Engineering Perspectives in Filtration and Separation, Vol. 4, No. 3, September 2026
ISSN:3107-5290

Development of Microalgae-Based Bioremediation Systems for Simultaneous Nutrient Removal and Biomass Production from Municipal Wastewater

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Abstract--- Municipal wastewater contains significant levels of nutrients such as nitrogen and phosphorus that might lead to eutrophication if released without being treated properly. Traditional wastewater treatments mostly concentrate on the removal of pollutants, while microalgal bioremediation is known to provide both the removal of pollutants and production of biomass simultaneously. This research provides a bioremediation scheme based on Chlorella vulgaris for simultaneous removal and production of biomass from municipal wastewater. This methodological approach involves the characterization of the wastewater, wastewater pre-treatment, cultivation of microalgal cultures, photobioreactor operations, biomass harvesting, and assessment of treatment efficiency. The cultivation period is considered to be 14 days. The system efficiency is measured by total nitrogen removal efficiency, ammonium nitrogen reduction efficiency, total phosphorus removal efficiency, COD reduction efficiency, biomass concentration, and biomass productivity. The performance data set used here shows that total nitrogen reduction efficiency is 80%, ammonium nitrogen reduction efficiency is 83.93%, total phosphorus reduction efficiency is 85%, and COD reduction efficiency is 70%. The biomass concentration goes up from 0.20 to 1.65 g/L, implying a biomass productivity value of 0.1036 g/L/day. All these data make it possible to get a quantitative criterion for the study of dependence between nutrient removal from wastewater and biomass formation. The approach proposed here will help to develop a new technology of wastewater purification where reduction of pollutants is associated with biomass recovery.

Keywords--- Microalgae, Municipal Wastewater, Bioremediation, Nutrient Removal, Biomass Production, Nitrogen Recovery, Phosphorus Removal.

Received: 19 - 06 - 2026; Revised: 10 - 07 - 2026; Accepted: 18 - 08 - 2026; Published: 30 - 09 - 2026

I. Introduction

Municipal Wastewater and Environmental Concerns

Domestic wastewater is composed of organic matter, suspended solids, nitrogen, and phosphorus derived from various domestic, commercial, and institutional operations. Failure to treat properly before disposal can lead to deterioration of the quality of receiving water and eutrophication due to nutrient overload. High levels of nutrients like nitrogen and phosphorus cause excess algae growth, lowering dissolved oxygen content in the water body. For this reason, wastewater treatment technology should incorporate organic pollution control as well as nutrient removal.

Biological wastewater treatment systems use microbial activity for removal of organics and nutrients from wastewater. Even though this treatment process is effective within controlled operating conditions, nutrient removal might necessitate additional treatment steps, aeration, chemical addition, and sludge handling (Nguyen et al., 2022). This makes the process complex and increases resource utilization. Therefore, valuable materials recovery from wastewater has become an important issue in wastewater treatment technology development.

Microalgae-Based Wastewater Bioremediation

The process of biological treatment of wastewater using microalgae can be explained by the assimilation of nitrogen and phosphorus from the wastewater. In this case, nitrogen will help in the formation of proteins and nucleic acids, while phosphorus will help in the transfer of energy and metabolism of cells. In addition, the cultivation of microalgae in wastewater helps in the reduction of organic pollutants through interaction with associated microorganisms and alterations of physicochemical characteristics of wastewater (El-Sheekh et al., 2025).

Some of the commonly studied microalgae that can be used in wastewater cultivation include Chlorella vulgaris. It is chosen because of its ability to accumulate biomass and absorb nutrients from the wastewater. Its cultivation in wastewater will allow for testing the effectiveness of treatment and biomass production.

Research Motivation

While the possible benefits associated with microalgae treatment could be numerous, the successful simultaneous removal of nutrients and biomass generation depends on a number of interrelated operational parameters. Such parameters include light, temperature, pH level, initial nutrient concentration, inoculum density, as well as the cultivation time that affects microalgal growth and treatment effectiveness.

In this connection, an integrated system of cultivation must be developed to analyze wastewater properties, set cultivation parameters, measure nutrient removal, and quantify biomass generation. A laboratory photobioreactor is used to control the above-mentioned parameters.

Objectives and Contributions

The main aim is to design a bioremediation strategy using Chlorella vulgaris that would help to remove nutrients and produce biomass from municipal wastewater simultaneously. The particular aims of the research are:

1. Characterization of municipal wastewater in terms of selected physicochemical parameters.
2. Development of controlled microalgal cultivation conditions in a laboratory-scale photobioreactor.
3. Evaluation of reduction in nitrogen, phosphorus, and organic pollutants content during cultivation.
4. Measurement of microalgal biomass production and productivity.
5. Study of interrelationship between nutrient removal and biomass production.

The proposed research includes wastewater characterization, controlled microalgal cultivation, evaluation of treatment performance, and biomass production in a single framework. It forms a basis for assessing the potential of using microalgae in municipal wastewater treatment as a resource-oriented biological system.

II. Literature Review

Development of Microalgae-Based Wastewater Treatment

Wastewater Treatment Using Microalgae as a Biological Method of Reducing Nutrients and Producing Recoverable Biomass. Wastewater treatment using microalgae has become one of the popular methods of biological wastewater treatment where both the nutrients are reduced along with biomass production (Ahmad et al., 2021; Geremia et al., 2021). Various types of cultivation setups such as open ponding system, closed photobioreactors, and others have been explored in the context of wastewater treatment (de Cassia Soares Brandão et al., 2023). Open setups are easy to handle and do not require much infrastructure, but they are vulnerable to changes in the environment.

Selection of Cultivation System Is Based on Waste Stream Characteristics, Goals of Treatment, Available Resources, and the Need for Control. A controlled photobioreactor should be used to study the correlation between nutrient removal and biomass generation.

Mechanisms of Nitrogen and Phosphorus Removal

The process of nitrogen removal through microalgal cultivation mainly involves assimilation of nitrogen by cells (Ortega-Blas et al., 2025). Ammonia and nitrate may be utilized for the creation of cell elements necessary for protein production and growth (Leong et al., 2021). Nitrogen may further be reduced through the process of ammonia evaporation, microbial conversion, and other physicochemical methods dependent on the pH, temperature, and cultivation conditions (Dammak et al., 2023). Thus, the total reduction of nitrogen in the

wastewater cannot be solely assigned to microalgal assimilation without proper experimental investigation (Singh et al., 2023; Ali et al., 2024).

The process of phosphorus removal is mainly connected with its uptake and utilization in phosphorus-containing compounds. Phosphorus is needed for microalgae to create energy, nucleic acids, and membranes. Phosphorus may also be removed through the process of precipitation and adsorption. Biological and physicochemical mechanisms contribute to the phosphorus removal effectiveness.

Factors Influencing Microalgal Cultivation

The growth rate and nutrient elimination depend on the environmental and operational factors (Nedaei & Shokrkar, 2025). Light intensity and photoperiod affect the process of photosynthesis, and temperature impacts metabolism and cell growth. The initial value of pH determines the availability of nutrients and carbon assimilation as well as the balance of dissolved components. Moreover, inoculum density and nutrients composition in wastewater define the initial parameters of cultivation (Chen et al., 2020).

The lack of light leads to low photosynthesis rates, and the excess of light results in photoinhibition. Temperature variations and inappropriate pH values impact growth rate negatively. Thus, the maintenance of adequate conditions is necessary for constant biomass production and nutrient removal.

Biomass Production and Recovery Potential

The production of microalgal biomass serves as a potential resource that is created in the process of wastewater treatment. This process depends on nutrient supply, photosynthesis rate, growth period, and harvesting method. Microalgal biomass can be obtained by sedimentation, filtration, centrifugation, or any other technique of biomass separation. The choice of the harvesting technique depends on the concentration of biomass, the nature of cells, and costs.

The use of microalgal biomass in bioenergy generation, the agriculture industry, or any other bioprocesses is potentially possible. Nevertheless, the biomass produced using municipal wastewater should be subjected to some quality testing prior to further application since the pollutants might accumulate in biomass (Ahiahonu et al., 2024).

Literature Search Strategy and Research Gap

The literature review covers various topics on wastewater treatment with the help of microalgae, the processes of nitrogen and phosphorus uptake, cultivation in photobioreactors, production of biomass, and recovery of resources. These research areas are defined based on the combinations of keywords related to municipal wastewater, Chlorella vulgaris, nutrient removal, microalgal cultivation, and biomass harvesting. They are being compared in regard to cultivation configuration, mechanisms of treatment, operational needs, and recovery opportunities.

Table 1: Comparative Assessment of Microalgae-Based Wastewater Treatment Approaches

Treatment approach	Operational characteristics	Nutrient removal potential	Biomass recovery potential	Major limitation
Open pond cultivation	Natural or assisted mixing with sunlight exposure	Nitrogen and phosphorus uptake	Moderate to high	Weather dependency and contamination
Closed photobioreactor	Controlled illumination and cultivation conditions	Controlled nutrient assimilation	High under optimized conditions	Higher construction and operating costs
Attached microalgal system	Biomass growth on supporting surfaces	Nutrient uptake and surface-associated processes	Facilitates biomass separation	Surface fouling and limited growth area
Integrated algal–bacterial system	Combined algal photosynthesis and microbial activity	Combined nutrient and organic matter reduction	Biomass generation through biological growth	Complex process interactions
Suspended microalgal cultivation	Free-floating cells in wastewater	Nutrient uptake through direct cell–water interaction	Requires downstream harvesting	Biomass separation difficulties

Previous studies provide an example of the ability of microalgae to reduce nutrients and produce biomass. However, the analysis of these results separately can hardly give any idea about their interrelation under controlled cultivation of wastewater. Furthermore, the differences in wastewater composition and operational

parameters complicate performance comparison. In this way, the present study will cover all these issues through characterization of wastewater, controlled cultivation in photobioreactors, nutrient removal and biomass production. The comparison of major configurations of treatment is presented in table 1.

III. Methodology

Development Framework

In particular, the developed methodology of bioremediation includes wastewater analysis, microalgae cultivation preparation, cultivation itself, nutrient removal evaluation, and biomass harvest. The first step is related to wastewater collection and physicochemical analysis for setting the initial conditions of wastewater treatment. The wastewater is prepared for cultivation and inoculated by Chlorella vulgaris in a laboratory scale photobioreactor. The controlled illumination, temperature, and photoperiods facilitate microalgae growth during cultivation. Nutrient changes and biomass accumulation are used for evaluation of treatment efficiency and biomass productivity. The entire sequence of the methodological steps is described in figure 1.

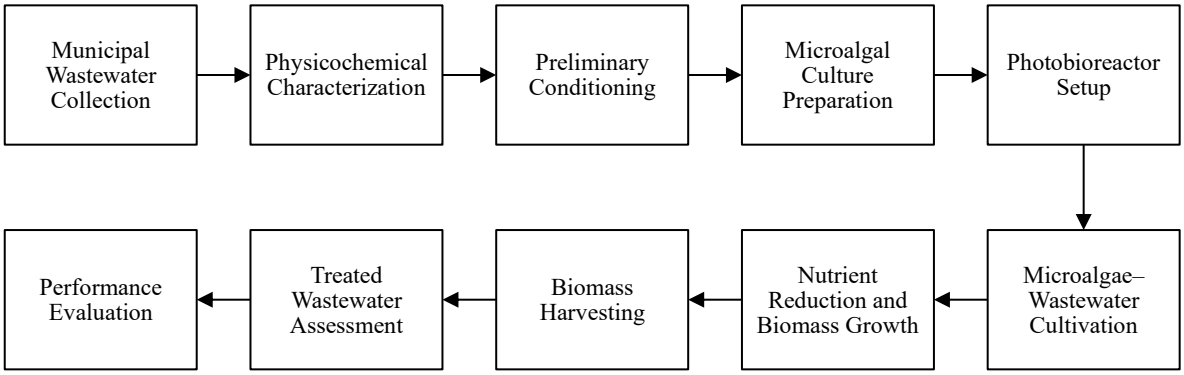


Figure 1: Overall Methodological Framework of the Developed Microalgae-Based Bioremediation System

Wastewater Characterization and Preparation

It is noted that municipal wastewater is the cultivation medium for assessing microalgal nutrient uptake and biomass formation. The initial properties of wastewater are analyzed by measuring such parameters as pH, COD, BOD, total nitrogen, ammonium nitrogen, total phosphorus, and turbidity. Such properties will be used as reference data for changes in wastewater quality during cultivation.

Preliminary wastewater conditioning is introduced to eliminate the coarse suspended matter that might affect cultivation and measurement of wastewater quality. Initial physicochemical properties are utilized as reference data to calculate nutrient elimination and removal of organic pollutants. It is important to perform wastewater preparation to preserve nutrient compounds for microalgal cultivation.

Microalgal Culture and Photobioreactor Configuration

The choice of Chlorella vulgaris as the microalgae is justified by the ability of these organisms to assimilate nutrients and their adaptability to cultivation in wastewater. The microalgal culture is added to the prepared wastewater with an initial biomass concentration of 0.20 g/L. The cultivation of microalgae is carried out using a laboratory-scale photobioreactor with a working volume of 2 L. The design of the photobioreactor ensures the conditions for the cultivation of microalgae, which is illustrated in figure 2.

The process parameters are controlled as follows: temperature of 25±2°C, initial pH equal to 7.5, light intensity of 150 μmol photons/m^2/s. The illumination schedule involves 16 h of light and 8 h of darkness per day. The duration of the cultivation is defined as 14 days.

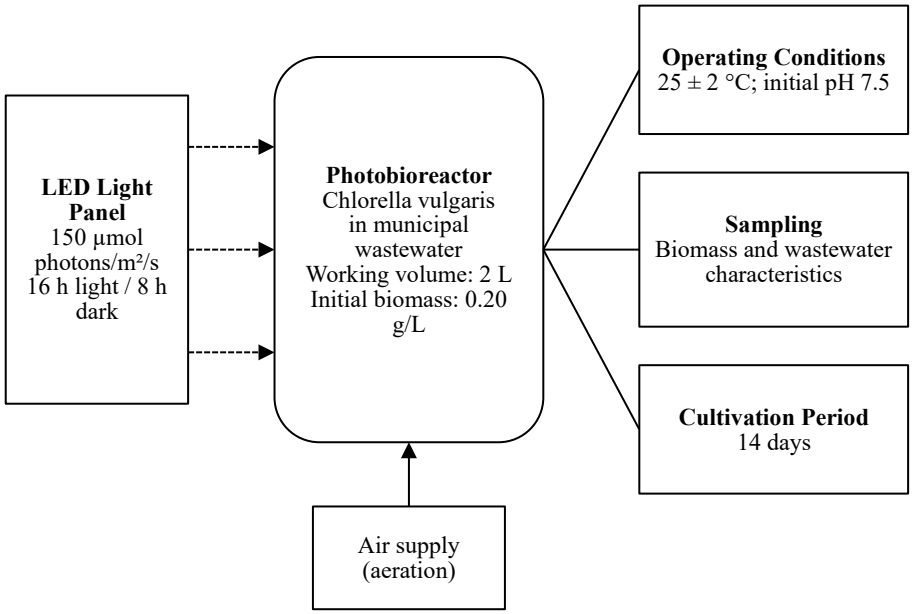


Figure 2: Experimental Configuration of the Microalgae-Based Wastewater Bioremediation Reactor

Nutrient Removal and Biomass Production Assessment

The microalgae use nitrogen and phosphorus during the cultivation process for cell development. Nitrogen helps develop protein and other nitrogen-containing substances, while phosphorus assists in cellular energy transport and development. There are other biological processes and physicochemical reactions that may have an impact on the levels of nutrients.

Biomass level is measured regularly every two days to determine the development of microalgae. Levels of nutrients in the wastewater are determined to determine the levels of change in total nitrogen, ammonium nitrogen, and total phosphorus. Changes in COD levels are also considered to determine changes in organic pollution levels. The biomass is then separated from the wastewater.

Performance Evaluation Parameters

The efficiency of the bioremediation process is assessed using nitrogen/phosphorus removal efficiency, COD removal efficiency, biomass generation, and average biomass productivity. Removal efficiencies of nitrogen and phosphorus are computed based on their initial and final concentration as per equation (1) and equation (2).

$$\eta_N = \frac{N_i - N_f}{N_i} \times 100 \quad (1)$$

$$\eta_P = \frac{P_i - P_f}{P_i} \times 100 \quad (2)$$

Where $N_i$and $N_f$represent the initial and final total nitrogen concentrations, respectively, while $P_i$and $P_f$represent the corresponding total phosphorus concentrations.

Average biomass productivity is calculated using equation (3):

$$P_B = \frac{X_f - X_i}{t_f - t_i} \quad (3)$$

Where $X_i$and $X_f$denote the initial and final biomass concentrations, respectively, and $t_i$and $t_f$represent the corresponding cultivation times. The calculated productivity provides an estimate of average biomass accumulation per unit volume per day. The principal operating conditions and evaluation parameters are summarized in table 2.

Table 2: Operational Parameters and Performance Evaluation Metrics

Parameter	Specification	Unit
Microalgal species	*Chlorella vulgaris*	—
Cultivation system	Laboratory-scale photobioreactor	—
Working volume	2	L
Cultivation duration	14	days
Temperature	25 ± 2	°C
Initial pH	7.5	—
Light intensity	150	μmol photons/m^2/s
Photoperiod	16:8	h
Initial biomass concentration	0.20	g/L
Sampling interval	2	days
Total nitrogen	Initial and final concentration	mg/L
Total phosphorus	Initial and final concentration	mg/L
COD	Initial and final concentration	mg/L
Biomass productivity	Change in biomass per unit time	g/L/day

IV. Results and Discussion

Initial Physicochemical Characteristics of Municipal Wastewater

The initial water characteristics act as the benchmark to assess the efficiency of the microalgal bioremediation system. These parameters include pH, COD, BOD, total nitrogen, ammonia nitrogen, total phosphorus, and turbidity. The initial nutrient levels indicate the presence of nitrogen and phosphorous for microalgal growth. Physico-chemical properties of water to be assessed during treatment are presented in table 1.

Table 3: Physicochemical Characteristics of Municipal Wastewater

Parameter	Initial concentration	Unit
pH	7.50	—
COD	180	mg/L
BOD	85	mg/L
Total nitrogen	45.0	mg/L
Ammonium nitrogen	28.0	mg/L
Total phosphorus	8.0	mg/L
Turbidity	42	NTU

Nutrients such as total nitrogen and phosphorus, which are present in the initial wastewater at 45.0 mg/L and 8.0 mg/L, respectively, signify that the water supports microalgal growth. The initial organic pollutants contained in the wastewater in terms of COD are 180 mg/L. These are the reference values for determining changes that occur during cultivation.

Microalgal Growth and Biomass Production

Growth of the microalgae is measured in terms of biomass concentration, which is checked on alternate days during the 14-day period of cultivation. The biomass concentration grows from an initial value of 0.20 g/L to a final value of 1.65 g/L on day 14. Growth is an indicator of biomass accumulation under the given cultivation conditions.

Biomass growth curve is shown in figure 3. Growth curve shows rapid growth during the early and intermediate stages of cultivation with a subsequent slow growth at later stage.

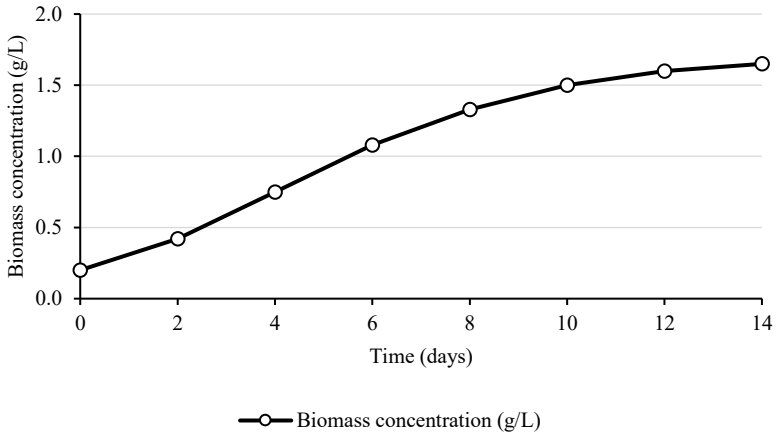


Figure 3: Temporal Variation of Microalgal Biomass Concentration During Cultivation

The average biomass productivity is calculated from the difference between the initial and final biomass concentrations over 14 days and is represented in equation (4).

$$P_B = \frac{1.65 - 0.20}{14} = 0.1036 \text{ g/L/day} \qquad (4)$$

The resulting average productivity is 0.1036 g/L/day, with a net biomass accumulation of 1.45 g/L. This parameter provides an overall measure of biomass generation during the cultivation period.

Nitrogen Removal Performance

The removal of nitrogen is based on the difference in total nitrogen concentration during the culture process. The total nitrogen concentration at the beginning is 45.0 mg/L, whereas the final total nitrogen concentration reduces to 9.0 mg/L. The efficiency of removal is 80% on day 14.

The removal of nitrogen may be attributed to microalgal assimilation and some other biological and physicochemical activities taking place in the culture process. Ammonium nitrogen reduces from 28.0 mg/L to 4.5 mg/L, which is equivalent to 83.93% removal. Yet, the separate removal process needs further investigation through nitrogen speciation and mass balance calculations. The time-dependent removal of nitrogen and efficiency are shown in figure 4.

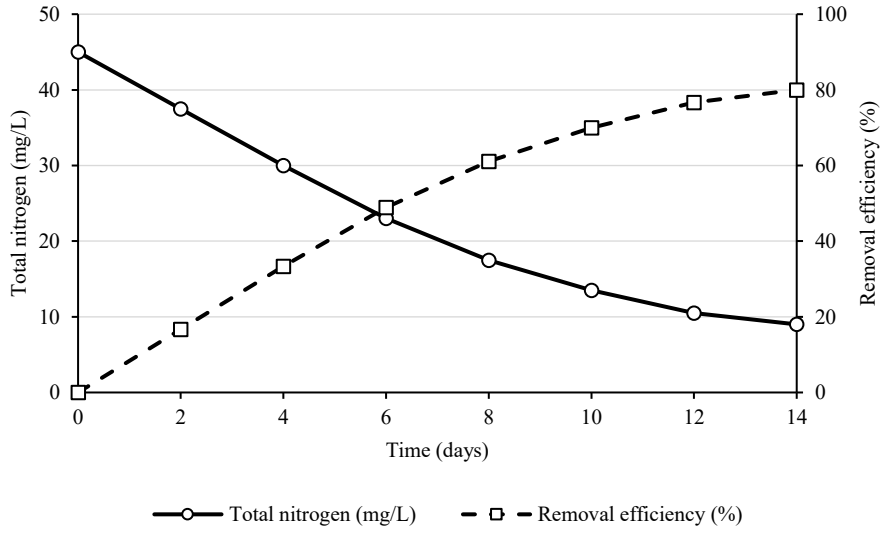


Figure 4: Variation in Total Nitrogen Concentration and Removal Efficiency During Cultivation

This overall decrease implies the capability of the growth system to lower the concentration of nitrogen in the effluent water while facilitating the growth of microalgae biomass. The overall total nitrogen concentration is the main factor used in determining the overall nitrogen removal efficiency.

Phosphorus Removal and Organic Pollutant Reduction

Reduction in phosphorus is determined by measuring the total phosphorus before and after the experiment. The phosphorus concentration drops from 8.0 mg/L to 1.2 mg/L, which is a decrease of 85% throughout the process of cultivation. This decrease may occur due to microalgal absorption, incorporation into cellular material, and physicochemical elimination processes.

COD drops from 180 mg/L to 54 mg/L, which is a 70% reduction. This may be related to the interaction between microalgae and microorganisms that can be found in wastewater, as well as changes in the organic matter during cultivation. It is important to conduct further experiments in order to understand the effect of individual mechanisms.

Overall decrease in nitrogen, phosphorus, and COD demonstrates the effectiveness of combining microalgal cultivation with wastewater treatment. But the concentration changes by themselves are not enough to determine the contribution of each individual process.

Relationship Between Nutrient Removal and Biomass Recovery

The link between biomass production and nutrient removal is linked together in the sense that nitrogen and phosphorus form parts of the building blocks of cells. As microalgal biomass is produced, some nutrients present in the system will be used for cell building. The biomass will then be separated from the waste water using the suitable method of harvesting. The correlation between wastewater nutrient removal, microalgal growth and biomass production is illustrated in figure 5.

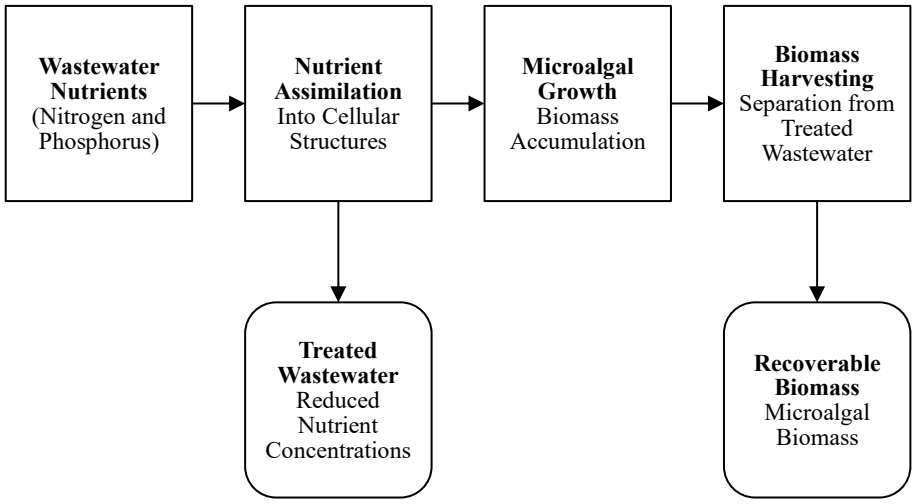


Figure 5: Integrated Relationship between Nutrient Assimilation, Microalgal Growth, And Biomass Recovery

This process leads to the production of two different products which include lower concentration of nutrients in the effluent and biomass of microalgae which can be recovered from the process. It is important to determine the amount of nutrients converted to biomass because it is important to distinguish biological assimilation from other types of removal processes.

Overall Treatment Performance and Practical Considerations

The performance indicators that were assessed illustrate simultaneous reductions in concentrations of major pollutants in the wastewater and increase in microalgal biomass. Specifically, total nitrogen and phosphorus show reductions of 80% and 85%, respectively, while COD reduces by 70%. The biomass concentration rises from 0.20 to 1.65 g/L, giving an average productivity of biomass of 0.1036 g/L/day.

This experiment shows the viability of the method of using microalgae as both wastewater purification agent and biomass generator. However, practical application of this method demands consideration of such issues as lighting regime, temperature regulation, harvesting of biomass, its contamination, and consumption of energy.

Stability of long-term cultivation and quality of harvested biomass should be taken into account in order to assess further use of biomass.

For further assessment of the technology, one should repeat experiments, calculate the mass balance of nutrients, study biomass composition and compare it with other wastewater treatment schemes. Also, pilot plant tests should be conducted.

V. Conclusion

The bioremediation system based on Chlorella vulgaris is designed to investigate the possibility of co-removal of nutrients and biomass generation from municipal wastewater. This approach includes wastewater characterization, growth in a controlled photobioreactor system, nutrient removal evaluation, and biomass production within the same system. Based on the tested data set, there is the following reduction: 80% for total nitrogen, 83.93% for ammonium nitrogen, 85% for total phosphorus, and 70% for chemical oxygen demand. There is biomass generation increase from 0.20 to 1.65 g/L during the 14-day cultivation, thus, the average biomass production rate equals 0.1036 g/L/day. This result reflects the possible connection between nutrient removal from wastewater and biomass generation by microalgae.

The integration of nutrient removal and biomass production allows for enhancement of wastewater resource recovery, along with reduction of effluent disposal rich in nutrients. Biomass, which could be recovered during this process, has a potential to be used further; however, its quality needs to be analyzed properly before making any conclusion about that. At the same time, the efficiency of the suggested approach is dependent upon cultivation stability, nutrient availability, illumination, temperature, and biomass recovery. Future research should be oriented towards conducting experiments multiple times, performing nutrient mass balance analysis, characterization of microalgae biomass, and individual nutrient removal mechanisms study. It is also important to optimize operating parameters of photobioreactors and evaluate energy consumption in order to check the feasibility of the whole process. The pilot-scale testing should involve investigation of treatment stability, biomass recovery, and cost-effectiveness.

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