

# Enhancing Domestic Wastewater Treatment by *Spirulina platensis* in a Photobioreactor Through Light Intensity Control

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## ABSTRACT

Untreated domestic wastewater can pollute the environment and pose risks to human health. Biological treatment using microalgae offers a promising approach to reducing the concentrations of nutrients and organic compounds in wastewater. *Spirulina platensis* is a microalgal species capable of utilizing organic compounds in wastewater through photosynthesis. This study aimed to analyze the effect of light intensity on the efficiency of nitrogen (N) and phosphorus (P) removal from domestic wastewater used as a microalgal growth medium. The research further explored the potential of photobioreactor-based innovations to reduce wastewater contaminants under varying light intensities of 3000, 4000, and 5000 lux. A quantitative experimental approach was used to evaluate the effectiveness of *Spirulina platensis* in treating domestic wastewater. The results showed that optimal N and P removal occurred at a light intensity of 5000 lux, with removal efficiencies after 7 days of treatment of 90.35% and 90.45% for N and P, respectively. This light intensity created favorable conditions for photosynthesis, supporting optimal microalgal growth and improving the efficiency of contaminant removal from wastewater. These findings highlight the potential of microalgae-based photobioreactors as an effective and sustainable alternative for treating domestic wastewater.

**Keywords-**photobioreactor; microalgae bioremediation; nutrient removal; light intensity control; *Spirulina platensis*

## I. INTRODUCTION

Domestic wastewater is generated as a byproduct of human activity and contains a variety of pollutants, including organic, inorganic, and bacterial pollutants, which can contribute to the potential contamination of water bodies [1]. Domestic wastewater is the most abundant type of wastewater, and its mismanagement can significantly affect environmental quality. Uncontrolled discharge will increase Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD), thereby reducing dissolved oxygen (DO) levels and adversely

affecting fish and other biota in surface and groundwater sources [2]. As in the case of Pakistan's Pinyari Canal and Phuleli Canal, untreated urban wastewater discharge led to a sharp decline in water quality, rendering the water unsafe for consumption [3, 4]. Moreover, domestic wastewater is a major contributor to nutrient pollution, accounting for over 50% of non-point N and P loads in aquatic ecosystems in developing countries, where excessive nutrient inputs accelerate eutrophication, leading to ecological imbalance and water quality deterioration [5].

Communal domestic wastewater treatment plants in Indonesia generally use biological processes, such as anaerobic or aerobic systems, that effectively decompose organic matter but are less effective at completely removing N and P from wastewater. N compounds, such as ammonia and nitrate, and P-containing substances from domestic waste, including detergents, often persist and are discharged into water bodies, triggering eutrophication, characterized by excessive algal growth and reduced dissolved oxygen. A comparable case was reported in Iraq, where multiple effluent measurements from the Amarah Wastewater Treatment Plant exceeded discharge standards for ammonia, nitrate, and phosphate [6]. Advanced treatment technologies are needed to overcome the limitations of conventional biological processes for removing N and P from domestic wastewater and to prevent eutrophication. These approaches use a more efficient combination of biological, physical, and chemical methods.

Wastewater treatment methods, such as the Moving Bed Biofilm Reactor (MBBR) with anoxic-aerobic stages, effectively remove up to 90% of ammonia and significantly reduce COD through the attached microbial biofilm on the moving medium. Furthermore, phytoremediation methods have been shown to reduce BOD by 70-96%, COD by 70-86%, and ammonia by 90-99% in a natural and affordable manner. The use of microorganisms, plants, or microalgae [7, 8] offers many advantages, including environmental sustainability, economic efficiency, and high adaptability.

Numerous studies have investigated microalgal species capable of bioremediating nutrients, pollutants, and pathogens from wastewater [9, 10]. Microalgae are unicellular organisms with diverse shapes and forms, and many species can grow in a variety of aquatic habitats [11]. Microalgae are highly stress-tolerant and can undergo various physiological adjustments under stress, which in turn alter their nutrient profile and biomass composition. Microalgae demonstrate remarkable adaptability, enabling them to survive in diverse, often harsh environments, including seawater and wastewater. With strong bioremediation potential, microalgae can remove nutrients, heavy metals, emerging contaminants (ECs), and pathogens from wastewater [12].

Microalgae, including *Laminaria japonica*, *Spirogyra*, *Chlorella* sp., *Spirulina platensis*, *Euglena* sp., and many others, can be utilized in wastewater treatment [13, 14]. Microalgae have rapid growth capabilities and can adapt to various types of wastewater, such as domestic, livestock, coking industry, and palm oil industry wastewater [15-19], while simultaneously reducing concentrations of both organic and inorganic pollutants, including N, P, microplastics, and heavy metals [20, 21]. The growth of microalgae can be influenced by light, carbon-to-nitrogen ratio (C/N) ratio, pH, temperature, and retention time. When these factors are combined, microalgae can adapt and thrive under changing wastewater conditions [22]. The presence of microalgae can provide information about the properties of a water body and thus can be used as an indicator of water quality. For example, the abundance of microalgae species increases with higher levels of organic contaminants in the water, such as nitrate and phosphate [23]. Furthermore, microalgae can be used in

various applications: as a renewable energy source [9], as raw materials for biofuels, animal feed [10, 24, 25], and biofertilizers [26, 27].

Several microalgal species are notable for their distinctive properties [28], among which *Spirulina platensis* is particularly significant. *Spirulina platensis* is a microscopic, filamentous cyanobacterium distinguished by its blue-green pigmentation and spiral trichome structure [29]. It contains approximately 62% amino acids, and its soft cell wall, composed of complex sugars and proteins, enhances digestibility due to its exceptionally high protein content that exceeds that of meat, fish, and soybean meal [30]. Previous studies have reported that *S. platensis* can be used to remove nutrients from wastewater [29, 31-33]. This type of microalgae grows well in growth media with a pH of about 8.5–9.5 and an optimum temperature of 30-32 °C [34]. However, while the effects of pH and temperature are well established, the role of light intensity in nutrient removal efficiency in domestic wastewater systems remains understudied. Further research on optimizing light intensity is urgently needed to realize the full potential of *Spirulina* cultivation in domestic wastewater. Therefore, this study aims to analyze the effect of light intensity on the efficiency of N and P removal from domestic wastewater used for microalgae growth. This study explores the potential of photobioreactor innovation to reduce contaminants in wastewater, which serves as a medium for microalgae growth.

## II. ROLE OF MICROALGAE IN WASTEWATER TREATMENT

N and P can be assimilated by microalgae to produce their own biomass. The mechanism of nutrient N and P removal by microalgae is shown in Figure 1. N removal in microalgae occurs in three fundamental steps: transport, reduction, and binding. Microalgae assimilate inorganic N from wastewater primarily in the form of ammonium ( $\text{NH}_4^+$ ), nitrate ( $\text{NO}_3^-$ ), and nitrite ( $\text{NO}_2^-$ ), using specific transport proteins embedded in the cell membrane. Among these N species, ammonium is preferentially utilized because it can be directly incorporated into cellular metabolism without enzymatic reduction, making the process rapid and energy-efficient [12].

In contrast, nitrate and nitrite must undergo a two-step enzymatic reduction process: nitrate is first reduced to nitrite by nitrate reductase in the cytosol using NADH as the electron donor, and nitrite is subsequently reduced to ammonium by nitrite reductase [32] in the chloroplast, using ferredoxin as the sole electron donor. This reductive assimilation requires energy in the form of ATP and reducing equivalents such as NADPH. The ammonium generated either through direct uptake or enzymatic reduction is then incorporated into organic N compounds via the glutamine synthetase–glutamate synthase (GS–GOGAT) pathway and, to a lesser extent, via the glutamate dehydrogenase (GDH) pathway [35]. Within these pathways, ammonium is fixed into amino acids, which are subsequently used for protein synthesis and the production of N-containing macromolecules essential for growth and metabolism [36]. This mechanistic sequence not only facilitates the assimilation of N into biomass but also underpins microalgae's capacity to effectively remove N from wastewater, highlighting their potential for sustainable nutrient

recovery. Cyanobacteria, such as *Spirulina platensis*, exhibit a comparable relationship between N assimilation and the assimilation of nitrite and ammonium N, which occurs primarily in the cytoplasm [35].

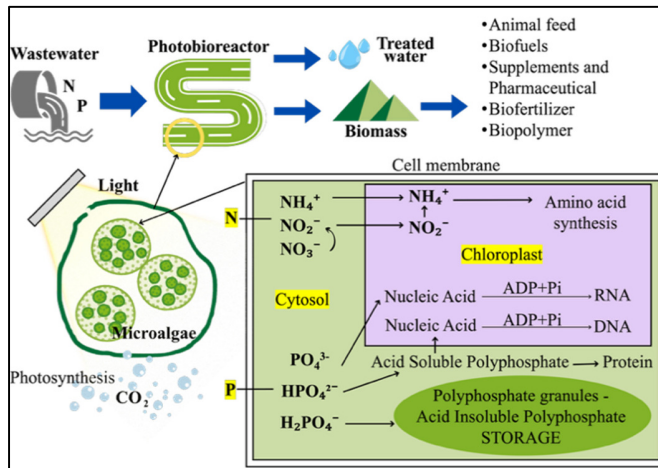


Fig. 1. Schematic illustration of microalgae utilization in wastewater treatment, especially on N and P assimilation and storage in microalgae cells. (Modified from [12, 32, 35-39]).

P removal from wastewater by microalgae occurs through three phosphorylation pathways: substrate-level phosphorylation, oxidative phosphorylation, and photosynthetic phosphorylation [12]. In substrate-level phosphorylation, phosphate groups are directly transferred from phosphorylated intermediates to adenosine diphosphate (ADP), forming adenosine triphosphate (ATP) during glycolysis and the tricarboxylic acid (TCA) cycle. This process incorporates P into essential metabolic intermediates. Oxidative phosphorylation occurs in the mitochondria, where the electron transport chain generates energy that drives ATP synthesis by coupling inorganic phosphate to ADP via ATP synthase.

This mechanism provides energy for diverse cellular functions, including nutrient assimilation and biomass growth. Photosynthetic phosphorylation, or photophosphorylation, occurs in the chloroplasts, where light energy captured by the photosynthetic electron transport chain drives the phosphorylation of ADP to ATP, thereby enhancing P assimilation under illuminated conditions and promoting primary metabolism. Collectively, these complementary phosphorylation pathways enable microalgae to efficiently convert inorganic phosphate into biologically active forms, supporting their growth and productivity in nutrient-enriched environments. Beyond immediate metabolic needs, microalgae can also absorb excess phosphate and store it intracellularly, a phenomenon known as "luxury uptake," which can account for up to 53% of total cellular P [12]. Excess phosphate is stored as acid-insoluble polyphosphate granules, which serve as long-term reserves and buffer against nutrient fluctuations. Acid-soluble polyphosphates act as intermediates, providing phosphate for nucleic acid and protein synthesis, while the granules act as storage bodies that can be mobilized during P scarcity [12, 36, 37, 39].

### III. MATERIALS AND METHODS

The methods employed in this study are illustrated in the flowchart in Figure 1. The diagram presents the research stages, beginning with sampling and characterization testing of Wastewater Treatment Plants (WWTP) effluent, microalgae cultivation, photobioreactor assembly and operation, followed by water quality monitoring (before and after passing through the photobioreactor) and data analysis.

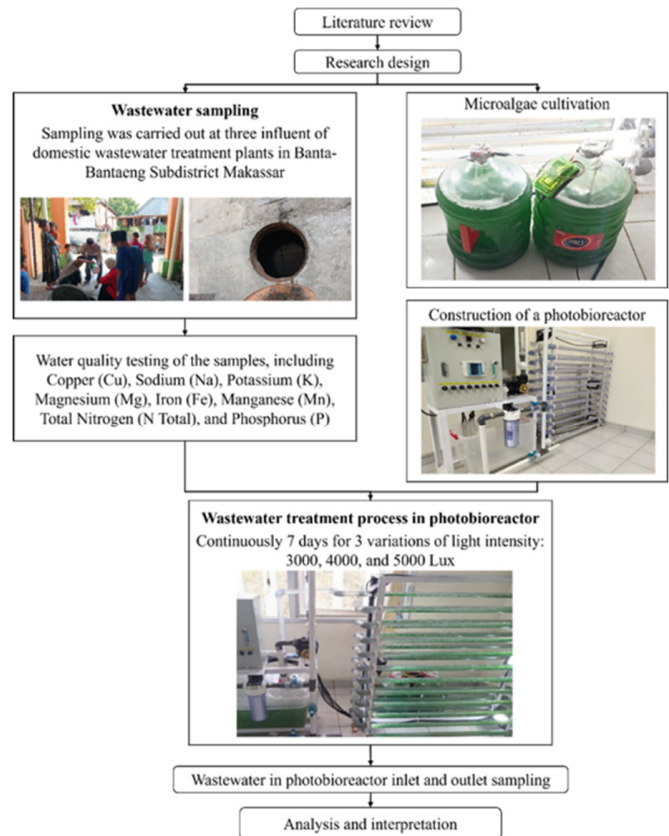


Fig. 2. Research flowchart.

#### A. Sampling and Characterization Testing of Wastewater Treatment Plant (WWTP) Effluents

Wastewater samples were collected from three WWTPs in Makassar City, South Sulawesi. Sampling was conducted in accordance with the Indonesian National Standard (SNI) 6989.59:2008 [40] for wastewater sampling procedures. The wastewater samples were filtered to remove large particles and sand, then tested for initial characteristics. The measurement process for determining the concentrations of water quality parameters in the samples was conducted at the Water Quality Laboratory, Department of Environmental Engineering, Faculty of Engineering, Hasanuddin University.

#### B. Microalgae Cultivation

*Spirulina platensis* microalgae used in this study were obtained from the Takalar Brackish Water Aquaculture Center, South Sulawesi. The initial process began with the cultivation of microalgae in the laboratory to ensure that the number of

microalgae cells was sufficient for larger-scale research. Cultivation of *Spirulina platensis* microalgae was stopped when the growth of microalgae cells was in the exponential phase and reached  $1 \times 10^6$  cells/ml.

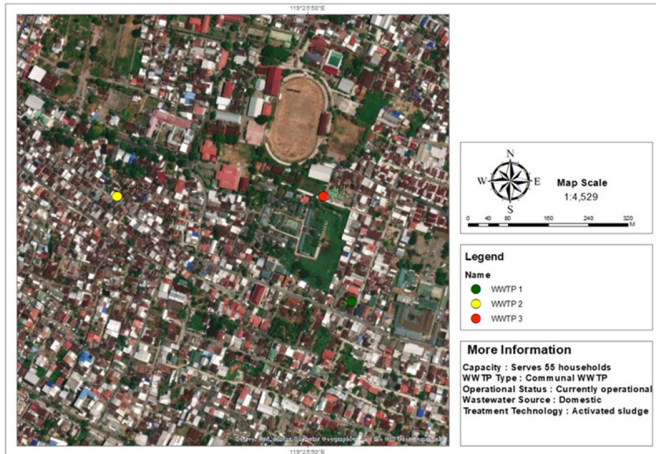


Fig. 3. The location of wastewater sampling.

The culture media used distilled water and added nutrients to support microalgae growth. The nutrient composition was specifically formulated to support microalgae biomass production and photosynthetic function. Aeration was maintained throughout the cultivation process to continuously supply oxygen and carbon dioxide to the culture medium until optimal conditions for the subsequent phase were achieved. In addition, illumination at 5000 lux was provided using photobioreactor LED lights to maximize photosynthesis. Under stable aeration and lighting conditions, microalgae exhibited rapid exponential growth.

### C. Photobioreactors Assembly and Operation

In this study, microalgae were cultivated within a photobioreactor (Figure 4) utilizing wastewater as the growth medium. The use of wastewater not only reduces production costs but also supports wastewater treatment, thereby alleviating environmental pollution. Photobioreactors constructed from transparent polycarbonate (acrylic) enable effective light penetration, which is vital for microalgal photosynthesis. The bioreactor, designed with a tubular configuration, is portable and adaptable to the available land area. The photobioreactor has a 50-liter capacity and is equipped with a control panel that regulates reactor operations, including pumps, airflow, and lighting. Below the control panel is a tank that stores domestic wastewater and microalgae. The tank is connected to a pump to ensure continuous media circulation through the pipes, thereby facilitating uniform distribution of nutrients and light. In addition, LED lights were employed in this study to provide controlled variations in light intensity, offering a flexible range of illumination as required.

Wastewater treatment in photobioreactors begins with an acclimatization process. Acclimatization is required to ensure that the microalgae can survive and maintain photosynthetic activity. This method effectively reduces the risk of microalgae

stress due to sudden changes in environmental conditions. The media mixture in phase one of acclimatization contained 50% domestic wastewater and 50% microalgae, allowing the microalgae to acclimatize in an initial phase while preventing exposure to high concentrations of wastewater that may contain toxic compounds. During condition monitoring, temperature and pH were maintained within the optimal range for microalgae growth, which is approximately pH 8.5-11 and 25°C-35°C. On day four, the wastewater concentration increased to 75%, and the microalgae concentration decreased to 25%. This study used a quantitative experimental design to evaluate the effectiveness of *Spirulina platensis* in treating domestic wastewater. The independent variable was light intensity, tested at three levels: 3000, 4000, and 5000 lux. The dependent variables were N and P concentrations, which were measured daily and analyzed in the laboratory to determine removal efficiency. To support optimal growth conditions, pH and temperature were periodically monitored as environmental indicators.

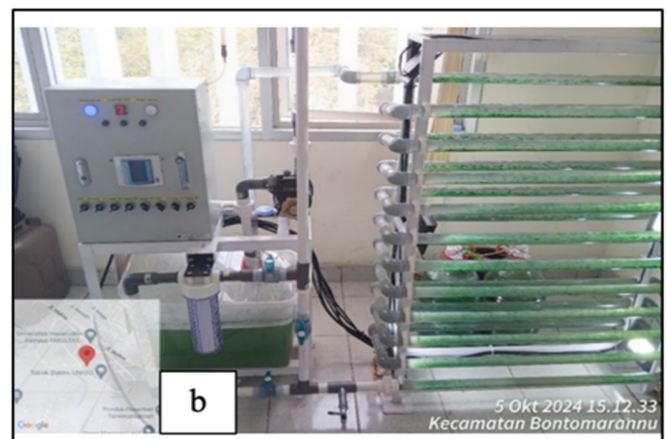
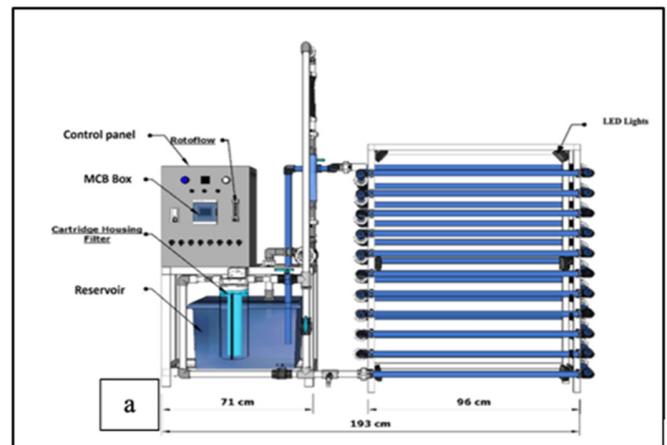


Fig. 4. (a) Photobioreactor design, and (b) wastewater treatment in the photobioreactor.

### D. Photobioreactors Data Collection and Analysis

The cultivation process is carried out continuously in a photobioreactor, with operational parameters including light intensity, aeration, and nutrient supply. Aeration and lighting

are maintained continuously for 24 hours to ensure optimal environmental conditions for *Spirulina platensis* growth. The reduction in N and P levels from domestic wastewater treatment results is analyzed using parameter tests. Data analysis uses the formula in equation (1), where A represents parameter levels at the inlet and B represents parameter levels at the outlet [41]. Removal efficiency reflects the percentage of nutrient uptake by microalgae in the photobioreactor.

$$\text{Removal Efficiency} = \frac{A-B}{A} \times 100\% \quad (1)$$

The experimental data were analyzed in IBM SPSS to evaluate the effect of light intensity on N and P removal. Before statistical testing, the Shapiro–Wilk test was conducted to assess normality. When the dependent variables did not meet the assumption of normality, a robust statistical test was applied to ensure that the results remained valid and reliable [42].

#### IV. RESULTS AND DISCUSSION

##### A. Characteristics of Wastewater Treatment Plants' Effluent

*Spirulina platensis* is effective for the remediation of domestic wastewaters because it uses the nutrients in the wastewaters for growth. The characterization of the domestic wastewater samples used in this study is shown in Table I.

TABLE I. CHARACTERISTICS OF WASTEWATER TREATMENT PLANTS' EFFLUENT

Parameter	Units	Wastewater Treatment Plant		
		1	2	3
Total Suspended Solid (TSS)	mg/L	45	13	12
pH	-	7.03	7	7.12
Biochemical Oxygen Demand (BOD <sub>5</sub> )	mg/L	13.57	15.16	15.96
Chemical Oxygen Demand (COD)	mg/L	58.90	60.04	67.33
Ammonia (NH <sub>3</sub> )	mg/L	11.59	9.82	10.44
Nitrogen Total	mg/L	28.84	11.09	7.76
Phosphorus (P)	mg/L	6.57	3.33	3.82
Copper (Cu)	mg/L	0.01	0.01	0.02
Sodium (Na)	mg/L	8.03	8.17	8.97
Potassium (K)	mg/L	8.06	9.66	10.76
Magnesium (Mg)	mg/L	13.77	15.89	9.53
Iron (Fe)	mg/L	1.072	0.50	0.35
Manganese (Mn)	mg/L	0.85	0.33	1.29

The parameter concentrations in the table above provide insight into the quality of treated domestic wastewater across WWTPs. BOD<sub>5</sub> and COD, key indicators of organic loading in wastewater, are comparatively elevated. High concentrations of heavy metals, such as copper and iron, can cause environmental contamination when they exceed safe thresholds. These metals are toxic to aquatic organisms and bioaccumulate, potentially disrupting the food web [43].

Total suspended solids (TSS) were also elevated, reaching a maximum of 45 mg/L at WWTP 1. Such levels reduce light penetration in water bodies, suppress photosynthesis in aquatic biota, and promote sedimentation that degrades benthic habitats. The elevated concentrations of total N and P at WWTP 1 indicate that the effluent remains highly nutrient-

enriched, which could induce eutrophication if released untreated into receiving water bodies. Eutrophication fosters excessive algal proliferation, reducing dissolved oxygen levels and leading to subsequent mortality among aquatic biota. Elevated N and P levels in wastewater are a principal driver of eutrophication in natural water systems, thereby compromising aquatic ecosystems. Effective assimilation of these nutrients can be achieved through bioremediation using microalgae, such as *Spirulina* sp.

N and P are the most relevant parameters for domestic wastewater treatment using the microalga *Spirulina platensis*, as they are essential macronutrients that support robust microalgal proliferation. The elevated concentrations of N and phosphate documented in Table I make this wastewater an optimal nutrient reservoir for microalgae-mediated bioremediation, promoting efficient nutrient sequestration and biomass accumulation. Microalgae naturally absorb inorganic nutrients such as N and P through photosynthesis and cellular metabolism, thereby significantly reducing the concentrations of these pollutants in wastewater.

##### B. Removal Efficiency of Nitrogen

The forms of N directly available to microalgae are free ammonia (NH<sub>3</sub>) and nitrate (NO<sub>3</sub><sup>-</sup>), which support the synthesis of lipids, amino acids, and vegetative cells. Among these, nitrate is the predominant form of N in natural waters and serves as a primary nutrient for both plants and microalgae [44]. Data on Total Nitrogen (TN) removal efficiency are shown in Figure 5.

Based on Figure 5a, all light intensities removed N from wastewater. N removal efficiency began at the start of growth and peaked on the 3rd day, with values ranging from 37.44% to 53.70% across all light-intensity levels. Meanwhile, as shown in Figure 5b, the total removal efficiency of the photobioreactor after 7 days at light intensities of 3000, 4000, and 5000 Lux is 80.42%, 87.31%, and 90.35%, respectively.

In the early stages of microalgae growth in a photobioreactor, N uptake efficiency is low because the microalgae are in the lag/adaptation phase. During this growth phase, the microalgae are still adapting to new environmental conditions, including increased light intensity and N concentration in the medium. N uptake efficiency decreases from days 4 to 7 due to insufficient available N in the medium. This is due to the increase in microalgal cell density during the previous phase, which causes N scarcity as rapidly growing microalgal cells compete for N. This decrease in nutrient uptake efficiency is consistent with a decrease in microalgal numbers. This indicates that the microalgae have completed the stationary phase and are progressing toward the death phase, characterized by reduced metabolic activity, reduced nutrient uptake capacity, reduced cell number, and cessation of cell division, as the microalgae are no longer able to photosynthesize effectively.

The light intensity of 5000 Lux in this study achieved the highest daily N absorption efficiency of 53.70% on the 3rd day, with a total removal efficiency of 90.35%. This indicates that lamps at this light intensity are quite effective at removing N from wastewater by microalgae in the photobioreactor. A light

intensity of 5000 Lux is optimal for accelerating photosynthesis and for producing sufficient energy to efficiently absorb N from the medium. This study's finding is higher than [31], which reported a TN removal efficiency of 49.71% using *Spirulina platensis* in domestic wastewater at 5000 Lux. Moreover, it is similar to the work of the authors in [45], who achieved nearly complete TN removal within 10 days.

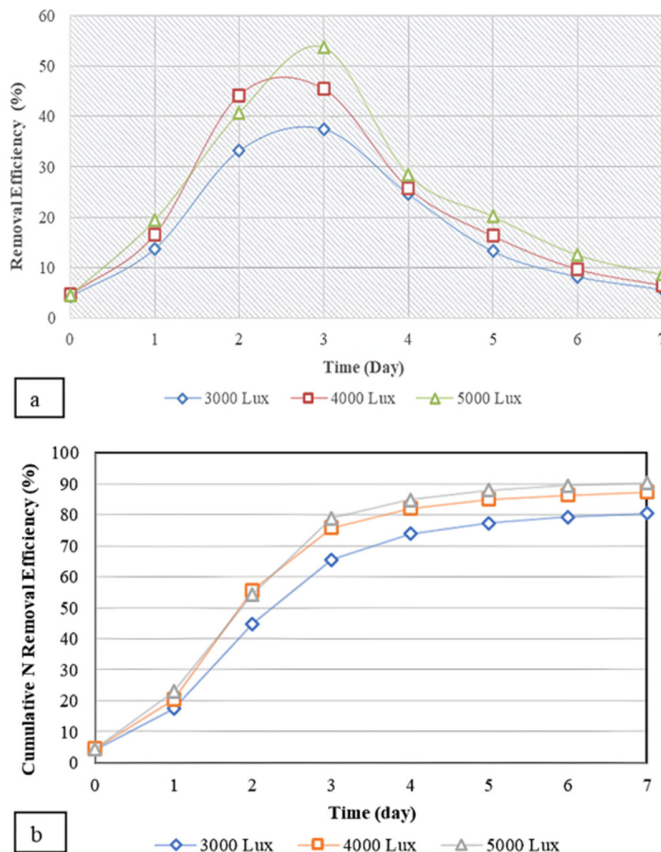


Fig. 5. (a) Nitrogen daily removal efficiency, and (b) cumulative removal efficiency from domestic wastewater in various light intensities.

N removal efficiency can be influenced by several factors, including pH, temperature, and the concentration of ammonium ions ( $\text{NH}_4^+$ ) in the solution [46]. In domestic wastewater, N commonly occurs as ammonia ( $\text{NH}_3$ ) and ammonium ( $\text{NH}_4^+$ ), with their relative proportions depending on pH. At higher pH levels, the equilibrium shifts toward the more volatile  $\text{NH}_3$ , which can be released into the atmosphere. One possible explanation for the reduced removal of TN is the inhibitory effect of free ammonia ( $\text{NH}_3$ ) on microbial metabolism. Because of its lipophilic nature,  $\text{NH}_3$  readily diffuses into cells and is converted to ammonium ions to maintain equilibrium. This conversion disrupts ionic balance by promoting potassium efflux and requiring continuous energy expenditure, thereby impairing microbial growth. Moreover, intracellular ammonium accumulation may interfere with protein synthesis, further inhibiting cellular activity and ultimately reducing N removal efficiency [47].

### C. Removal Efficiency of Phosphorus

The P content in domestic wastewater is an element required by microalgae. The author in [34] stated that P is used as a fertilizer, food additive, and detergent, amounting to 79%, 11%, and 7%, respectively. The remaining 3% is for other purposes. P is obtained from phosphate ( $\text{PO}_4^{3-}$ ), which serves as a nutrient source for *Spirulina platensis*, particularly for energy metabolism, energy transfer, and membrane stabilization. Data on total P removal efficiency are shown in Figure 6.

According to Figure 6a, P removal was observed from the start of growth, although it remained relatively low. Subsequently, P removal increased, peaking on the 3rd day and ranging from 24.67% to 61.40%. This change suggests that the microalgae are in the exponential growth phase, during which their metabolic activity is maximized, and cell division is optimal. The efficiency of P removal decreased from day 4 to day 7. This is a sign that microalgae are slowly declining in terms of growth and viability as the P in the growth medium depletes. The cells have entered the stationary phase, during which cell growth decreases due to nutrient depletion, even though the light intensity should be sufficient. The change in P removal efficiency over time is consistent with microalgal growth theory [22], in which, once light intensity is high, photosynthesis occurs during the initial days of culture growth; after this point, growth is highly dependent on nutrient availability. The highest daily removal efficiency, 61.40%, occurred in the test treatment variation at a light intensity of 5000 Lux.

Meanwhile, in Figure 6b, the cumulative P removal efficiency across different light intensities shows that microalgal performance depends on illumination. P removal increased progressively with both light intensity and cultivation time, with the highest efficiency consistently achieved at 5000 Lux. At this intensity, removal occurred rapidly, exceeding 45% within two days and reaching 90.45% on the last day, higher than in other similar studies [31, 45]. This result indicates accelerated nutrient uptake and efficient assimilation. In contrast, cultures maintained at 4000 Lux exhibited a more gradual increase, achieving 63.98% removal by the end of the experiment. The lowest removal efficiency was recorded at 3000 Lux, with only 52.58% removal after seven days, reflecting a slower uptake rate.

This finding indicates that the light intensity plays a pivotal role in the P reduction process by microalgae in the photobioreactor. An intensity of 5000 Lux provides sufficient energy for photosynthesis, during which microalgae optimally absorb P to produce biomass. Light intensity, along with nutrient availability, is a critical factor influencing microalgal growth. Increased light intensity enhances photosynthetic activity by providing more energy, thereby promoting higher growth rates.

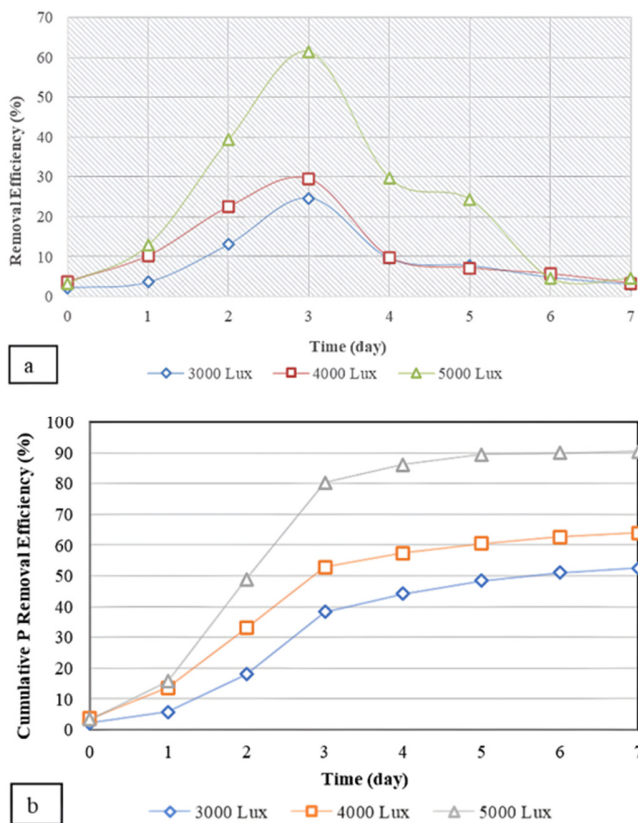


Fig. 6. (a) Daily phosphorus removal efficiency and (b) cumulative removal efficiency from domestic wastewater at various light intensities.

D. Statistical Analysis of the Light Intensity Effect

Data analysis was conducted in IBM SPSS using the Shapiro-Wilk normality test. The results showed that the N parameter data yielded a p-value < 0.001, indicating non-normality. Authors in [48] noted that in environmental research contexts, such as wastewater treatment, data are often non-normally distributed, given the many natural variables that influence N distribution and uptake. In this study, the data found to be non-normally distributed may be influenced by the natural variability of N levels that gradually appear in vegetation and are affected by changes in light intensity, which, in turn, are directly and indirectly influenced by environmental conditions such as pH and temperature. The results of the robust regression analysis on the N and P variables are presented in Table II.

TABLE II. STATISTICAL TEST OF THE EFFECT OF LIGHT INTENSITY ON NITROGEN AND PHOSPHORUS

Paramater	B	Std. Error	t	Sig.
Nitrogen	-0.536	0.960	0.559	0.583
Phosphorus	-0.465	0.192	-2.427	0.025

According to Table II, the robust regression analysis yielded a coefficient (B) of -0.536 for light intensity, indicating that each 1-unit increase in light intensity was associated with a 0.536-unit decrease in N concentration. This negative coefficient indicates an inverse relationship, in which higher

light intensity corresponds to lower N levels in the treated wastewater. However, the robust regression analysis yielded a significant coefficient of 0.583 for N, which exceeded the 0.05 threshold. This indicates that light intensity did not have a statistically significant effect on the reduction in N concentrations. These findings may instead be influenced by other factors that regulate microalgal N uptake, such as growth stage, physiological condition, or cellular metabolic activity, all of which play important roles in determining N assimilation rates.

Meanwhile, in the robust regression analysis of P parameters, the regression coefficient (B) for light intensity is -0.465, indicating that each 1-unit increase in light intensity is associated with a 0.465 mg/L decrease in P levels. The significance value is 0.025, which is less than 0.05. This demonstrates that the relationship between light intensity and P concentrations is statistically significant. This finding highlights that light intensity plays a more critical role in P removal than in N removal by microalgae due to fundamental differences in their metabolic assimilation pathways. P uptake, particularly as acid-soluble phosphate (ASP), is tightly coupled to photosynthetic activity, which is directly driven by light availability. Light intensity significantly enhances the capacity for luxury uptake, a process in which microalgae absorb and store P in excess of their immediate metabolic needs. This surplus P is stored intracellularly, often as polyphosphates, and is later mobilized when external P becomes scarce (see Figure 1). Under high light intensity, microalgae exhibited significantly greater ASP utilization, resulting in higher photosynthetic rates and more efficient P removal. The increased light intensity accelerated its metabolic utilization, suggesting that light predominantly affects utilization rather than accumulation of P within cells [49].

In contrast, N removal is less directly influenced by light intensity because N uptake and assimilation are more closely tied to biomass growth and cellular protein synthesis, processes that can occur in both light and dark conditions. Although elevated light can enhance N uptake to some extent, its effect is less tightly coupled to metabolic pathways than with P [49, 50]. This distinction underscores the greater dependence of P removal on light intensity and explains why P removal in this study is more sensitive to changes in light intensity than N removal.

V. CONCLUSION

This study developed a photobioreactor for cultivating microalgae using wastewater as the growth medium. Environmental conditions, including nutrients, temperature, and pH, were adjusted to meet the microalgae's requirements. Light intensity, a growth-supporting factor, was varied to determine the optimal conditions for microalgal performance. The experimental results showed that light intensity significantly affected the removal efficiency of nitrogen (N) and phosphorus (P) from wastewater. Among the three tested light-intensity variations, 5000 lux produced the highest daily and cumulative removal efficiencies over seven days, with N removal ranging from 53.70% to 90.35% and P removal from 61.40% to 90.45%. These findings indicate that a light intensity of 5000 lux is optimal for reducing N and P. This light intensity

creates favorable conditions for microalgae to carry out efficient photosynthesis, support optimal growth rates, and enhance contaminant removal from domestic wastewater.

The novelty of this study lies in the integrated evaluation of a photobioreactor system that combines controlled environmental conditions with systematic optimization of light intensity to enhance nutrient removal from domestic wastewater. The removal efficiencies obtained are comparable to those reported in previous studies, confirming the effectiveness of the proposed system and demonstrating its potential for sustainable, environmentally friendly wastewater treatment. These findings underscore the importance of optimizing light intensity, a key operational parameter, to maximize microalgal performance and improve nutrient removal efficiency in photobioreactor-based wastewater treatment systems.

#### DECLARATION OF COMPETING INTERESTS

Not applicable to this work

#### ACKNOWLEDGMENT

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#### DATA AVAILABILITY

All data generated or analyzed during this study are included in this published article.

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