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Key Determinants of Algal Biomass Growth for Bioenergy: A Comprehensive Review

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Abstract

Microalgae is an essential source of renewable bioenergy like biofuels and biohydrogen production due to their high lipid content and rapid growth rate. These eukaryotic organisms exist in an array of habitats, encompassing photobioreactors, closed ponds, and open ponds. But in a photobioreactor or closed system, which provide controlled environment for the cultivation of microalgae a number of variables must be optimized. Because various physio-chemical factors i.e. nutrient availability, light intensity, temperature, pH, mixing/aeration, and salinity, affecting microalgal growth, proliferation, and morphology. However, techno-economic improvements can be made in optimizing and controlling the growth phase of biomass processing. Analysing every factor influencing algae growth and talking about the favourable conditions, strategies and methodology to optimization of factors to achieve better results is the main goal of this review paper. This review aims to serve as a valuable resource for future researchers or anyone who interested to produce maximum algae without any obstruction. A novel aspect of this research is the employment of how to optimize algal growth by adjusting various parameters in a photo bioreactor to improve large-scale cultivation productivity of algae. Thus, the present study aims to investigate factors affecting algae growth and their optimizing methodology which is based on the literature's findings.

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Introduction

Microalgae have been drawing wide attention as a next-generation feedstock for biofuel production because they are known to provide much higher efficiency compared with terrestrial plants. In contrast to traditional biofuel sources such as corn and sugarcane that require large agricultural land and freshwater, however, An environmentally friendly and sustainable substitute is offered by microalgae.[1] Rapid biomass accumulation due to exceptionally short generations makes algae one of the most productive sources for bioenergy.[2] This feature makes

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microalgae possible to be harvested more than once a year, thus greatly increasing their biomass productivity and biofuel production. The growth and yield of microalgae are affected by various ecological and operational elements, including intensity of light, temperature, nutrient levels, CO_2 concentration, pH, and mixing conditions.[3] Optimization of these factors is thus of utmost importance for the large-scale algal biomass production system, including open ponds and photobioreactors (PBRs).[4] In particular, photobioreactors provide a carefully regulated environment wherein microalgal productivity can expediently increase, resulting in improved biomass yield and lipid accumulation, essential for biofuel production.[5]

Ultimately, this review seeks to advance the transition toward sustainable bioenergy by providing a comprehensive foundation for optimizing microalgal cultivation, paving the way for microalgae to become a cornerstone of renewable energy systems in a carbon-constrained world.[6] Algae, a wide range of photosynthetic organisms, have received substantial interest due to their applications in biofuel production, wastewater treatment, and bioproduct development.[7] Algal Production is controlled by a multifaceted interaction of natural and dietary parameters like temperature, light, pH, CO_2 level, supplement supply, blending, and saltiness.[8] Several research papers over the years have investigated these parameters, offering significant insights into the optimization of algal cultivation for different purposes.[9]

Although some species, like Scenedesmus and Spirulina, can withstand a wider range of temperatures (10–40°C), temperature plays a critical role in algal physiology.[10] Most species will grow best at temperatures between 20°C and 30°C.Light is the source of energy for photosynthesis, and certain wavelengths (blue and red) and irradiance (33–400 μmol m^{-2} s^{-1}) will optimize growth, with too much light leading to photoinhibition.11 pH of the growth medium between 7.5 and 8.0 influences carbon supply and biomass yield, and deviation causes inhibition of growth.[12] Cellular functions are supported by nutrient media like iron, phosphorus, and nitrogen as well as trace metals.[13] CO_2 concentration has a direct effect on photosynthetic efficiency.[14] Aeration guarantees a homogeneous supply of light and nutrients, and salinity has an impact on cellular homeostasis, with the tolerance being species-dependent, and thus growth and lipid synthesis.[15]

Through the integration of information from various literature's findings, this paper attempts to clarify the synergistic action of these factors on algal productivity and growth.[16] The results are meant to inform the optimization of cultivation methods for industrial uses, including biofuel production and bioproduct development, as well as addressing scaling-up issues in algal systems.[17] This review examines the crucial physicochemical factors that influence the accumulation of microalgal biomass and its suitability for biofuel synthesis, including temperature, light, pH, nutrient composition, carbon availability, mixing dynamics, and salinity.[18]

This work's main goal is to investigate possible methods for improving these interrelated elements in order to maximize algal development. Drawing from the earlier presented findings, this study aimed to identify the process underlying biomass development and production for a range of uses, including bioenergy, which are influenced by environmental and biological factors. This study was intended to help future researchers and new algae manufacturers.

Methodology

This review is based on a systematic literature analysis aimed at identifying the key factors influencing algal biomass growth for bioenergy. Only those papers were included that were based on microalgae and experimental data. Key information such as algae species used, growth conditions, and rearing methods were collected from the selected studies. These data were analysed thematically to understand the key factors influencing algal biomass productivity. Further detailed discussion and analysis is included.

Factors Affecting Algae Growth

Temperature

It is crucial to the growth of algae, and the ideal temperature range must be maintained during experiments involving algae.[19] Between 20 and 30 °C is the optimal temperature range for the development and yield of many algal species. *Chlorella* vulgaris thrives at temperatures between 25 and 30 °C and can also survive in more extreme conditions, reaching up to 30 to 35 °C. Species of Scenedesmus may survive in temperatures between 10°C to 40°C. Spirulina species show a growth range of 20 to 40°C, although high temperatures lower protein and carbohydrate levels. Algal productivity gives a positive response to increased water temperature but stops increasing when respiration from increased temperature raises the level of photorespiration. Variation in the ideal temperature below which the highest amount of algal growth was achieved is observed for the positive influences of nutrients and light, with regard to species.[20] Maximum growth and reproductive success generally occur within the temperature range of 15 to 25°C.[21] Numerous strains utilized in the production of biofuel grow best at temperatures between 20°C and 30°C.[22] up until the perfect temperature. microalgal growth generally increases; beyond that, growth is inhibited by additional temperature increases. Temperatures below 16°C or above 35°C negatively affect microalgal growth. For some species, growth is best between 22°C and 31°C, with the peak growth observed at 27°C. At temperatures below 19°C or above 32°C, growth is severely impeded.[23]

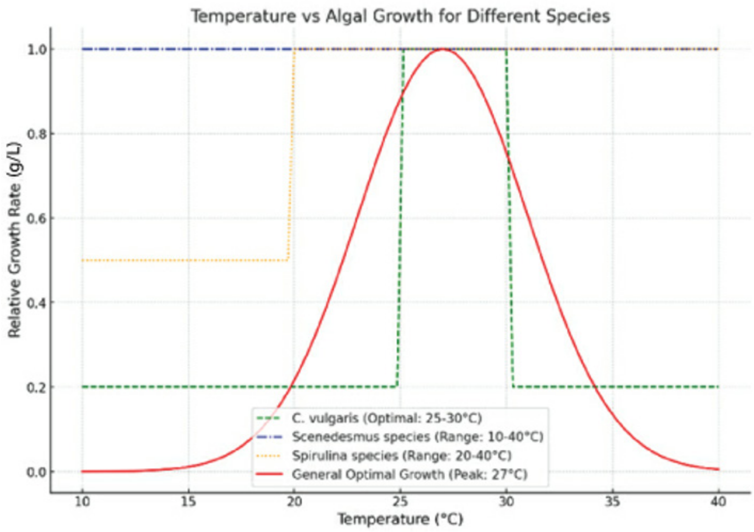

Fig. 1: Effects of temperature on various algae growth rate

Source: The figure included in this section have been generated by the author using data collected and analyzed during the course of this study.

X-axis: Temperature (10–40°C)
Y-axis: Relative Growth Rate (0–1)

Fig.1.0 shows how different algal species grow at different temperatures.

The general trend (red curve) shows that algal growth peaks at 27°C.

Overall, most algal species grow optimally around 25–30°C.

Based on data from the literature, a figure shows how temperature and the growth rate of different algae species relate to one another.

- **C. vulgaris:** Growth is optimal between 25-30°C.
- **Scenedesmus species:** Growth occurs across a broad range of 10-40°C.
- **Spirulina species:** Can grow between 20-40°C but with temperature effects on biochemical composition.
- **General Optimal Growth:** A Gaussian curve illustrates maximum growth at 27°C, with significant decline outside this range.

We have rigorously examined the potential effects of both lower and higher temperatures on microalgal growth based on the data above. In order to increase algal biomass, it is crucial that we maintain ideal temperature conditions.

Light

The primary source of energy for algae is light. Light intensity changes with the depth of water, seasonally, and from day to night.[24] From the surface of the pond down to a depth, light irradiation decreases due to the water body, suspended particulates, and biomass.25 The range of light irradiance is 33 μmol m² s^{-1} to 400 μmol m² s^{-1}. Chlorophyll-a and chlorophyll-b, the two primary pigments in green algae that absorb light, are particularly sensitive to red and blue light wavelengths.

As a result, green algae show improved growth under these light conditions. Algal growth increases as light intensity rises, but only up to a certain threshold.[26] Low phosphorus concentrations reduce the impact of light, and the effects of phosphorus are lessened at lower light intensities.[27] Research has shown that green algae grow more when exposed to blue and red light as chlorophyll a and b are primarily responsible for capturing light and are most responsive to these wavelengths. Three light conditions affect microalgal growth: light inhibition, light saturation, and light limitation. Under light-limiting conditions, growth increases as intensity of light rises. Reduced photosynthetic activity occurs during light saturation due to insufficient electron turnover compared to photon absorption rates, leading to inhibited photosynthesis. When light intensity exceeds a certain point, it causes irreversible damage to the photosynthetic system, a phenomenon known as photoinhibition.[28]

According to a study, microalgae thrive at wavelengths of 420–470 nm for blue light and 660 nm for red light, with growth rates rising with increasing light intensity.[29] However, direct exposure to sunlight can damage microalgal cells, while a lack of light negatively affects their growth. Research on *Chlorella* vulgaris biomass productivity using LED lights (red, blue, warm white, and natural white) at light intensities of 3,700, 5,920, and 8,140 lux (50, 80, and 110 μmol/[m²/s]) showed that the most efficient way to increase biomass productivity and photosynthetic rate was with warm white light (380–760 nm) at 80 μmol/[m²/s]).

This study shows the importance of choosing the correct light spectrum and intensity for specific algae species. For *Chlorella* vulgaris, warm white light (which covers a broad range of wavelengths) was found to be the most effective at stimulating both biomass productivity and photosynthetic rates. The research also highlights the non-linear relationship between light intensity and biomass productivity.

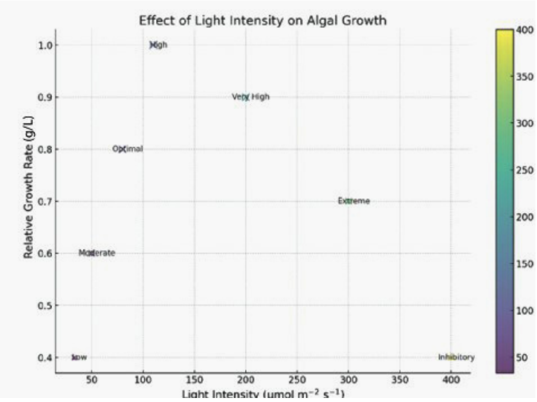

Fig. 2: The impact of light intensity on the growth of algae.

Source: The figure included in this section have been generated by the author using data collected and analyzed during the course of this study.

The relationship between light intensity and the relative growth rate of algae is represnted in a fig.2.0

X-axis: Light Intensity (μmol m^{-2} s^{-1})
Y-axis: Relative Growth Rate (g/L)

Key Observations

The optimal algal growth (~1.0 g/L) occurs at a light intensity of about 100 μmol m^{-2} s^{-1}, labelled as "High"., Low light intensity (~40 μmol m^{-2} s^{-1}) leads to a reduced growth rate (~0.4 g/L), indicating insufficient energy for photosynthesis.

As light intensity increases beyond the optimal point. Growth rate slightly declines at Very High (200) and Extreme (300) intensities.

At 400 μmol m^{-2} s^{-1}, labelled "Inhibitory", the growth rate drops further to ~0.4 g/L again, likely due to photoinhibition.

Color Bar

Indicates light intensity values with a gradient from purple (low) to yellow (high), providing a visual cue for the intensity levels at each point.

pH

According to the analysis of variance conducted through the literature review, while there was no growth between pH 1.4 and pH 2.4, the largest growth was seen at pH 7.4.[30] At pH values of 5 and 6, acid production did not substantially impede cell growth or decrease biomass productivity.[31] The maximum biomass productivity of the microalga was observed at pH of 7.0.[32] Moderate alkalinity promotes growth, as evidenced by the microalgae's optimal growth at pH 8.0. When the pH was between 7.5 and 8.0, the best growth was observed.[33] In both acidic and alkaline pH environments, algae can thrive.[34] Importantly, the number of carbonaceous species in water is determined by pH, which is a critical factor.[35] Because high pH levels reduce the amount of carbon available from CO^2, they inhibit algal growth.

CO_2/O_2

Carbon dioxide (CO_2), which is essential for photosynthesis and biomass production, is the primary carbon source for microalgae. Researchers have recently concentrated on how various CO_2 concentrations affect the growth, productivity, and biochemical makeup of algae.[36] In 2022, a study on Scenedesmus bajacalifornicus BBKLP-07 revealed that providing 15 percent CO_2 led to a maximum CO_2 fixation rate of and biomass productivity of 0.061 ± 0.0007 g/l/day would be achieved 0.12 ± 0.002 g/l/day. The highest level of lipid and carbohydrate were recorded 25.81% and 26.19% of dry cell weight, respectively at 25% CO_2. Another experiment on the macroalga Ulva intestinalis looked at the effect of CO_2 levels and it is found that the relative growth rate (RGR) was 2.31±0.07 percent g/day at 1 percent CO_2, but it dropped to 0.81±0.05 percent g/day at 5 percent CO_2. This suggests that extremely high CO_2 concentrations can actually inhibit growth.[37] Foods, medicines, biofuels, and bioplastics are among the products that microalgae produce from CO_2 in addition to using it for growth. Between 2020 and 2025, research has concentrated on the application of microalgae-based CO_2 capture and utilization (bio-CCU) as a sustainable alternative to traditional automobiles.[38]

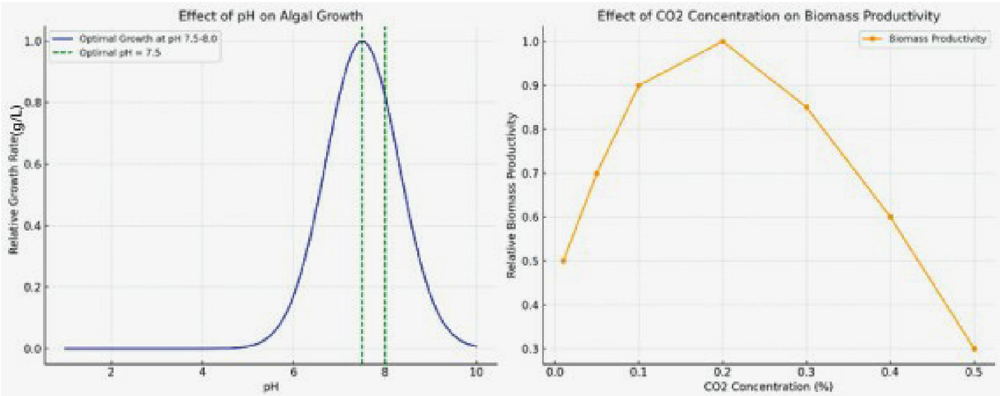

Fig. 3: Impact of pH and CO_2 concentration on algal biomass productivity

Source: The figure included in this section have been generated by the author using data collected and analyzed during the course of this study.

Left Figure: Effect of pH on Algal growth
X-axis: pH
Y-axis: Relative Growth Rate (g/L)

Key Insights: Algal growth is negligible at low pH (<6).

Growth begins rising steeply around pH 6.5, reaching a peak near pH 7.5–8.0.

Growth drops sharply beyond pH 8.5.
Optimal pH range is 7.5 to 8.0 (marked with green dashed lines).

Maximum growth rate ≈ 1.0 g/L at pH ~7.5.

Right Figure: Effect of CO_2 Concentration on Biomass Productivity
X-axis: CO_2 Concentration (%)
Y-axis: Relative Biomass Productivity

Key Insights: Productivity increases from 0% to 0.2% CO_2, reaching a peak at 0.2%.
After 0.2%, productivity declines, indicating CO_2 saturation or toxicity.

At 0.5% CO_2, productivity drops to its lowest (~0.3), indicating inhibition.
The optimal CO_2 concentration for maximum biomass productivity is 0.2%.

Effect of pH on Algal Growth

- Growth is optimal between **pH 7.5 and 8.0**, with a sharp decline outside this range.
- No growth occurs at extreme acidic conditions (pH < 2.5).

Effect of CO_2 Concentration on Biomass Productivity

- Biomass productivity peaks at an optimal CO2 concentration of 0.2%.
- Beyond this, productivity declines due to potential inhibitory effects.

Nutrient Media
Microalgal reproduction relies on the availability of nitrogen, phosphorus, sulphur, and trace elements, which are vital for sustaining cellular metabolism and photosynthesis.[39] Nitrogen supports protein and nucleic acid synthesis, while sulphur plays a role in enzymatic activities. Trace elements act as cofactors in metabolic pathways. Phosphorus is particularly crucial among these elements.[40] It is a structural component of nucleotides, phospholipids, and ATP, which are essential for energy transfer, cell membrane integrity, and cell division. At the phosphorus level of 0.02 mg/L, this element promotes microalgal growth.[41] Nitrogen is a key component in algal proteins, constituting 7% to 20% of cell dry weight, and its reduction impairs oxygen evolution, CO_2 fixation, chlorophyll content, and tissue production.[42] Phosphorus, not nitrogen, is the primary limiting nutrient in many natural environments. It is necessary for the growth of biomass.[43] Trace metals, though required in very small amounts, are crucial for algal physiology. Iron, in particular, is vital for photosynthesis, respiration, and nitrogen assimilation, and its limitation reduces chlorophyll concentrations.[44] Nitrate and phosphate play roles in regulating the production of carbohydrates, fats, and proteins in microalgae, and phosphorus is involved in essential cellular functions such as energy transfer, photosynthesis, and detoxification in algal cells.[45] Thus, for efficient and sustainable microalgal cultivation, it is important to maintain an optimized balance of these nutrients, particularly phosphorus, to ensure high growth rates and biomass yield.[46]

Table 1: Summary of parameters affecting algae growth

No.	Parameters	Favourable Condition	Importance
1	pH	Optimal pH range of 7.5–8.5	pH below 6 or above 9 can reduce growth rates and biomass productivity.[14,41,18]
2	Light	400–700 nm (PAR), intensity 100–200 μmol/m²/s	Optimal light enhances photosynthesis; high intensity may cause photoinhibition.[7,37,32]
3	Temperature	25–30 °C	Growth rates decline below 15 °C or above 35 °C, affecting lipid content.[10,20,41]

4	CO_2/O_2 Balance	0.5–2% CO_2 concentration	Higher CO_2 boosts photosynthesis; imbalance reduces efficiency.[8,40,38]
5	Mixing	Moderate turbulence (0.2–0.5 m/s flow rate)	Ensures uniform light, nutrient distribution, and prevents cell sedimentation.[4,3]
6	Nutrient Media	N:P ratio of 16:1, key salts (KNO_3, Na_2HPO_4)	Optimized nutrient media enhances growth and isolates target species.[21,34,16]
7	Salinity	15–35 ppt (species -dependent)	Maintains osmotic balance; high salinity may enhance lipid production.[26,42,43]

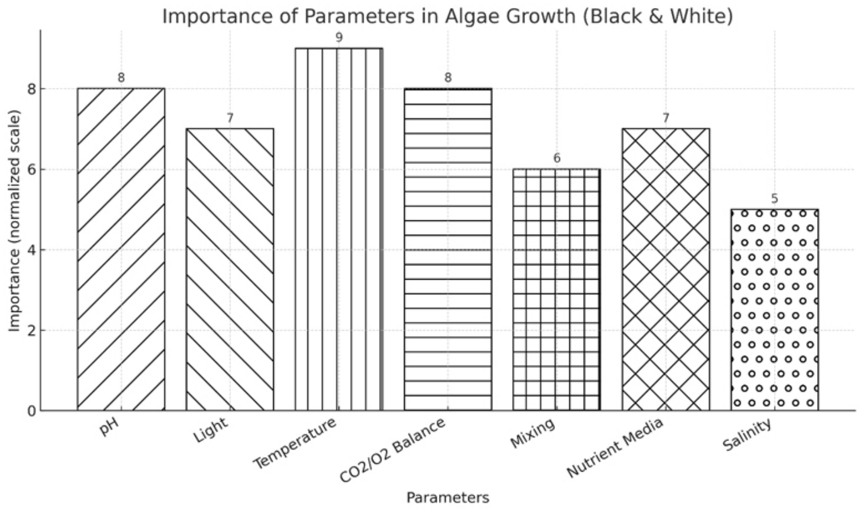

Fig. 4: Importance of Parameters in Algae Growth

Source: The figure included in this section have been generated by the author using data collected and analyzed during the course of this study.

Figure 4 illustrating the key factors affecting algal growth.

- pH – Extremely important (8/10)
- Light – Moderate significance (7/10)
- Temperature – Most important (9/10)
- CO_2/O_2 Balance – High importance (8/10)
- Mixing – Low importance (6/10)
- Nutrient Media – Moderate importance (7/10)
- Salinity – Least important (5/10)
- Algal biomass productivity and growth rate are influenced by all of these factors combined.

Mixing/Aeration

In an open pond system or photo bioreactor, mixing is a very successful method for ensuring that all of the cells receive the same amount of light, nutrients, and temperature.[47] It prevents sedimentation and provides better light exposure to all microalgal cells. The effects of various agitation methods, including stirring, aeration, and their combination, on Scenedesmus obliquus biomass productivity have been assessed in a number of studies conducted in the last few years (2022-25).[48] A study conducted in 2022 observed that mechanical stirring alone significantly enhanced the biomass productivity compared to aeration or a combination of both. Stirring was found to improve nutrient mixing, light penetration, and temperature homogeneity, resulting in higher biomass yield and better lipid accumulation. Further research in 2024 emphasized the synergistic effect of dual mixing (aeration + stirring). While stirring alone was effective, the combination method helped improve carbon dioxide diffusion and reduced oxygen accumulation, which supported more consistent growth rates and enhanced photosynthetic activity in *Scenedesmus obliquus.*

Salinity

Salinity is a crucial environmental factor that significantly impacts algae growth. Different algal species have varying tolerances to salinity, which influences their growth rate, distribution, and overall health. It can be adjusted using sodium chloride, and it has been observed that increased salinity tends to reduce algal growth. It is considered an important parameter for maintaining homeostasis within algal cells.[49] Maintaining proper cellular composition becomes especially important when salinity or other factors fluctuate. Changes in salinity levels, either higher or lower than the species adapted natural conditions, can alter growth and cell composition.[50] For instance, Algal lipid production may rise in response to elevated salinity levels. However, osmotic and oxidative stress caused by seawater's high salinity, usually around 3 percent NaCl (w/v), can hinder the growth of freshwater organisms.[51]

Furthermore, there are a number of methods for improving microalgae's resistance to salinity, but each has drawbacks. For example, the practical use of random mutagenesis to isolate strains is limited due to its unpredictable and non-reproducible nature.[52] Moreover, genetic engineering's industrial application is hindered by its complexity and expense. Conversely, adaptive laboratory evolution (ALE) is a simple and effective technique that has been demonstrated to support microalgae's growth and adaptability in the face of selective pressures.[53] By strengthening the antioxidant system, the osmoprotectant glycine betaine (GB) can lessen the adverse effects of salinity. It is well known that nitric oxide (NO) increases an organism's resilience by protecting it from oxidative stress and initiating stress-response pathways.[54]

Result and Discussion

The review examined the main factors affecting microalgae biomass growth including temperature (20–30°C), light (100–200 μmol m^{-2} s^{-1}, red/blue), pH (7.5–8.0), concentration of CO_2 (0.2–2%), nutrients, mixing and salinity. The proper balance of these factors is necessary for microalgae growth and bioenergy production. For instance, photoinhibition is caused by too much light, but a proper balance of CO_2 and pH enhances the efficiency of photosynthesis. The discussion also established that photobioreactors (PBRs) are useful in managing these factors, even though they are expensive. Species optimization and innovative strategies like the application of glycine betaine can enhance the stress resistance of microalgae and make bioenergy production sustainable and cost-effective.

Conclusion

The study examined the results and the mechanisms of various environmental factors such as light, temperature, pH, salinity, aeration and nutrient components such as carbon, nitrogen, phosphorus, iron and trace metals, including their effects on algal growth. It also provides information on maintaining or achieving optimum conditions for efficient expansion of the algae production system for long-term production of biofuels and other algal-derived products. To improve biomass productivity, require adequate light exposure, artificial light source in controlled environments. Adjust intensity and duration based on algae species, as deep waters may limit algae access. Maintain nutrient balance to prevent eutrophication and regularly monitor nutrient levels in controlled environments to avoid over-fertilization. There is an ideal temperature range for each kind of algae. The temperature range of most freshwater algae prefer is 20°C to 30°C (68°F to 86°F), while marine species may thrive at lower or higher temperatures. Temperature fluctuations can stress the algae and affect productivity. In controlled systems, regularly monitor and adjust the pH of the water. The pH can be managed using buffers or adjusting CO_2 levels. Optimize CO_2 levels to avoid acidification of the system. Select algae species appropriate for the salinity levels of your water. For example, marine algae will not thrive in freshwater environments, and vice versa. These results indicate that by managing these factors - light, nutrients, temperature, pH, CO_2 and salinity you may optimize algae growth in both natural and controlled environments. Whether you're working with algae for biofuel production, aquaculture, or water purification, a holistic approach and optimization of key factor may lead to better growth and more sustainable outcomes.

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Conflict of Interest

The authors do not have any conflict of interest.

Data Availability Statement

The data supporting in this review are derived from publicly available published studies, which are cited in the reference list of this manuscript. No new experimental data were generated or analyzed in this study.

Ethics Statement

This research did not involve human participants, animal subjects, or any material that requires ethical approval.

Informed Consent Statement

This study did not involve human participants, and therefore, informed consent was not required.

Permission to Reproduce Material from Other Sources

Not Applicable

Author Contributions

- **Dr. R.N. Singh:** Visualization, Analysis, Supervision,
- **Bobby Singare:** Data collection, Writing, Review and Editing, Writing – Original Draft, Conceptualization, Methodology.

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