecological functions, and a decline in biodiversity[4]. Consequently, post-harvest wastewater and water discharged during pond water exchanges (if applicable) must be treated prior to release into the environment.

Conventional chemical and physicochemical approaches for treating shrimp pond wastewater frequently rely on synthetic chemicals and face significant challenges related to secondary pollution ríks. In contrast, biological methods stand out due to their low operational costs, ease of implementation, and environmental friendliness, making them a preferred choice for treating wastewater containing organic matter, particularly readily biodegradable compounds[5]. Microalgae demonstrate effective nutrient uptake, such as nitrogen and phosphorus, from wastewater, thereby reducing the risk of water pollution and eutrophication[6]. The *S.platensis* is distinguished by the valuable applications of its harvested biomass compared to other algal species. The microalgal biomass obtained after wastewater treatment holds significant potential for wide-ranging applications in cosmetics, pharmaceuticals, food, and other value-added products, yielding considerable economic benefits[7]. Furthermore, the cultivation technique for *S.platensis* is simple, cost-effective, exhibits superior treatment efficiency, and is well-adapted to the humid tropical monsoon climate of southern Vietnam.

HRAPs stand out as an advanced system designed to optimize microalgal growth and efficiently treat wastewater. HRAPs feature rectangular or oval pond structures equipped with centrally located paddle-wheels for mixing, with a depth ranging from 300 to 500 mm, maximizing light and nutrient utilization to promote algal growth while recovering high-quality biomass[8]. This technology is particularly suitable for treating wastewater from shrimp ponds, where excess nutrients post-harvest can be sustainably reused[9]. Previous studies have separately examined the use of *Spirulina platensis* for treating shrimp aquaculture wastewater and the application of HRAPs in wastewater treatment. However, studies focusing on optimizing nutrient conditions and light regimes for HRAPs systems under conditions in Vietnam are still limited. For these reasons, the research's topic "Optimizing Nutrient and Light Regimes for Shrimp Pond Wastewater Treatment by *Spirulina platensis HRAPs*" aimed to enhance wastewater treatment efficiency and maximize the potential of algal biomass for practical applications. The research comprises three components: (1) Determining optimal nutrient conditions for algal biomass production; (2) Identifying optimal light conditions for algal biomass production; and (3) Evaluating the performance of shrimp pond wastewater treatment using HRAPs technology and *S. platensis.*

MATERIALS AND METHODS

Materials

Wastewater samples from shrimp ponds were collected post-harvest in Binh Dai District, Ben Tre Province, Vietnam, subjected to preliminary settling, and stored under refrigeration to minimize quality changes prior to experimentation. Key pollution parameters analyzed included pH, chemical oxygen demand (COD), biochemical oxygen demand over five days (BOD_5), ammonium, nitrate, total nitrogen (TN), total phosphorus (TP), total suspended solids (TSS), and coliforms counts.

The *S.platensis* strain was sourced from Tra Vinh University and cultivated to increase biomass in the laboratory of Environmental Technology, University of Sciences. The microalgae was grown in Zarrouk's nutrient medium[10] as standard Zarrouk.

To implement the experiments below, *S. platensis* was cultivated in both cultures, the standard Zarrouk medium and a modified Zarrouk medium ($NaNO_3$ replaced with KNO_3).

Experimental design

Optimizing Nutrient Conditions for Algal Biomass

Determining optimal nutrient conditions for algal biomass production before conducting wastewater treatment experiments in HRAPs, five experiments (NT1, NT2, NT3, NT4, NT5), as detailed in Table 1, were implemented for this purpose.

These experiments were replicated three times and conducted in 500 mL Erlenmeyer flasks, placed under white light with an intensity of 3000 lux, following a 12/24-hour light cycle (12 hours of artificial light from lamps and 12 hours of natural light). Continuous aeration was provided throughout the experiment to ensure optimal conditions for algal growth.

Optimizing Light Conditions for Algal Biomass

Three treatments (NT6, NT7 and NT8) were arranged in a completely randomized block design, utilizing red light (wavelength 664 nm), blue light (wavelength 432 nm), and white light, with a consistent light intensity of 3000 lux (Table 2).

Table 2: Light Optimization Experimental Conditions (Source: Authors)

Treatment	NT6	NT7	NT8
Light Color	Red	Blue	White
Light intensity	3000 lux	3000 lux	3000 lux

The nutrient medium selected for the optimal light condition investigation was based on the results from the most suitable nutrient condition assessment. The experiment was conducted in the laboratory at room temperature. Each treatment was replicated three times and set up in 500 mL Erlenmeyer flasks, with continuous aeration provided throughout the study. The light source for the microalgae was supplied by 10 W/h LED lamps manufactured by Phuong Nam Company, Vietnam.

HRAPs Model

Designed HRAPs Model

The HRAPs system was designed for wastewater treatment under laboratory conditions, with the operating water level maintained at a depth of 200 mm to optimize dissolved oxygen (DO) concentrations within the range of 6-8 mg/L, and the total tank height set at 300 mm. The tank was constructed from transparent acrylic material, with dimensions of length × width × height (600 mm x 400 mm x 300 mm), and the working water level was 200 mm. To facilitate flow, create circulation zones, and enhance mixing for improved contact between wastewater and algae, the tank was divided into four channels, each with a width of 150 mm (Figure 1).

The system was equipped with a paddle stirrer operating at 30 rpm, which facilitated uniform flow circulation and maintained stable dissolved oxygen levels, thereby fulfilling the technical requirements for effective wastewater treatment.

Operation of HRAPs Model

The experimental model was established with optimal nutritional and light conditions derived from the two previous studies. The lighting system utilized red LED lights, ensuring a light intensity of 3000 lux at the water surface, with a photoperiod of 12/24 hours. *S. platensis* was cultured in a medium consisting of 90% wastewater combined with 10% modified Zarrouk medium. The experiment was conducted over 14 days. Water samples were collected daily at 12:00 for analysis of COD, Nitrate (NO_3^-), and TP. In contrast, BOD_5, Ammonium (NH_4^+), TN, TSS, and Coliforms were analyzed only for the influent and effluent samples. Algal samples were collected daily to determine chlorophyll-a content and optical density (OD560) [11].

Wastewater samples in HRAPs model were collected daily at 12:00 to analyze the following parameters: temperature, pH, light intensity, DO (Dissolved Oxygen), COD (Chemical Oxygen Demand), NO_3^- (Nitrate), and TP (Total Phosphorus). Among these, temperature and pH in the algal culture medium for all three experiments were measured once daily at 08:00 using a HANNA pH meter, pH was maintained between 8.5-10 [12]. Light intensity was measured using a TCVN-LM03 light meter. Dissolved oxygen concentration was measured once daily at 16:00.

Assessment of Microalgal Growth

Calibration Curve Relating Optical Density (OD) to Dry Weight of Microalgae

The dry weight of the biomass was determined based on the optical absorbance at a wavelength of 560 nm [11]. One gram of dried algae was used to prepare standard solutions with varying concentrations. A linear regression relationship between OD and dry weight was established following the method of Lavens and Sorgeloos (1997), with the equation $y = 0.0014x + 0.0272$, where y represents the optical absorbance at 560 nm (OD560), and x is the dry weight of the algae (mg/L) [13]. Algal samples were collected daily to measure optical absorbance at 560 nm, using

Table 1: Nutrient Optimization Experimental Conditions (Source: Authors)

Treatment	NT1	NT2	NT3	NT4	NT5
Nutrient medium	100% Standard Zarrouk	100% Modified Zarrouk (NaNO3 replaced with KNO3)	100% Wastewater	90% Wastewater + 10% Standard Zarrouk	90% Wastewater + 10% Modified Zarrouk

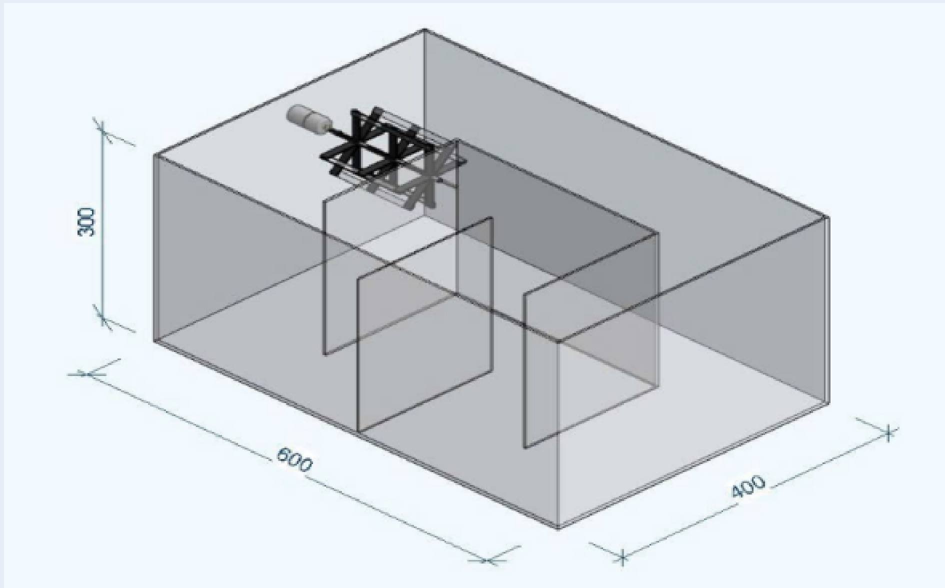

Figure 1: Simulation of the HRAPs system in study (Source: Authors)

a blank sample derived from control flasks prepared under the same conditions as the experimental flasks but without algae. The corresponding dry weight was then calculated based on the calibration curve equation in Figure 2.

Determining Chlorophyll-a Concentration in Microalgae

The chlorophyll *a* content was determined using UV-Vis spectrophotometry at characteristic wavelengths[14]

$$C_t = \frac{[11.46 \times (OD_{663} - OD_{750}) - 2.16 \times (OD_{645} - OD_{750})\ 0.10 \times (OD_{630} - OD_{750}) - 25.2 \times (OD_{772} - OD_{850})] \times V_1}{V \times \sigma}$$

Where:

- *V:* Volume of the sample (0.04 L)
- *V1:* Volume of acetone (20 mL)
- *σ:* Cuvette path length (1 cm)
- *OD:* Optical density

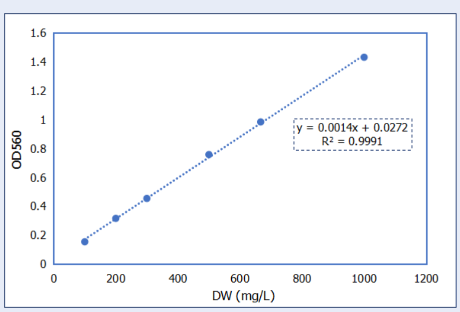

Figure 2: Calibration curve for *S. platensis* dry weight (Source: Authors)

Data Analysis

Data were processed using Microsoft Excel software for basic calculations and data visualization. Two-way analysis of variance (ANOVA) was conducted using SPSS version 20.0 and Microsoft Office Excel 2016 to assess the statistical significance between experimental groups, with a significance level set at $p < 0.05$.

RESULTS AND DISCUSSIONS

Optimal Nutritional Condition

The results of biomass growth assessment for *S.platensis* after 14 days under different experimental treatments were presented in graphs Figure 3. Statistical analysis revealed significant differences in algal dry weight among the nutritional conditions ($p < 0.05$) and over time ($p < 0.05$). The average dry weight of biomass on day 14 for each treatment was as follows: 1173.43 ± 5.05 mg/L for NT1, 1275.93 ±11.62 mg/L for NT2, 634.14 ± 5.05 mg/L for NT3, 1035.57 ± 2.02 mg/L for NT4 and 1123.43 ± 10.10 mg/L for NT5. Analysis of growth kinetics after 14 days using the exponential growth model equation [15] showed that the specific growth rate (SGR) ranged from 0.16 to 0.22 day^{-1}, with NT2 exhibiting the highest value (0.22 + 0.05 day^{-1}), reflecting optimal growth efficiency in the modified Zarrouk medium. Doubling time (DT) varied from 3.20 to 4.26 days, with NT3 showing the longest duration (4.26 ± 0.35 days), indicating delayed doubling due to suboptimal nutritional conditions. Biomass productivity (BP) ranged from 42.88 to 92.25 mg/L/day, with the highest value observed in NT2 (92.25 ± 2.02 mg/L/day), demonstrating consistency in results and confirming the superior potential of the modified nutritional medium in enhancing biomass yield. NT2 got the highest dry weight (1275.93 ± 11.62 mg/L), SGR (0.22 ± 0.05 day^{-1}), shortest DT (3.20 ± 0.47 days), and superior BP (92.25 ± 2.02 mg/L/day), indicating that the modified Zarrouk medium promoted algal growth with the higher biomass concentrations compared to the control medium. These findings aligned with the study by Gour et al. (2018), where replacing $NaNO_3$ with KNO_3 significantly improved microalgal growth rates [16]. Potassium is an essential nutrient for *Spirulina* development, and growth performance is enhanced when KNO_3 is used as a nitrogen source instead of $NaNO_3$ [17]. These results reinforced the role of KNO_3 as a potential alternative nitrogen source, contributing to the optimization of *S.platensis* growth.

In contrast, NT1 exhibited a dry weight of 1173.43 ± 5.05 mg/L, an SGR of 0.21 ± 0.04 day^{-1}, and a BP of 84.34 ± 0.81 mg/L/day. Although high, these values were inferior to those of NT2, possibly due to differences in nutrient composition. Treatment NT3 recorded the lowest dry weight among all treatments (634.14 ± 5.05 mg/L), with a maximum of 738.07 ± 3.54 mg/L on day 12 of cultivation, reflecting nutrient deficiency or the presence of inhibitory compounds. This resulted in a low SGR (0.16 ± 0.03 day^{-1}), a high DT (4.26 ± 0.35 days), and a low BP (42.88 ± 0.71 mg/L/day).

Subsequently, treatments 4 (NT4) and 5 (NT5) evaluated real wastewater combined with algae under optimized light and nutrient conditions as established previously. NT4 consisted of 90% wastewater blended with 10% standard Zarrouk medium, while NT5 comprised 90% wastewater blended with 10% modified Zarrouk medium. The results demonstrated that NT4 achieved a DW of 1035.57 ± 2.02 mg/L, SGR of 0.20 ± 0.05 day^{-1}, DT of 3.47 ± 0.28 days, and a BP of 73.74 ± 0.20 mg/L/day. In contrast, NT5 achieved a DW of 1123.43 ± 10.10 mg/L, an SGR of 0.21 ± 0.03 day^{-1}, the DT of 3.37 ± 0.43 days, and the BP of 80.47 ± 1.92 mg/L/day. The comparable performance between NT2 and NT5 indicated that the modified nutrient medium not only enhances biomass production but also reduced the algal doubling time. Consequently, NT5 was selected as the optimal treatment for shrimp pond wastewater treatment and utilized for subsequent experiments. This treatment provided a balance between microalgal growth efficiency and pollutant removal capacity. The 90% wastewater blending ratio contributed to improve treatment efficiency and reduced nutrient input costs, while the 10% modified Zarrouk medium provided essential trace elements, thereby simultaneously optimizing wastewater treatment and biomass of *S.platensis*. This approach differs from many previous studies, which primarily focused on optimizing growth in synthetic media without adequately addressing real wastewater conditions. Thus, the added value of this study lies not only in identifying optimal nutrient conditions for the growth of *S.platensis*, but also in demonstrating that minimal and selective nutrient supplementation can significantly enhance microalgal growth performance and the practical applicability of the alga in shrimp pond wastewater treatment systems.

Optimal Light Condition

To determine the optimal light color for microalgal growth, NT5 (previously identified as optimal for nutrient composition) was used as the baseline for subsequent experiments. The results indicated that red light made the highest growth performance, with a dry biomass weight on day 14 of 1371.52 ± 15.76 mg/L, significantly surpassing blue light (952.60 ±32.37 mg/L) and white light (1265.57 ± 14.27 mg/L), as illustrated in Figure 4.

Two-way analysis of variance (ANOVA) revealed statistically significant differences in dry biomass weight between treatments ($p < 0.05$) and over time ($p <$

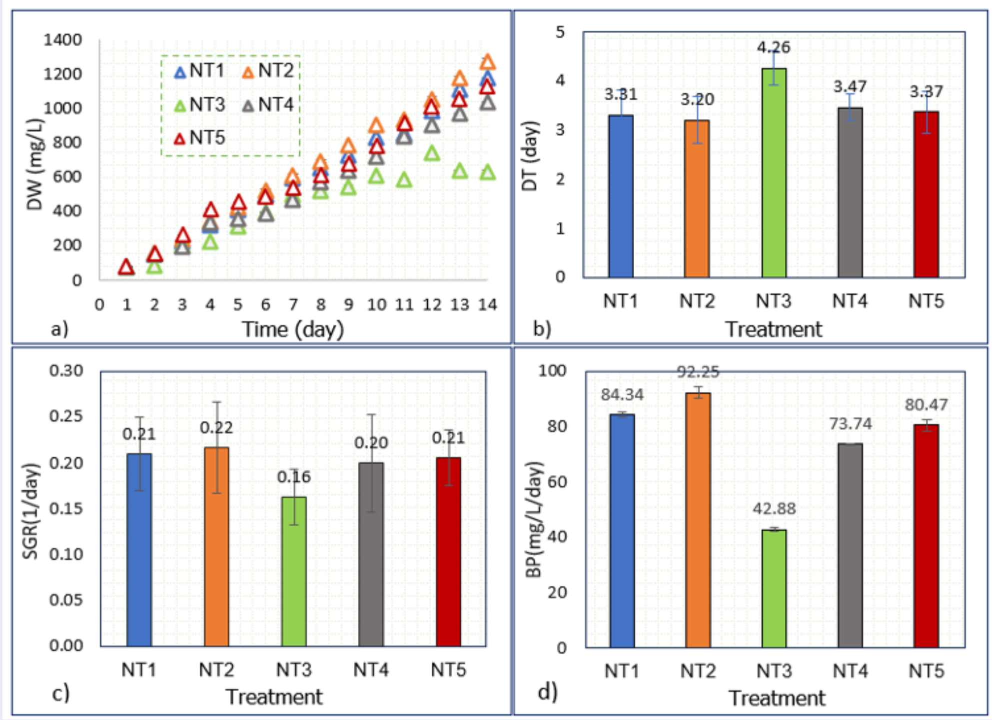

Figure 3: The optimal nutritional conditions: (a) Dry biomass weight of *S. platensis* ; (b) Doubling time of *S. platensis*; (c) Specific growth rate of *S. platensis*; (d) Biomass productivity of *S. platensis* (Source: Authors)

0.05). The highest specific growth rate (SGR) was recorded in treatment 6 (NT6) at 0.18 $\pm$ 0.01 day^{-1}, compared to treatment 7 (NT7) at 0.15 + 0.01 day^{-1} and treatment 8 (NT8) at 0.17 $\pm$ 0.02 day^{-1}. Doubling times (DT) were 3.93 $\pm$ 0.21 days for NT6, 4.63 $\pm$ 0.32 days for NT7, and 3.97 $\pm$ 0.18 days for NT8. Biomass productivity in NT6 reached 94.87 $\pm$ 3.52 mg/L/day, significantly higher than NT7 (62.82 $\pm$ 2.63 mg/L/day) and NT8 (87.32 $\pm$ 2.75 mg/L/day). These results consistently support NT6 and confirm that red-light not only enhances photosynthetic efficiency but also significantly increases the biomass of *S.platensis*.

This finding highlights the potential for practical applications in sustainable wastewater treatment systems for aquaculture. The results align with previous studies, such as Prates et al. (2018), who reported the highest biomass accumulation in microalgae under continuous red-light exposure [18], and Chen et al. (2010), who identified red light as the ideal condition for promoting algal growth [19].

However, the key distinction and novel contribution of the present study lies in confirming the effectiveness of red light under real shrimp pond wastewater conditions, where nutrient composition is complex and interactions between microalgae and heterotrophic microbial communities occur. This mechanism can be explained by the strong activation of photosynthetic pigments under red light, which enhances nutrient uptake and assimilation compared with white and blue light. Light intensity and wavelength are known to significantly influence microalgal growth and photosynthetic activity through direct interactions with photosynthetic pigments, thereby affecting biomass productivity [20]. In the context of shrimp aquaculture wastewater treatment, light not only affects microalgal growth but also indirectly governs pollutant removal efficiency. Enhanced microalgal biomass production under red light increases nitrogen and phosphorus uptake and promotes synergistic interactions between microalgae and bacteria, thereby improving wastewater treatment performance in HRAPs systems. These findings indicate that red light is not merely a factor for biomass optimization but also a critical operational parameter in biological treatment systems. Therefore, red light is recommended as the optimal illumination condition for microalgae-based applications in shrimp aquaculture wastewater treatment.

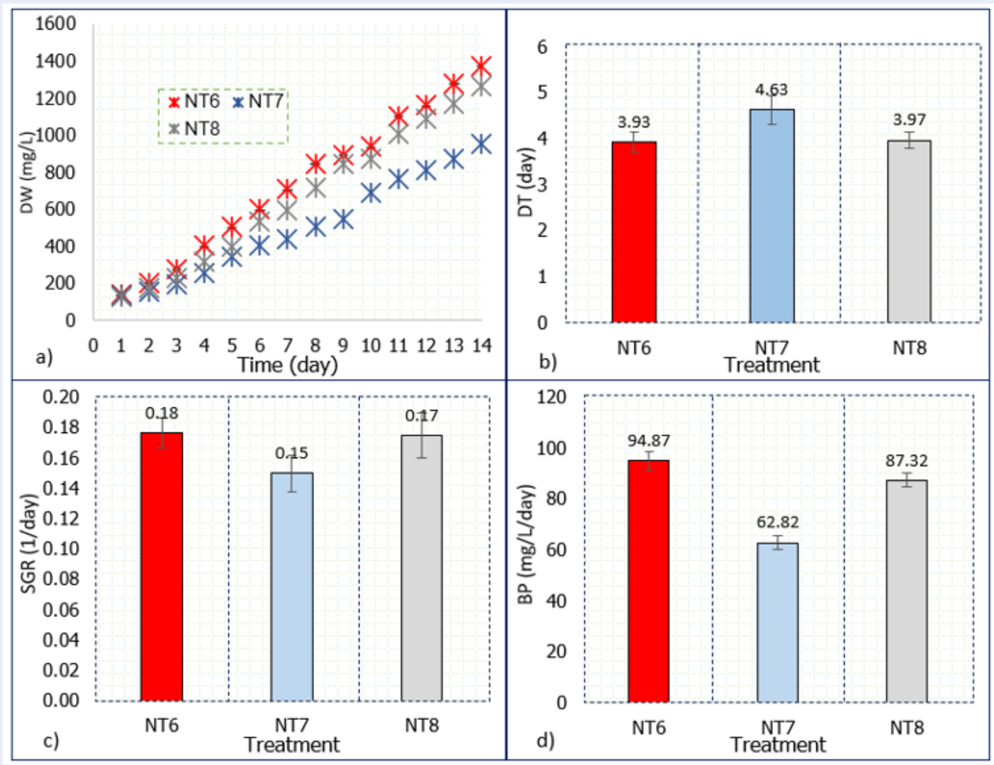

Figure 4: The optimal Light conditions; (a) Dry weight biomass of *S. platensis*; (b) Doubling time of of *S.platensis*; (c) Specific growth rate of *S. platensis*; (d) Biomass productivity of *S. platensis* (Source: Authors)

HRAPs Model Operation

S.platensis Biomass

The growth performance of *S. platensis* biomass in HRAPs was presented in Figure 5. The study results indicate that the dry weight of *S.platensis* biomass increased from 65.76 + 6.36 mg/L to 586.91 ± 145.12 mg/L. Correspondingly, the chlorophyll-a content also rose from 1.47 ± 0.35 mg/L to 4.62 ± 0.88 mg/L, reflecting the effective adaptation and growth of the algae under optimal conditions.

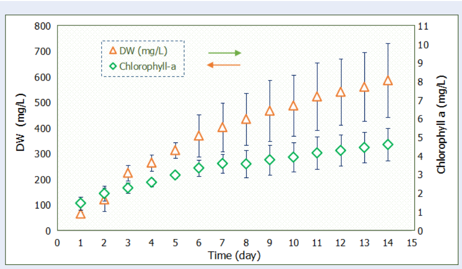

Figure 5: Dry biomass weight and chlorophyll-a concentration of *S. platensis* (Source: Authors)

Kinetic parameter analysis after 14 days revealed the average parameters of specific growth rate (SGR) of 0.17 ± 0.03 day^{-1}, a doubling time (DT) of 4.12 ± 1.42 days, and biomass productivity of 40.09 ± 13.08 mg/L/day during the observation period. These results not only confirmed the superior growth potential of *S.platensis* but also demonstrate its high efficiency in nutrient utilization and wastewater treatment (Figure 6).

Figure 6: *S. platensis* on the 14th day in HRAPs model (Source: Authors)

Effectiveness of Shrimp Pond Wastewater Treatment in HRAPs Model

The efficiency of *S.platensis* in treating shrimp pond wastewater under optimal culture conditions was presented in Figure 7. On day 14^{th} of cultivation, the concentrations of organic matter in the culture medium were recorded as 87.74 ± 57.04 mg/L for COD and 29.47 ± 12.08 mg/L for BOD_5, corresponding to removal efficiencies of 85.44 ± 10.84% and 91.76 ± 1.82%, respectively. Kinetic analysis of the data collected throughout the experimental period revealed that COD removal followed a first-order kinetic model, with a correlation coefficient R^2 = 0.9657 and a rate constant k of 0.155 day^{-1}. This value was higher than that reported by Selvaraj et al (2025) (k = 0.114 ± 0.05 day^{-1}), confirming the potential of *S.platensis* for pollutant removal under optimal conditions[21]. These findings highlighted the capability of microalgae to remove pollutants from water, with the treatment mechanisms attributed to adsorption, accumulation, and biodegradation by microalgae[22]. *S.platensis* utilized organic compounds as nutrients to support its growth and biomass production. Additionally, algae and bacteria could degrade pollutants by producing enzymes during their growth phase, breaking down toxic compounds into simpler, non-toxic forms[21]. This study showed a significant improvement in treatment efficiency. This difference can be explained by the simultaneous optimization of nutrient and light conditions, thereby enhancing photosynthetic activity and the ability of *S.platensis* to assimilate organic compounds.

The research results demonstrate that *S.platensis* exhibited significant nutrient removal capabilities after 14 days, achieving treatment efficiencies of 92.59 ± 6.43 % for total phosphorus (TP), 89.10 ± 8.31% for total nitrogen (TN), 87.93 + 9.32% for nitrate (NO_3^--N), and 94.62 ± 1.12% for ammonium (NH_4^+-N). The remaining nutrient concentrations were recorded as 0.35 ±0.14 mg/L (TP), 11.71 ± 3.76 mg/L (TN), 11.01 ± 3.51 mg/L (NO_3^--N), and 0.06 ± 0.03 mg/L (NH_4^+-N). These findings highlighted the nutrient assimilation capacity of *S. platensis* and confirm its potential in treating shrimp pond wastewater. Nitrogen and phosphorus significantly were major contributors to wastewater pollution, leading to eutrophication and reduced dissolved oxygen levels in aquatic environments. Microalgae could be capable of efficiently assimilating both macro- and micronutrients from wastewater, converting them into algal biomass[23]. Phosphorus removal in the system primarily occurred through two pathways: chemical precipitation and biomass assimilation[24]. Nitrogen was removed from wastewater through biological processes including nitrification, denitrification, and volatilization[25]. Algae contributed to this process by directly absorbing nitrogen compounds in the forms of nitrate (NO_3^-), nitrite (NO_2^-), and ammonium (NH_4^+)[21]. The concentrations of total suspended solids (TSS) and coliforms significantly decreased, with TSS reducing from 41.67 + 11.79 mg/L to 3.75 ± 1.77 mg/L, achieving a treatment efficiency of 91.00 ± 1.77% (Figure 3.5). Additionally, the coliforms concentration in the wastewater markedly decreased from $1.01 \times 10^5 \pm 1.27 \times 10^5$ MPN/100 mL to 5.00 ± 7.07 MPN/100 mL, with a removal efficiency of 99.99%. This reduction was attributed to changes in pH within the environment. During rapid photosynthesis, the algae's demand for carbon dioxide exceeds the amount produced by bacterial respiration in the wastewater. Consequently, algae utilize carbonate and bicarbonate ions, dissociating them to produce carbon dioxide for their use, which generates hydroxyl ions and increases the pH. When photosynthesis slows, free carbon dioxide accumulates, and the pH returned to normal levels. This pH fluctuation was the primary mechanism for coliforms removal in the system[26]. This research offers a scientific basis for integrating wastewater treatment and microalgal biomass recovery in HRAPs systems, paving the way for larger-scale investigations into circular economy approaches and sustainable aquaculture development.

CONCLUSION AND RECOMMENDATIONS

This study demonstrates that the High Rate Algal Pond (HRAPs) system utilizing *S. platensis* under optimized nutrient and light conditions represents an effective and sustainable solution for treating shrimp pond wastewater. The modified Zarrouk medium combined with red light not only promotes microalgal biomass production but also significantly improves wastewater quality. These findings underscore the broad application potential of HRAPs, extending beyond aquaculture wastewater treatment to various other industrial sectors. This approach offers an environmentally friendly, sustainable, and scalable solution for the aquaculture industry. To facilitate practical implementation, future research should focus on optimizing operational costs and conducting a comprehensive evaluation of the model's economic feasibility.

COMPETING INTERESTS

The authors declare that they have no conflict of interest.

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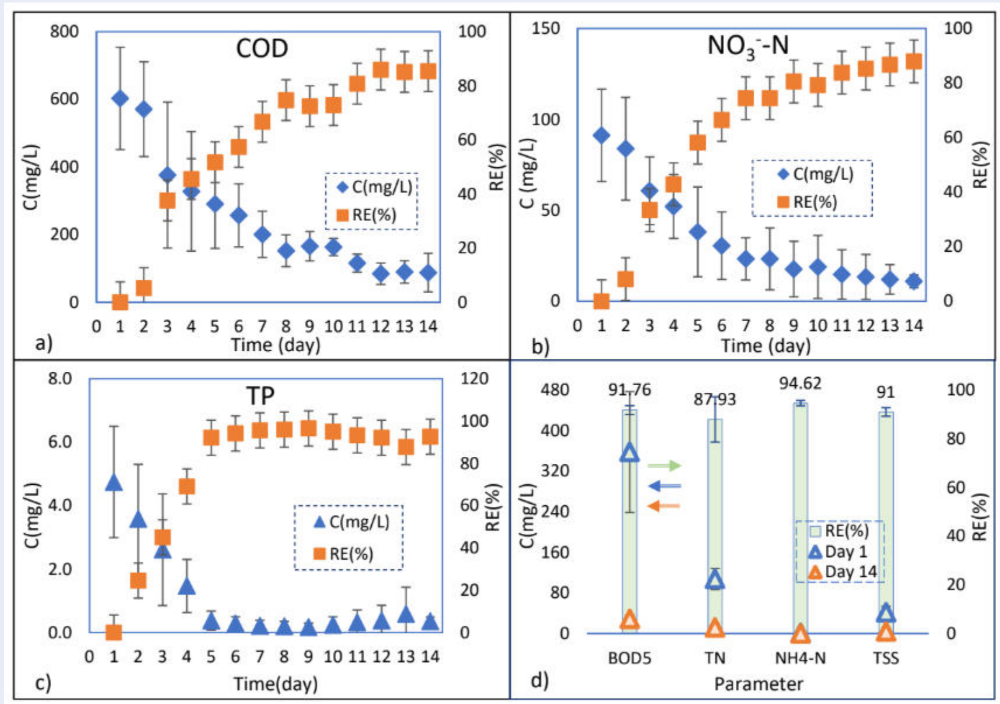

Figure 7: Removal Efficiency of shrimp pond wastewater treatment in HRAPs model: a) COD, b) TP, c) NO_3^--N, d) BOD5, TN, NH_4-N, and TSS (Source: Authors)

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AUTHOR CONTRIBUTIONS

Tran Huy Nhon conceived the study, designed the experiments, conducted the experiments, analyzed the data, interpreted the results, prepared the figures, and wrote the original manuscript. Tran Thi Kim Phung supervised the research, contributed to the experimental design, analyzed the data and reviewed the manuscript. Dang Diep Yen Nga supervised the study, contributed to data interpretation, reviewed and edited the manuscript. All authors have read and approved the final version of the manuscript.

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Bài nghiên cứu

Tối ưu hóa chế độ dinh dưỡng và ánh sáng cho xử lý nước thải ao nuôi tôm bằng *Spirulina platensis* trong hệ thống Hồ tảo cao tải

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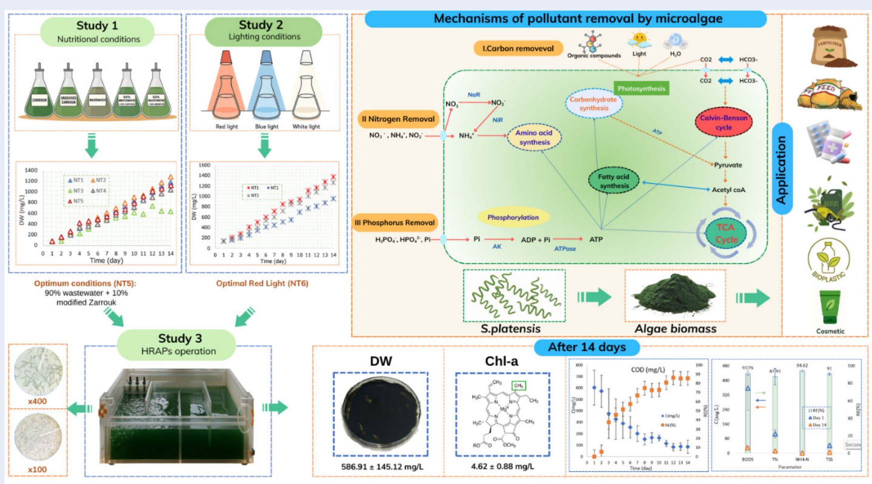
TÓM TẮT

Ô nhiễm nước thải từ hoạt động nuôi tôm là một thách thức đáng chú ý đối với môi trường, đòi hỏi các giải pháp xử lý hiệu quả và bền vững. Nghiên cứu này nhằm tối ưu hóa khả năng xử lý nước thải ao nuôi tôm của *Spirulina platensis* (*S.platensis*) trong hệ thống hồ tảo cao tải (High-Rate Algal Ponds - HRAPs) thông qua việc kết hợp bổ sung dinh dưỡng và tăng cường điều kiện chiếu sáng. Kết quả cho thấy môi trường Zarrouk cải tiến mang lại khả năng sinh trưởng cao nhất, với trọng lượng khô (DW) của *S.platensis* đạt 1123.43 ± 10.10 mg/L vào ngày thứ 14. Ánh sáng đỏ vượt trội so với ánh sáng xanh và ánh sáng trắng, đạt sinh khối khô 1371.52 ± 15.76 mg/L, tốc độ sinh trưởng riêng (SGR) 0.18 ± 0.01 ngày^{-1}, thời gian nhân đôi (DT) 3.93 ± 0.21 ngày và năng suất sinh khối (BP) 94.87 ± 3.52 mg/L/ngày ($p < 0.05$). Hệ thống HRAPs vận hành dưới ánh sáng đỏ và được bổ sung môi trường Zarrouk cải tiến đạt hiệu suất loại bỏ nhu cầu oxy hóa học (COD) là 85.44 ± 10.84%, nhu cầu oxy sinh hóa (BOD_5) là 91.76 ± 1.82%, tổng phosphorus (TP) là 92.59 ± 6.43%, tổng nitrogen (TN) là 89.10 ± 8.31%, nitrate (NO_3^--N) là 87.93 ± 9.32%, ammonium (NH_4^+-N) là 94.62 ± 1.12%, tổng chất rắn lơ lửng (TSS) là 91.00 ± 1.77% và Coliform đạt 99.99%. Sinh khối S.*platensis* hấp thụ hiệu quả các chất dinh dưỡng trong quá trình sinh trưởng từ môi trường nuôi cấy kết hợp chất thải ao nuôi tôm và cộng đồng vi sinh vật dị dưỡng. Sau 14 ngày, sinh khối *S.platensis* đạt trọng lượng khô 586.91 ± 145.12 mg/L và hàm lượng chlorophyll *a* đạt 4.62 ± 0.88 mg/L. Các kết quả cũng cho thấy hệ thống HRAPs sử dụng *S. platensis* không chỉ mang lại hiệu quả xử lý nước thải cao mà còn thúc đẩy công nghệ xanh, góp phần hỗ trợ mô hình kinh tế tuần hoàn thông qua việc tái sử dụng sinh khối tảo cho các mục đích nông nghiệp và năng lượng. Kết quả nghiên cứu khẳng định tiềm năng của hệ thống HRAPs trong điều kiện tối ưu như một giải pháp xử lý nước thải nuôi trồng thủy sản bền vững, thân thiện với môi trường và có triển vọng triển khai trên quy mô lớn (Hình 1).

Tóm tắt đồ họa (Nguồn: nhóm tác giả)



Từ khoá: *Spirulina platensis*, sinh khối tảo, khối lượng khô, HRAPs, nước thải ao nuôi tôm

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