

THE POTENTIAL OF ALGAE-BASED MATERIALS
FOR CARBON SEQUESTRATION AND ENERGY
SAVINGS IN SUSTAINABLE BUILDING DESIGN

BY

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ABSTRACT

Microalgae are photosynthetic microorganisms known for their rapid growth, high photosynthetic efficiency, and diverse biochemical compositions. These characteristics make them promising agents for both ecological and industrial applications. Beyond their established roles in bioenergy, food, and pharmaceuticals, microalgae offer substantial environmental benefits, particularly in carbon dioxide (CO₂) sequestration and oxygen production. In urban environments, the Urban Heat Island (UHI) effect exacerbates local temperature increases, driven by heat-absorbing materials like concrete and asphalt, reduced vegetation, and high energy demand for cooling. This study investigates the potential of algae-based materials to address UHI impacts by acting as dual-purpose solutions for carbon sequestration and energy efficiency in sustainable building design. The research has three primary objectives: (i) to assess the impact of growth medium, pH, and photoperiod on the growth and chromaticity of green microalgae and cyanobacteria; (ii) to evaluate the ability of microalgae to sequester carbon under varying environmental stresses; and (iii) to explore the role of algae-based materials in modulating light intensity, thereby reducing indoor lighting requirements and lowering cooling energy consumption. The findings revealed that *Pseudanabaena amphigranulata* demonstrated optimal performance under a 12:12 light–dark cycle at pH 8, achieving a cell density of 2.4, a biomass of 0.87 g/L, and a carbon sequestration rate of 1.36 g/L CO₂e. This species also exhibited the highest chlorophyll absorbance (4.01) and effectively reduced indoor light intensity by 66.86%, from 1550 lux to 620 lux. These results highlight the significant potential of algae-based materials to enhance carbon sequestration and energy-saving capabilities in building design. In conclusion, this study underscores the multifunctional role of algae-based materials in creating climate-responsive, energy-efficient building systems. By integrating algae into sustainable design practices, this research positions algae-based materials as a valuable tool in mitigating UHI effects, reducing energy consumption, and promoting a resilient built environment.

ملخص البحث

الطحالب الدقيقة هي كائنات ضوئية دقيقة تتميز بسرعة نموها، وكفاءتها العالية في التمثيل الضوئي، وتنوع تراكيبها الكيميائية الحيوية، مما يجعلها خيارًا واعدًا للتطبيقات الصناعية والبيئية. وبالإضافة إلى أدوارها المعروفة في مجالات الطاقة الحيوية والغذاء والمنتجات الدوائية، تقدّم الطحالب الدقيقة فوائد بيئية مهمة، ولا سيما في احتجاز ثاني أكسيد الكربون (CO_2) وإنتاج الأكسجين. وفي البيئات الحضرية، تُفاهم ظاهرة الجزيرة الحرارية الحضرية (UHI) من ارتفاع درجات الحرارة المحلية، بفعل مواد البناء الممتصة للحرارة مثل الخرسانة والأسفلت، وقلة الغطاء النباتي، والطلب المرتفع على الطاقة للتبريد. وتبحث هذه الدراسة في إمكانية توظيف المواد المعتمدة على الطحالب لمواجهة تأثيرات UHI كحلول مزدوجة تجمع بين احتجاز الكربون وتحسين كفاءة الطاقة في تصميم المباني المستدامة. سعت الدراسة إلى تحقيق ثلاثة أهداف رئيسية: (1) تقييم تأثير الوسط الغذائي، ودرجة الحموضة (pH)، ودورة الإضاءة على نمو الطحالب الخضراء والسيانوبكتيريا وخصائصها اللونية؛ (2) قياس قدرة الطحالب على احتجاز الكربون في ظل ظروف بيئية متغيرة؛ (3) دراسة دور المواد الطحلبية في تعديل شدة الضوء بما يقلل الحاجة للإضاءة الاصطناعية ويخفض استهلاك الطاقة للتبريد. أظهرت النتائج أن نوع *Pseudanabaena amphigranulata* حقق أفضل أداء عند درجة الحموضة (pH) 8، وتحت دورة إضاءة مظلمة-مضيئة (12:12)، حيث بلغ متوسط الكثافة الخلوية 2.4، والكتلة الحيوية 0.87 غ/لتر، ومعدل احتجاز الكربون 1.36 غ/لتر CO_2e . كما أظهر هذا النوع أعلى امتصاص للكلوروفيل (4.01)، وساهم في خفض شدة الإضاءة الداخلية بنسبة 66.86%، من 1550 لكس إلى 620 لكس. وتؤكد هذه النتائج أن المواد المستندة إلى الطحالب تمثل خيارًا واعدًا لتحسين احتجاز الكربون

وتعزيز كفاءة الطاقة في المباني. وتتلخص الدراسة إلى أن دمج الطحالب في التصميم المستدام يمكن أن يسهم في تطوير أنظمة معمارية متجاوبة مع المناخ، تقلل من استهلاك الطاقة، وتحد من آثار ظاهرة الجزيرة الحرارية الحضرية، مما يعزز مرونة واستدامة البيئة العمرانية.



APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Master of Science in Built Environment.

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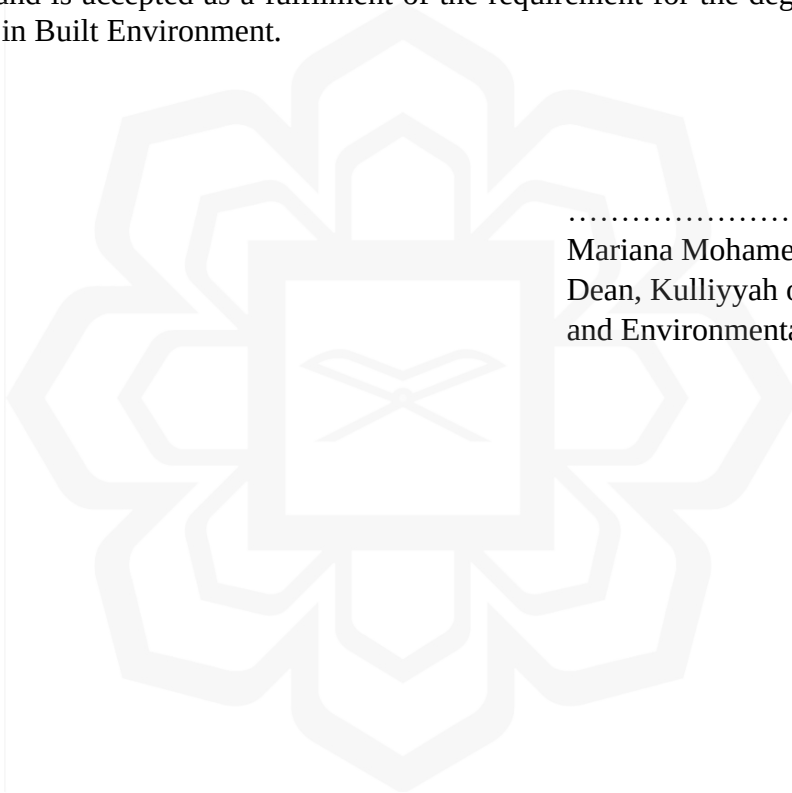
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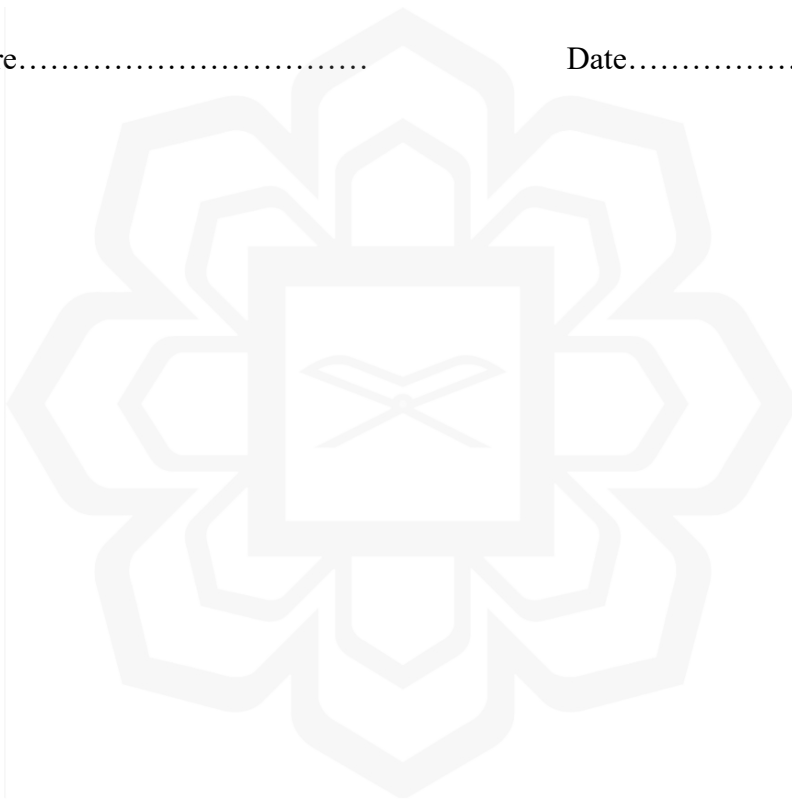
DECLARATION

I hereby declare that this dissertation is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

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LIST OF SYMBOLS

%	Percentage
<	Less than
>	More than
µg/g	Microgram per gram
µL	Microliter
µm	Micrometer
a*	Red-green component of a colour
b*	Yellow-blue component of a colour
cm	Centimeter
CO ₂	Carbon dioxide
g	Gram
Kg	Kilogram
kWh	Kilowatt-hours
L*	Difference in lightness or darkness
lux	Luminous flux per unit area
M	molar
mL	Milliliter
mm	Millimeter
nm	Nanometer
O ₂	Oxygen
°C	Degree celcius
Pa	Pascal
R ²	Coefficient of determination
Sqm	Square meter
v/v	Volume per volume
Δ	Delta

LIST OF ABBREVIATIONS

ABC	Algae Biotechnology Consortium
BBM	Bold's Basal Medium
BIQ	Bio Intelligent Quotient
CIE	International Commission on Illumination
DW	Dried weight
EV	eigenvalues
FDA	Food and Drug Administration
FL	Factor loading
GBI	Green Building Index
HCl	hydrochloric acid
H ₂ CO ₃	Carbonic acid
KOH	Potassium hydroxide
NaOH	Sodium hydroxide
OD	Optical density
PBR	Photobioreactor
PCs	Principal components
Ppm	Part per million
RSD	Relative standard deviation
UV	Ultraviolet

CHAPTER ONE

INTRODUCTION

1.1 RESEARCH BACKGROUND

Microalgae are photosynthetic microorganisms with rapid growth rates, high photosynthetic efficiency, and diverse biochemical compositions, making them promising agents for ecological and industrial applications. Beyond their established use in bioenergy, food, and pharmaceuticals, microalgae also offer significant environmental benefits through carbon dioxide (CO₂) sequestration and oxygen production (Chisti, 2007). In urban areas, however, the Urban Heat Island (UHI) effect, caused by the concentration of heat-absorbing materials such as concrete and asphalt, reduced vegetation, and high energy consumption, exacerbates local temperatures. This leads to increased energy demand for cooling and contributes to greenhouse gas emissions (Santamouris, 2020). To mitigate these impacts, innovative and sustainable building materials are needed. Algae-based materials, which serve as both carbon sequestration agents and energy-efficient components, offer a potential solution for sustainable building design to reduce the UHI effects and lower energy consumption (Gomes et al., 2020).

1.2 PROBLEM STATEMENT

The UHI effect in urban environments is contributing to higher local temperatures, increased cooling demands, and higher energy consumption, which exacerbate climate change and environmental degradation (Cao et al., 2021). Traditional building materials, such as concrete and asphalt, absorb and retain heat, further intensifying the UHI effect and contributing to high energy demands (Oke, 2017). At the same time, many conventional materials do not actively address carbon sequestration or energy efficiency. In contrast, algae-based materials have the potential to mitigate both the UHI

effect and energy demand. However, the application of algae-based materials in the built environment, particularly for carbon sequestration and energy savings, is under-researched (Zhang et al., 2018). This study aims to explore the potential of algae-based materials for addressing these issues and contributing to more sustainable building practices.

1.3 RESEARCH GAP

While microalgae have been widely studied for their potential in bioenergy and environmental applications, their integration into building design remains under-explored (Sharma and Singh, 2020). The interaction between algae growth conditions such as medium composition, pH, and photoperiod and their ability to sequester carbon and reduce energy consumption through light modulation is not well understood (Xu et al., 2019). There is also a lack of empirical data on the performance of algae-based materials in real-world building applications, particularly in mitigating the UHI effect and reducing cooling loads. This research aims to fill this gap by investigating the use of algae-based materials in sustainable building design, focusing on their role in carbon sequestration and energy savings.

1.4 RESEARCH QUESTIONS

To address the research gap, the following research questions guide this study:

1. How do different growth media, pH levels, and photoperiods affect the growth performance and chromaticity of green microalgae and cyanobacteria?
2. What is the efficiency of microalgae in sequestering carbon under varying environmental stresses, and how does this relate to their growth performance?

3. How do algae-based materials influence indoor light intensity, and can they contribute to reducing artificial lighting and cooling loads in buildings?

1.5 RESEARCH AIM

The aim of this research is to explore the potential of algae-based materials as dual-purpose solutions for carbon sequestration and energy savings in sustainable building design. Specifically, this study seeks to investigate how algae-based materials can contribute to mitigating the Urban Heat Island (UHI) effect, reducing energy consumption, and enhancing sustainability in urban buildings by acting as both carbon sinks and energy-efficient components.

1.6 RESEARCH OBJECTIVES

The objectives of this research are:

1. To examine the effects of growth medium, pH, and photoperiod on the growth and chromaticity of green microalgae and cyanobacteria.
2. To evaluate the efficiency of microalgae in sequestering carbon under different environmental stresses, including variations in pH and light exposure.
3. To assess the role of algae-based materials in modulating light intensity to reduce indoor lighting needs and lower cooling loads, thereby contributing to energy savings.

1.7 RESEARCH SIGNIFICANCE

This research is significant because it explores an innovative and sustainable solution for mitigating the UHI effect and reducing energy consumption in urban buildings. Algae-based materials, by serving as both carbon sinks and energy-saving agents, offer a dual benefit that traditional materials do not provide. The study will contribute to the development of sustainable building materials by demonstrating how algae can be integrated into building systems to address pressing environmental and energy issues. Furthermore, the findings of this research will inform the future design and implementation of algae-based systems in the built environment, offering a new path toward sustainable urban development.

1.8 RESEARCH SCOPE AND LIMITATIONS

This study investigates the potential of algae-based materials in sustainable building design, focusing on their ability to sequester carbon and reduce energy consumption. The research will specifically examine three species of microalgae (Green Algae and Cyanobacteria), assessing their growth performance, carbon sequestration potential, and role in modulating light intensity. The scope of the study is limited to laboratory-based experiments and does not extend to large-scale field applications. The study will evaluate the algae under controlled conditions, considering various factors such as growth medium, pH levels, photoperiods, and their effects on biomass production, chlorophyll content, and carbon sequestration rates. Furthermore, the potential of algae-based materials to reduce indoor light intensity and cooling loads will be assessed in simulated building environments.

While the study provides valuable insights into the performance of algae-based materials, there are several limitations to consider:

- i. **Controlled Laboratory Conditions:** The experiments will be conducted under controlled laboratory conditions, which may not fully replicate the real-world environmental stresses that algae-based materials would experience in actual building applications. Therefore, the scalability and long-term durability of algae-based materials in real-world scenarios remain uncertain.
- ii. **Species Selection:** This study explored the potential of two cyanobacteria species, *Pseudanabaena amphigranulata* (*P. amphigranulata*) and *Alkalinema* sp., alongside two green algae species, *Chlamydomonas radiosa* (*C. radiosa*) and *Desmodesmus brasiliensis* (*D. brasiliensis*), due to their distinct biological characteristics and ecological advantages that align with the study's objectives of carbon sequestration and energy savings in sustainable building design.
- iii. **Diversity of Algal Strains:** The selection of two cyanobacteria species and two green algae species allow for a comprehensive study of algae-based materials. By focusing on both cyanobacteria and green algae, the research covers a broad spectrum of algal characteristics such as pigmentation, growth rate, light absorption, and resilience to environmental stresses. This diversity provides a better understanding of how different algae species can perform under varying conditions, offering more potential for practical applications in building systems.
- iv. **Limited Scope of Environmental Stressors:** The environmental conditions tested (e.g., pH, light intensity, and photoperiod) represent only a subset of the potential variables that may affect algae growth and performance in actual building environments. Additional environmental stressors, such as temperature fluctuations or pollutants, were not included in this study.
- v. **Lack of Real-World Application:** Although this study will assess the feasibility of algae-based materials in a controlled setting, it will not involve full-scale implementation or integration of algae-based systems in buildings. Real-world implementation would require further testing and validation of the material's performance, durability, and cost-effectiveness.

1.9 CONCLUSION

In conclusion, this chapter has provided an overview of the research background, objectives, and significance of exploring algae-based materials for carbon sequestration and energy savings in sustainable building design. The increasing severity of the UHI effect in urban environments, coupled with the growing demand for energy-efficient solutions, highlights the need for innovative building materials. Microalgae-based materials present a promising alternative, offering dual benefits of carbon capture and reduced energy consumption through light modulation. This research aims to address the gap in current knowledge by investigating algae's role in building design, providing insights into their potential for mitigating UHI effects and enhancing energy efficiency. The next chapter will review the existing literature on algae-based materials and their applications in sustainable architecture, laying the groundwork for the research methodology in Chapter 3.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

The built environment is at a critical juncture, where the convergence of ecological responsibility and architectural innovation is not just a goal but a necessity. With global challenges such as climate change and resource depletion escalating, the construction industry must evolve beyond traditional approaches. Algae-based materials are emerging as a key solution in this transformation, offering multifaceted benefits that align with the urgent need for carbon sequestration, energy efficiency, and sustainable design. These materials present an opportunity to rethink building envelopes, structural components, and energy systems in a way that integrates ecological principles with advanced architectural techniques.

The construction sector is a major contributor to global carbon emissions, responsible for nearly 37% of total energy-related CO₂ emissions (WHO UNEP, 2022). As urbanization accelerates and the climate crisis deepens, there is an increasing demand for regenerative and carbon-negative building strategies. In this context, algae, both microalgae and macroalgae (seaweed), have emerged as promising bio-based materials. Their unique biological, chemical, and physical properties make them highly suitable for sustainable building applications. Algae offer innovative possibilities in terms of carbon sequestration and energy conservation, two crucial aspects of green building design. This chapter provides an in-depth review of algae's potential in the built environment, drawing on a wide range of scientific, technological, and architectural literature. It begins by exploring the biology and classification of algae, followed by a detailed examination of their carbon sequestration mechanisms.

The review focuses on three primary areas where algae-based materials can make a significant impact in architecture. First, algae can be used in living façade

systems designed for CO₂ capture, where microalgae integrated into building facades absorb carbon dioxide from the atmosphere through photosynthesis, potentially reducing a building's carbon footprint. Second, algae-derived bio composites can be used for thermal insulation in buildings, offering an alternative to traditional materials while providing effective energy conservation. Lastly, photobioreactor-integrated building panels, which modulate light, heat, and carbon fluxes, represent an innovative approach to creating dynamic, energy-efficient building envelopes. A particular emphasis is placed on the quantification of key performance metrics such as carbon sequestration rates, thermal conductivity, and light transmission properties (lux intensity), as these factors are essential for assessing the viability of algae-based materials in real-world architectural applications. In conclusion, the chapter synthesizes insights from biology, materials science, environmental engineering, and sustainable architecture, identifying key research gaps and suggesting future directions for exploration. By advancing algae-based technologies, the building industry can take a significant step toward creating carbon-negative, energy-efficient buildings that address both environmental and societal needs.

2.2 ALGAE AND CLASSIFICATION

Algae constitute a diverse and polyphyletic assemblage of predominantly photosynthetic, eukaryotic (and in some cases prokaryotic) organisms that inhabit aquatic and moist terrestrial environments. Though not a formal taxonomic group, algae are unified by their ability to perform oxygenic photosynthesis using chlorophyll a, their lack of true roots, stems, and leaves, and their ecological role as primary producers in global carbon and nutrient cycles (Graham et al., 2009). Algae range from unicellular microalgae (e.g., *Chlorella*, Diatoms) to multicellular macroalgae (e.g., kelps, *Ulva*), and include both prokaryotic cyanobacteria (historically termed “blue-green algae”) and eukaryotic lineages. Their ecological versatility, metabolic diversity, and biotechnological potential—particularly in biofuels, food, and bioremediation—have made them subjects of intense scientific interest (Chisti, 2007; Borowitzka, 2013).

The classification of algae has evolved significantly over time, reflecting advances in microscopy, biochemistry, molecular phylogenetics, and genomics. Early systems, such as those by Fritsch (1935) and Bold and Wynne (1985), relied primarily on morphological and reproductive characteristics. However, modern taxonomy emphasises evolutionary relationships inferred from DNA sequence data (e.g., 18S rRNA, *rbcL*, *psaA*), pigment composition, cell wall ultrastructure, storage products, and flagellar apparatus morphology (Adl et al., 2019). As a result, algae are now distributed across multiple supergroups within the eukaryotic tree of life, underscoring their polyphyletic nature.

Currently, algae are broadly categorized into seven major phyla, though some classifications merge or split groups based on new evidence:

- 1. Cyanobacteria (*Cyanophyta*)**

Although prokaryotic and technically bacteria, cyanobacteria are often included in algal studies due to their photosynthetic function and historical association with algae. They perform oxygenic photosynthesis using chlorophyll *a* and phycobiliproteins (phycocyanin, phycoerythrin) and are responsible for Earth's Great Oxidation Event ~2.4 billion years ago (Schopf, 2011). Examples include *Synechococcus* and *Spirulina*. Their inclusion in algal discussions remains pragmatic, especially in applied contexts like wastewater treatment and biofertilizers.

- 2. Chlorophyta (Green Algae)**

Green algae are the closest relatives to land plants and share key features such as chlorophylls *a* and *b*, starch as a storage product, and cell walls composed of cellulose. They inhabit freshwater, marine, and terrestrial environments and exhibit remarkable morphological diversity—from unicellular (*Chlamydomonas*), colonial (*Volvox*), to filamentous (*Spirogyra*) and multicellular forms (*Ulva*). Molecular phylogenies place *Chlorophyta* within the *Archaeplastida* supergroup, alongside *Streptophyta* (which includes *embryophytes*) (Leliaert et al., 2012).

- 3. Rhodophyta (Red Algae)**

Red algae are primarily marine, multicellular organisms known for their red pigmentation due to phycoerythrin, which enables photosynthesis at greater

depths by capturing blue-green light. They lack flagella at all life stages and store floridean starch. Economically important species include *Porphyra* (nori) and *Gracilaria* (source of agar). *Rhodophyta* also belong to Archaeplastida and are considered one of the earliest diverging lineages of photosynthetic eukaryotes (Bhattacharya et al., 2015).

4. Phaeophyta (Brown Algae)

Brown algae are exclusively marine and include the largest algal forms, such as giant kelps (*Macrocystis*). They possess chlorophylls a and c, along with the carotenoid fucoxanthin, which imparts a brown or olive-green colour. Their storage product is laminarin, and cell walls contain alginates—valuable hydrocolloids used in food and pharmaceutical industries. Brown algae belong to the *Stramenopiles* (or *Heterokonta*) supergroup, which also includes diatoms and oomycetes (Silva et al., 2014).

5. Bacillariophyta (Diatoms)

Diatoms are unicellular or colonial microalgae encased in intricate, silica-based cell walls called frustules. They dominate phytoplankton communities in oceans and freshwater systems and contribute ~20% of global primary production (Armbrust, 2009). Like brown algae, they contain fucoxanthin and chlorophylls a and c, and store chrysolaminarin. Diatoms are also stramenopiles and are divided into centric (radial symmetry) and pennate (bilateral symmetry) forms.

6. Dinophyta (Dinoflagellates)

Dinoflagellates are mostly unicellular, motile algae with two dissimilar flagella—one transverse, one longitudinal—conferring a spinning motion. Many are photosynthetic (containing peridinin as a major carotenoid), but others are heterotrophic or symbiotic (e.g., *Symbiodinium* in coral reefs). Some species cause harmful algal blooms (e.g., “red tides”). Dinoflagellates belong to the *Alveolata* supergroup and exhibit unique genomic features, such as permanently condensed chromosomes and RNA editing (Taylor et al., 2008).

7. Euglenophyta (Euglenoids)

Euglenoids are freshwater, flagellated protists that can be photosynthetic or heterotrophic. Photosynthetic members (e.g., *Euglena gracilis*) contain chlorophylls a and b but acquired their plastids secondarily through

endosymbiosis with a green alga. They store paramylon and lack a rigid cell wall, instead possessing a flexible pellicle. *Euglenophyta* are classified within the *Excavata* supergroup (Leander, 2007).

The classification of algae is further complicated by endosymbiotic events that gave rise to secondary and tertiary plastids. Primary endosymbiosis—engulfment of a cyanobacterium by a eukaryotic host—gave rise to the Archaeplastida (green algae, red algae, glaucophytes). Subsequent secondary endosymbiosis—where a red or green alga was engulfed by another eukaryote—led to the plastids in stramenopiles, alveolates, and euglenoids (Keeling, 2013). This complex evolutionary history explains why pigment composition and plastid structure are critical classification criteria.

Modern systems, such as the Revised Classification of Eukaryotes (Adl et al., 2019), avoid the term “algae” as a formal category and instead distribute algal lineages across eukaryotic supergroups:

- *Archaeplastida: Chlorophyta, Rhodophyta*
- *SAR (Stramenopiles + Alveolata + Rhizaria): Bacillariophyta, Phaeophyta, Dinophyta*
- *Excavata: Euglenophyta*

Despite this phylogenetic clarity, the functional term “algae” persists in ecological, industrial, and educational contexts due to shared physiological and ecological traits.

In applied phycology, classification also considers biotechnological relevance. For instance, microalgae like *Chlorella* (*Chlorophyta*), *Nannochloropsis* (*Eustigmatophyceae*, a stramenopile group), and *Dunaliella* (*Chlorophyta*) are favored for biofuel production due to high lipid content. Macroalgae such as *Laminaria* (*Phaeophyta*) and *Gracilaria* (*Rhodophyta*) are cultivated for food, feed, and

hydrocolloids. Cyanobacteria like *Arthrospira* (formerly *Spirulina*) are used as protein-rich dietary supplements.

Accurate identification and classification are essential for strain selection, genetic engineering, and regulatory compliance in commercial applications. Molecular barcoding using markers like 18S rRNA, ITS, and *rbcL* has become standard for species delineation, complementing traditional microscopy and pigment analysis (Guiry, 2013).

In summary, algae represent a functionally coherent but phylogenetically scattered group of photosynthetic organisms. Their classification reflects a rich evolutionary tapestry shaped by endosymbiosis, adaptation, and diversification. Understanding this diversity is not only fundamental to evolutionary biology and ecology but also critical for harnessing algae in sustainable technologies. As genomic and bioinformatic tools advance, algal taxonomy will continue to refine, offering deeper insights into the origins and applications of these vital organisms.

Blue green algae or scientifically known as cyanobacteria are prokaryotes, lacking a true nucleus and membrane-bound organelles. However, it still can perform photosynthesis just like green algae. Cyanobacteria have a bluish-green colour due to presence of phycocyanin, masking the appearance of chlorophyll a, and make them able to grow under low light condition (Allaf and Peerhossaini, 2022). Two species of cyanobacteria that have been studied in this project is *P. ampniгранulata* and *Alkalinema* sp., where both species thrive in diverse freshwater habitats. *P. ampniгранulata*, a filamentous cyanobacterium, is part of genus *Pseudanabaena*, initially established by Lauterborn in 1915, and it comprised more than 33 species as of 2018. A study conducted by Khan and colleagues in 2018 explored the significant relationships between environmental factors and the morphological characteristics of *Pseudanabaena* sp. The experiment revealed that the microalgae displayed remarkable adaptability in cell dimensions and shape across varying temperature and photoperiod treatments, with the best conditions of 25 °C under a 12:12 light to dark cycle for optimal growth. Even though theoretically increase of light intensity can accelerated the

growth of *Pseudanabaena* sp., higher than $27 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$ could inversely inhibit their growth due to have reached the saturation point. Furthermore, in term of pH, the best condition for *Pseudanabaena* sp. is initially range from 7 to 9, and it could not survive at initial pH lower than 3 (Gao et al., 2018). *Alkalinema* sp is considered an alkalophilic microalgae even though it could survive and produced biomass in both acidic and alkali condition (pH values 4-11). It was characterised as alkalophilic mainly because these species were able to alter the final pH values to 8.40-9.9. Because of that, these cyanobacterial strains are frequently dominate and can be found in alkaline environments mainly saline-alkaline lakes. In terms of morphology, *Alkalinema* strains exhibit a distinctive trichome arrangement referred to as ornate (interwoven) mats. (Vaz et al., 2015). According to De Oliveira and colleagues in 2019, *Alkalinema* is confined to the geographic region of Brazil and the name of the genus was referring to the alkaline lakes from their first isolation.

On the other hand, green algae display a more prominent green colour due to the presence of chlorophyll and additional chlorophyll b, which is also found in land plant. It contributes to their efficient utilization of light for energy production. Two strain of green algae that have been studied in this project were *C. radiosa* and *D. brasileensis*. Generally, green microalgae present high photosynthetic activity. It reached high cell counts in adjusted pH 7.5 and photoperiod of 12:12 light to dark, for the seven days of cultivation (Rios et al., 2015). Table 2.1 show the application of those algae in industrial and built environment.

Table 2.1 Application of microalgae in industrial and built environment

Algae	Industry	Built Environment
<i>P. Amphigranulata</i>	Biofuel Production in biofuel production due to their lipid content (Karageorgou et al., 2022)	Bioremediation, wastewater treatment, particularly in nutrient removal (Ouhasssi et al., 2020).
<i>Alkalinema sp.</i>	Produce phycobiliproteins, which are valuable as natural colourings in various industries. Ability to fix atmospheric nitrogen, enhancing soil fertility. (Sahu, 2012).	not well-documented
<i>C. radiosa</i>	potential candidates to be used as an alternative lipid source in animal feed feedstock (Zakaria et al., 2020)	not well-documented
<i>D.brasiliensis</i>	Sustainable source of live feeds for aquaculture and other organisms (Zakaria et al., 2020) Contains lutein, a product with high added value, which has good efficiencies in the prevention and treatment of atherosclerosis, diabetic retinopathy and other chronic diseases (Shao et al., 2018).	not well-documented

2.3 FACTORS INFLUENCING MICROALGAL GROWTH, BIOMASS ACCUMULATION AND LIPID PRODUCTION

Microalgae, microscopic photosynthetic organisms belonging to diverse taxonomic groups including diatoms, green algae, cyanobacteria, and dinoflagellates, have emerged as pivotal biotechnological resources in the 21st century (Becker, 2007; Chisti, 2007). Their capacity to convert sunlight, carbon dioxide, and inorganic nutrients into high-value biomass underpins their application across multiple sectors: biofuels, nutraceuticals, pharmaceuticals, aquaculture feed, wastewater bioremediation, and carbon capture technologies (Mata et al., 2010; Singh and Gu, 2010; Wang et al., 2008). However, despite their immense potential, the commercial scalability of microalgal cultivation remains hindered by suboptimal growth rates, low lipid yields, susceptibility to contamination, and high operational costs (Ugwu et al., 2008; Li et al., 2008). These limitations are not inherent to the organisms themselves but stem from the complex

interaction of environmental, nutritional, and operational parameters that govern their physiology and productivity. As depicted in Figure 2.1, microalgal performance is modulated through three primary axes:

- i. Physical Parameters (pH, temperature, aeration, light, photoperiod)
- ii. Growth Media Composition (macronutrients: N, P, K, Mg, Ca; micronutrients: Fe, Zn, Cu, Mo, Co, Cl, vitamins B1, B7, B12)
- iii. Modes of Cultivation (autotrophic, heterotrophic, mixotrophic, photobeterotrophic)

Each axis exerts direct or indirect influence over cellular metabolism, leading to either enhanced biomass accumulation or targeted metabolite production — notably lipids, which are critical for biodiesel synthesis (Griffiths and Harrison, 2009). This chapter provides an exhaustive review of current scientific understanding regarding how these factors interact to shape microalgal growth dynamics. It synthesizes findings from foundational studies to contemporary advances, highlighting knowledge gaps and emerging trends. The ultimate aim is to establish a mechanistic framework for optimising microalgal cultivation systems tailored for specific industrial applications.

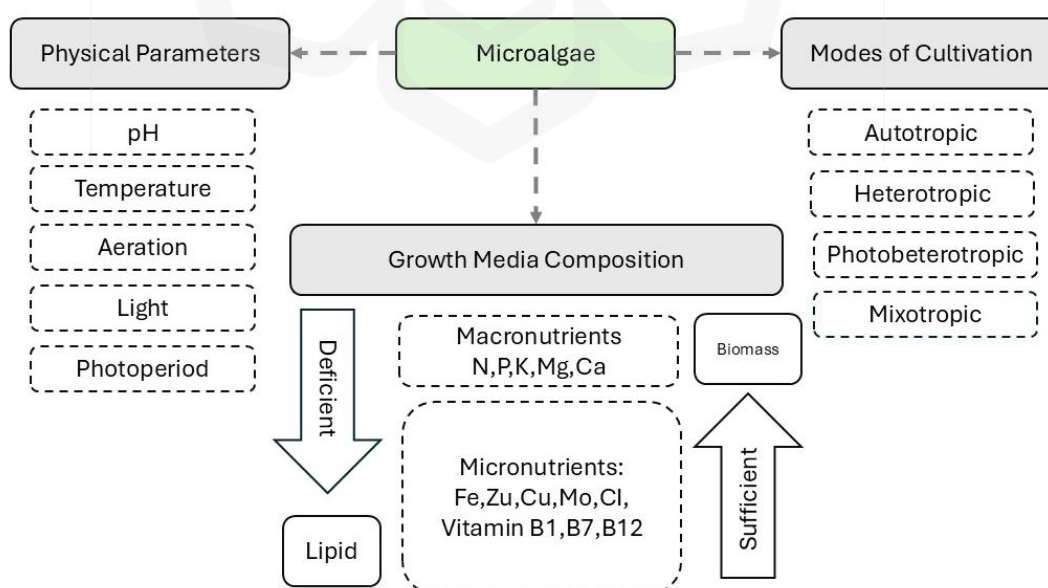


Figure 2.1 Factors affecting microalgae

2.4 PHYSICAL PARAMETERS GOVERNING MICROALGAL PHYSIOLOGY

2.4.1 pH: Regulation and Nutrient Availability

The pH of the culture medium profoundly influences microalgal physiology through its impact on enzyme activity, membrane permeability, ion speciation, and nutrient solubility (Kumar et al., 2010). Most microalgae exhibit optimal growth within a narrow pH range — typically between 6.5 and 8.5 — although some extremophiles can tolerate more acidic or alkaline conditions (Ramos et al., 2018). During active photosynthesis, microalgae consume dissolved CO₂, leading to an increase in medium pH due to the formation of bicarbonate (HCO₃⁻) and carbonate (CO₃²⁻) ions (Geider and Osborne, 1992). This phenomenon can result in pH drift beyond the physiological tolerance of many species, thereby inhibiting growth unless buffered or controlled via CO₂ supplementation (Chen et al., 2011). Moreover, pH affects the bioavailability of essential metals such as iron (Fe), zinc (Zn), and copper (Cu). At higher pH values (>8), Fe³⁺ tends to precipitate as insoluble hydroxides, reducing its uptake efficiency (Sunda and Huntsman, 1998). Conversely, lower pH enhances metal solubility but may induce toxicity if concentrations exceed cellular tolerance thresholds.

Several studies have demonstrated that maintaining pH stability significantly improves biomass yield. For instance, *Chlorella vulgaris* grown under controlled pH (7.0 ± 0.2) exhibited 30% higher biomass compared to uncontrolled cultures where pH rose above 9.0 (Li et al., 2014). Similarly, *Nannochloropsis oceanica* showed improved lipid content when cultivated at pH 7.5 versus pH 6.5, suggesting that pH also modulates metabolic fluxes toward storage compounds (Rodolfi et al., 2009). Advanced cultivation strategies now incorporate real-time pH monitoring coupled with automated CO₂ injection or acid/base dosing systems to maintain optimal conditions (Pulz and Gross, 2004). In open pond systems, natural buffering from bicarbonate-rich water sources or addition of limestone can mitigate extreme pH fluctuations (Borowitzka, 2013). In summary, pH serves as both a direct regulator of cellular function and an indirect modulator of nutrient bioavailability. Its precise control is therefore

indispensable for maximising microalgal productivity, especially in large-scale operations where environmental variability is pronounced.

2.4.2 Temperature: Thermal Optima and Stress Responses

Temperature is among the most influential abiotic factors affecting microalgal growth kinetics, biochemical composition, and survival (Chisti, 2007). Each species possesses a characteristic thermal optimum, usually falling within the mesophilic range of 20–30°C, though thermophilic strains (e.g., *Synechococcus* spp.) can thrive up to 50°C, while psychrophilic species (e.g., *Antarctic* diatoms) grow optimally below 10°C (Thomas and Dieckmann, 2002). Within the optimal range, enzymatic reaction rates follow the Q_{10} rule — doubling for every 10°C rise — until denaturation occurs at supra-optimal temperatures (Schmidt-Nielsen, 1997). Beyond this threshold, protein unfolding, membrane fluidity disruption, and oxidative stress lead to reduced photosynthetic efficiency and eventual cell death (Wang et al., 2014). Conversely, suboptimal temperatures slow down metabolic processes, prolonging generation times and reducing biomass productivity. For example, *Dunaliella salina* cultured at 15°C produced only 40% of the biomass achieved at 25°C (Ben-Amotz and Avron, 1983). However, cold stress has been shown to enhance certain secondary metabolites, such as carotenoids in *Haematococcus pluvialis*, making low-temperature cultivation strategically useful for pigment production (Fábregas et al., 2003). Thermal acclimation mechanisms allow some microalgae to adapt to fluctuating environments. These include changes in membrane lipid saturation (increasing unsaturated fatty acids at low temperatures), synthesis of heat-shock proteins (HSPs), and activation of antioxidant defence systems (Liu et al., 2018). Genetic engineering approaches targeting HSP expression have further enhanced thermotolerance in model species like *Chlamydomonas reinhardtii* (Zhang et al., 2016).

In industrial settings, temperature management poses significant challenges. Open raceway ponds are highly susceptible to diurnal and seasonal variations,

necessitating location-specific design considerations (e.g., tropical vs. temperate climates). Closed photobioreactors offer better thermal control through insulation, cooling jackets, or integrated heating systems, albeit at increased capital and energy costs (Richmond, 2004). Recent innovations include hybrid cultivation systems combining solar concentrators with waste heat recovery from industrial facilities, enabling year-round operation without excessive energy input (Slegers et al., 2013). Additionally, computational models predicting temperature-dependent growth rates based on Arrhenius kinetics are increasingly used to optimise reactor design and scheduling (Huang et al., 2019). Thus, while temperature cannot be entirely controlled in all cultivation scenarios, understanding species-specific thermal responses enables strategic selection and process adaptation to maximise productivity under prevailing climatic conditions.

2.4.3 Aeration and Gas Exchange

Aeration plays a dual role in microalgal cultivation: facilitating gas exchange (primarily O₂ removal and CO₂ supply) and ensuring adequate mixing to prevent sedimentation and promote uniform light exposure (Ugwu et al., 2008). Poorly aerated cultures suffer from oxygen buildup, which inhibits photosynthesis via photorespiration and reactive oxygen species (ROS) generation (Badger et al., 2006). Carbon dioxide supplementation is particularly crucial in high-density cultures where ambient air (0.04% CO₂) becomes limiting. Studies show that enriching the sparging gas with 1–5% CO₂ can boost biomass productivity by 20–50%, depending on species and system configuration (Cheng et al., 2006; Chen et al., 2011). However, excessive CO₂ lowers pH, requiring buffering or alkali addition to maintain neutrality. Mixing intensity must be carefully balanced. Insufficient mixing leads to stratification, shading effects, and nutrient gradients, reducing overall productivity. Over-mixing, however, introduces mechanical shear stress that damages delicate cell walls, especially in flagellated species like *Chlamydomonas* or *Tetraselmis* (Grobbelaar, 2000). Turbulent flow regimes generated by paddle wheels or airlift systems must therefore be calibrated to avoid cell lysis while ensuring homogeneity. Shear sensitivity varies widely among

microalgae. Diatoms and coccolithophores generally exhibit greater resistance than unicellular chlorophytes or cryptophytes (Zhou et al., 2017). Encapsulation techniques using alginate beads or immobilization on solid supports have been explored to protect sensitive strains during vigorous mixing (Lee et al., 2010).

Furthermore, aeration influences dissolved oxygen (DO) levels, which can reach supersaturation during peak photosynthetic activity. High DO concentrations inhibit Rubisco activity and trigger oxidative damage. Strategies to mitigate this include periodic degassing, use of anti-foaming agents, or integration of oxygen-selective membranes (Park et al., 2013). In closed photobioreactors, sparging with air-CO₂ mixtures is standard practice, whereas open ponds rely primarily on wind-driven surface agitation and occasional mechanical stirring. Recent developments include microbubble aeration systems that enhance gas transfer efficiency while minimising shear forces (Zhang et al., 2020). Overall, effective aeration strategy requires consideration of species-specific tolerance, reactor geometry, scale, and economic feasibility. Optimization often involves trade-offs between gas exchange efficiency, energy consumption, and cell viability.

2.4.4 Light Intensity and Quality: Photosynthetic Efficiency and Photoinhibition

Light is the primary energy source driving photosynthesis in autotrophic microalgae. Its intensity, spectral quality, duration (photoperiod), and distribution within the culture volume collectively determine photosynthetic efficiency and, consequently, growth rate and biomass yield (Hu et al., 2008). Photosynthetically Active Radiation (PAR), defined as wavelengths between 400–700 nm, constitutes the usable spectrum for most microalgae. Within this range, blue (450–495 nm) and red (620–700 nm) wavelengths are most efficiently absorbed by chlorophyll and accessory pigments (e.g., phycobilins, fucoxanthin) (Blankenship, 2014). Spectral tuning — adjusting LED lighting to match pigment absorption peaks — has been shown to improve quantum yield and reduce energy waste (Wagner et al., 2016). Light intensity follows a biphasic response curve:

increasing biomass productivity up to a saturation point (I_k), beyond which no further gains occur, followed by decline due to photoinhibition (Myers, 1980). I_k varies across species; for example, *Chlorella sorokiniana* saturates at $\sim 500 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$, while *Phaeodactylum tricornutum* tolerates up to $1,500 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$ (Barbosa et al., 2003).

Photoinhibition arises when excess photon energy overwhelms the photosystems' capacity to utilize it, leading to ROS production, PSII damage, and decreased electron transport rates (Nishiyama et al., 2006). Protective mechanisms include non-photochemical quenching (NPQ), xanthophyll cycle activation, and D1 protein turnover (Demmig-Adams & Adams, 1992). Some species, like *Dunaliella tertiolecta*, exhibit remarkable photoprotection capabilities, allowing them to thrive under high irradiance (Jin et al., 2017). Artificial lighting systems (LEDs, fluorescent lamps) enable precise control over light intensity and photoperiod, facilitating continuous cultivation regardless of daylight availability. However, electricity costs remain prohibitive for large-scale operations. Natural sunlight remains the preferred energy source, though its variability demands adaptive strategies such as vertical stacking, helical reactors, or dynamic shading devices (Richmond, 2004). Light distribution within dense cultures presents another challenge. Cells near the reactor surface receive excess light, while that deeper experience self-shading and become light-limited. This "light gradient" reduces average photosynthetic efficiency. Solutions include thin-layer reactors, internal illumination, pulsed lighting, or intermittent dark periods to allow recovery from photoinhibition (Grobbelaar, 2000).

Interestingly, some microalgae benefit from fluctuating light regimes mimicking natural diurnal cycles. Studies on *Chlamydomonas reinhardtii* showed that alternating 12h light/12h dark cycles yielded higher biomass than continuous illumination, likely due to reduced photodamage and enhanced respiration-mediated ATP regeneration (Zhu et al., 2019). In conclusion, light management is arguably the most critical parameter in microalgal cultivation. Advances in LED technology, photobioreactor design, and understanding of photo physiological responses continue to drive improvements in productivity and sustainability.

2.4.5 Photoperiod: Circadian Rhythms and Metabolic Synchronization

Photoperiod refers to the daily duration of light exposure and plays a vital role in synchronizing microalgal circadian rhythms with environmental cycles. While many microalgae can grow under continuous illumination, evidence suggests that rhythmic light-dark cycles enhance growth efficiency, nutrient assimilation, and metabolite partitioning (Matsuo and Kay, 2010). Circadian clocks regulate gene expression patterns governing photosynthesis, cell division, nitrogen fixation, and lipid biosynthesis. Disruption of these rhythms through constant light exposure can lead to desynchronization, resulting in reduced fitness and altered metabolic outputs (Morrow et al., 2006). For instance, *Chlamydomonas reinhardtii* exhibits higher starch accumulation under 12:12 L:D cycles compared to continuous light, indicating temporal regulation of carbohydrate storage (Matsuo et al., 2008). In lipid-producing strains, photoperiod manipulation can directly influence triacylglycerol (TAG) synthesis. *Nannochloropsis salina* grown under 16:8 L:D cycles accumulated 25% more neutral lipids than those under 24:0 conditions, attributed to enhanced expression of diacylglycerol acyltransferase (DGAT) genes during the dark phase (Yan et al., 2016).

Moreover, photoperiod affects cell cycle progression. Many microalgae synchronize cell division with the onset of darkness, ensuring daughter cells emerge into favourable light conditions (Noordkamp et al., 2000). Artificial extension of the dark period can delay mitosis, potentially improving biomass quality by allowing complete nutrient assimilation before replication. Seasonal photoperiod changes also influence outdoor cultivation outcomes. In temperate regions, shorter winter days limit productivity unless supplemented with artificial lighting. Conversely, long summer days may induce photoinhibition unless mitigated by shading or cooling strategies. Modern cultivation systems increasingly integrate programmable lighting schedules synchronized with strain-specific circadian profiles. Time-lapse imaging and transcriptomic analyses are being employed to identify optimal photoperiod regimens for different species and target products (Zhang et al., 2021). In essence, photoperiod is not merely a passive variable but an active regulator of microalgal physiology. Strategic manipulation of light-dark cycles offers a powerful tool for enhancing both quantity and quality of biomass production.

2.5 GROWTH MEDIA COMPOSITION: MACRONUTRIENTS AND MICRONUTRIENTS

2.5.1 Macronutrients: Nitrogen, Phosphorus, Potassium, Magnesium, Calcium

Macronutrients are required in relatively large quantities for structural and metabolic functions. Among them, nitrogen (N) and phosphorus (P) are most critical for biomass accumulation and are frequently limiting in natural and engineered systems.

2.5.1.1 Nitrogen (N)

Nitrogen is a key component of amino acids, nucleic acids, chlorophyll, and enzymes. Its availability directly correlates with growth rate and protein content. Common nitrogen sources include nitrate (NO_3^-), ammonium (NH_4^+), urea, and organic nitrogen compounds (Borowitzka, 2013). Nitrate is generally preferred over ammonium because it causes less pH drop and is less toxic at high concentrations. However, ammonium assimilation is energetically cheaper and faster, making it suitable for rapid growth phases (Turpin, 1991). Urea offers a cost-effective alternative but requires enzymatic hydrolysis before utilization, introducing lag phases in some species (Sharma et al., 2013). Nitrogen limitation is a well-established strategy to induce lipid accumulation. Under N-starvation, microalgae redirect carbon flux from protein and nucleic acid synthesis toward neutral lipid (TAG) storage as an energy reserve (Rodolfi et al., 2009). Species such as *Chlorella protothecoides*, *Scenedesmus obliquus*, and *Nannochloropsis oculata* show dramatic increases in lipid content (up to 50–60% dry weight) upon N-deprivation (Griffiths and Harrison, 2009). However, prolonged N-limitation severely suppresses growth, creating a trade-off between biomass and lipid yield. To overcome this, two-stage cultivation strategies have been developed: first, grow under N-sufficient conditions to achieve high biomass density; then, switch to N-deficient media to trigger lipid accumulation (Xiong et al., 2010).

2.5.1.2 Phosphorus (P)

Phosphorus is integral to ATP, phospholipids, DNA/RNA, and signalling molecules. Like nitrogen, phosphorus limitation triggers lipid accumulation, albeit less consistently across species (Wang et al., 2014). *Chlorella minutissima* and *Tetraselmis suecica* respond robustly to P-deprivation, whereas others show minimal lipid induction. Phosphate solubility is pH-dependent; at high pH, it forms insoluble calcium phosphates, reducing bioavailability. Therefore, phosphate supplementation must consider medium chemistry and potential precipitation issues (Sunda and Huntsman, 1998).

2.5.1.3 Potassium (K), Magnesium (Mg), Calcium (Ca)

Potassium regulates osmotic balance, enzyme activation, and stomatal-like pore function in some algae. Deficiency impairs photosynthesis and growth (Marschner, 2012). Magnesium is central to chlorophyll structure and photosystem integrity. Mg deficiency results in chlorosis and reduced photosynthetic efficiency (Chen et al., 2011). Calcium contributes to cell wall stability, signal transduction, and enzyme cofactor roles. While rarely limiting in freshwater media, Ca^{2+} concentration affects flocculation behaviour and harvesting efficiency (Zhou et al., 2017). Balanced macronutrient ratios are essential. The classic Redfield ratio (C:N:P = 106:16:1) derived from marine plankton applies broadly to microalgae, though deviations exist based on species and growth phase (Redfield, 1958). Customized media formulations accounting for stoichiometric needs improve productivity and reduce waste.

2.5.2 Micronutrients: Iron, Zinc, Copper, Molybdenum, Cobalt, Chloride, Vitamins

Micronutrients, though required in trace amounts, are indispensable for enzymatic catalysis, electron transport, and cofactor synthesis. Deficiencies can cause severe growth inhibition even when macronutrients are abundant.

2.5.2.1 Iron (Fe)

Iron is a cofactor for cytochromes, ferredoxins, and catalases involved in photosynthesis and respiration. Fe deficiency leads to chlorosis, reduced electron transport, and impaired lipid metabolism (Sunda and Huntsman, 1998). In seawater-based media, Fe is often added as chelated forms (e.g., Fe-EDTA) to prevent precipitation. Some microalgae possess siderophore-mediated Fe acquisition systems, enhancing competitiveness in oligotrophic environments (Maldonado and Price, 2001).

2.5.2.2 Zinc (Zn), Copper (Cu), Molybdenum (Mo), Cobalt (Co)

Zinc is essential for carbonic anhydrase and RNA polymerase. Cu participates in plastocyanin and superoxide dismutase. Mo is required for nitrate reductase and nitrogenase. Co is a component of vitamin B12, necessary for methionine synthase in some species (Borowitzka, 2013). Deficiencies manifest as specific enzymatic failures. For example, Mo deficiency blocks nitrate assimilation, forcing reliance on ammonium or organic N sources.

2.5.2.3 Chloride (Cl)

Chloride aids in osmoregulation and is a cofactor for photosystem II. Although rarely limiting, Cl⁻ deficiency can impair photosynthetic oxygen evolution (Marschner, 2012).

2.5.2.4 Vitamins: B1 (Thiamine), B7 (Biotin), B12 (Cobalamin)

Many microalgae are auxotrophic for one or more B-vitamins, meaning they cannot synthesize them de novo and require external supply. Vitamin B12 is particularly important for methionine and purine biosynthesis. Species like *Phaeodactylum tricornutum* and *Emiliana huxleyi* require exogenous B12, while others (e.g., *Chlorella*) can synthesize it (Croft et al., 2005). Vitamin B1 (thiamine) is involved in carbohydrate metabolism, and B7 (biotin) is essential for carboxylation reactions. Deficiencies can halt growth entirely unless supplemented. In axenic cultures, vitamin requirements must be meticulously met. In mixed cultures or wastewater-based systems, symbiotic bacteria often provide these vitamins, reducing the need for synthetic supplementation (González et al., 2017). Micronutrient optimization is often overlooked but can dramatically improve culture stability and productivity. Trace element cocktails such as those described by Fogg et al. (1973) or Guillard and Ryther (1962) remain widely used benchmarks.

2.5.3 Nutrient Limitation Strategies for Enhanced Lipid Production

As illustrated in Figure 2.1, nutrient deficiency — particularly nitrogen and phosphorus — drives lipid accumulation, while sufficient nutrition favours biomass. This dichotomy forms the basis of two-stage cultivation protocols designed to maximise both biomass and lipid yield. In Stage 1, microalgae are grown under nutrient-replete conditions to achieve high cell densities. In Stage 2, selected nutrients (usually N or P)

are withdrawn to induce stress-induced lipid biosynthesis. This approach decouples growth from storage metabolism, overcoming the inverse relationship between biomass and lipid content observed in single-stage systems (Xiong et al., 2010). Studies comparing single-stage vs. two-stage cultivation show consistent advantages for the latter. *Chlorella vulgaris* subjected to N-starvation after reaching stationary phase accumulated 48% lipid content compared to 22% in continuously N-limited cultures (Li et al., 2014). Similar results were reported for *Scenedesmus dimorphus* and *Nannochloropsis salina* (Yan et al., 2016). Alternative stressors such as silicon limitation (for diatoms), high salinity, or elevated CO₂ can also stimulate lipid production, offering flexibility based on species and system constraints (Wang et al., 2014). However, nutrient deprivation induces oxidative stress, triggering apoptosis in some species. Antioxidant supplementation (e.g., ascorbic acid, tocopherols) or genetic modification to overexpress stress-tolerance genes can mitigate cell death and improve lipid recovery (Liu et al., 2018).

Additionally, the timing and severity of nutrient withdrawal are critical. Premature induction reduces total biomass, while delayed induction may miss the window of maximal lipid synthesis capacity. Mathematical modelling and real-time monitoring of intracellular metabolites (e.g., via Raman spectroscopy) are emerging tools to optimise induction points (Zhang et al., 2020). In conclusion, nutrient limitation represents a powerful lever for manipulating microalgal metabolism. When combined with physical parameter optimization and appropriate cultivation modes, it enables precision control over product profiles — whether prioritizing biomass, lipids, or specialty compounds.

2.6 MODES OF CULTIVATION: AUTOTROPHIC, HETEROTROPHIC, MIXOTROPHIC, PHOTOHETEROTROPHIC

2.6.1 Autotrophic Cultivation: Harnessing Sunlight for Carbon Fixation

Autotrophic cultivation relies solely on photosynthesis for energy and carbon fixation, using CO₂ as the sole carbon source. It is the most sustainable mode, requiring minimal organic inputs and producing oxygen as a byproduct (Chisti, 2007). The advantages of microalgae cultivation include the use of low-cost substrates such as sunlight and atmospheric CO₂, making it an economically viable option for large-scale production. Additionally, microalgae are environmentally benign, offering a sustainable solution with minimal ecological impact. They are also well-suited for large-scale outdoor systems, where they can harness natural resources effectively. However, there are several disadvantages to consider. Microalgae cultivation is highly dependent on weather and geographic conditions, which can limit its consistency and productivity in certain regions. Growth rates are generally lower compared to heterotrophic systems, which can be a drawback for applications requiring rapid biomass accumulation. Furthermore, microalgae are susceptible to contamination by unwanted microorganisms and predation, which can negatively impact their growth and overall system efficiency. Common configurations include open raceway ponds (ORPs) and closed photobioreactors (PBRs). ORPs are inexpensive and scalable but suffer from poor light penetration, evaporation losses, and contamination risks (Richmond, 2004). PBRs offer superior control over environmental parameters but entail higher capital and maintenance costs (Pulz and Gross, 2004).

Species commonly cultivated autotrophically include *Chlorella*, *Spirulina*, *Dunaliella*, and *Nannochloropsis*. Productivity ranges from 0.1–1.0 g L⁻¹ day⁻¹ in ORPs to 1.0–3.0 g L⁻¹ day⁻¹ in optimised PBRs (Ugwu et al., 2008). Recent innovations focus on improving light utilization efficiency through novel reactor geometries (e.g., flat-panel, tubular, helical), internal lighting, and spectral tuning (Wagner et al., 2016). Integration with flue gas from power plants provides a dual benefit: CO₂ mitigation and cost reduction (Abd Rahaman et al., 2011). Despite challenges, autotrophy remains the

dominant mode for commercial microalgal production due to its alignment with circular economy principles and renewable resource utilization.

2.6.2 Heterotrophic Cultivation: Organic Carbon as Energy Source

Heterotrophic cultivation utilizes organic carbon sources (e.g., glucose, acetate, glycerol) instead of CO₂ for growth. Unlike autotrophs, heterotrophs do not require light and can grow in dark fermenters, like yeast or bacterial bioreactors (Li et al., 2008). Heterotrophic microalgae cultivation offers several advantages, including higher growth rates and biomass yields, making it a more efficient process compared to photosynthetic systems. Since it is independent of sunlight, this method allows for cultivation in controlled environments, enhancing the potential for year-round production. Additionally, it is easier to scale up and manage contamination, as the controlled conditions can limit exposure to external contaminants. However, there are notable disadvantages to consider. One of the main challenges is the high cost of organic substrates, which can increase the overall production expenses. There is also the potential for the accumulation of byproducts, such as ethanol or lactate, which could impact the efficiency and quality of the microalgae. Furthermore, heterotrophic systems are not truly sustainable unless waste-derived carbon sources are utilized, as the reliance on external organic substrates may contribute to unsustainable practices. Model heterotrophic species include *Chlorella protothecoides*, *Schizochytrium limacinum*, and *Auxenochlorella protothecoides*. Biomass productivities can reach 5–10 g L⁻¹ day⁻¹ — significantly higher than autotrophic systems (Chen et al., 2011).

Cost reduction strategies involve using low-value feedstocks such as lignocellulosic hydrolysates, molasses, or crude glycerol from biodiesel production (Zhou et al., 2017). Genetic engineering has enabled previously obligate autotrophs to metabolize organic carbon, expanding the pool of cultivable species (Dong et al., 2019). One major drawback is the loss of photosynthetic pigments and associated value-added compounds (e.g., carotenoids, phycobiliproteins). However, heterotrophy excels in

producing high-lipid biomass suitable for biodiesel or omega-3 fatty acids (e.g., DHA from *Schizochytrium*). Economic analyses suggest that heterotrophic cultivation becomes viable only when paired with cheap, abundant carbon sources or when targeting high-value products (Mata et al., 2010).

2.6.3 Mixotrophic Cultivation: Combining Autotrophy and Heterotrophy

Mixotrophic cultivation allows microalgae to simultaneously utilize both organic carbon and light for growth. This hybrid mode combines the benefits of rapid growth (from organics) with photosynthetic efficiency (from light), often yielding superior biomass and lipid productivity (Wang et al., 2008). Mechanistically, mixotrophy enables flexible carbon allocation: under light, cells fix CO₂ via Calvin cycle; in darkness or low light, they metabolize organic substrates via glycolysis and TCA cycle. Some species exhibit preferential use of one pathway depending on environmental cues (Zhang et al., 2016). Examples of mixotrophic species include *Chlorella vulgaris*, *Scenedesmus obliquus*, and *Tetraselmis suecica*. Studies show that mixotrophic *C. vulgaris* grown on glucose under 12:12 L:D cycles achieved 3.2 g L⁻¹ day⁻¹ biomass and 35% lipid content — outperforming both pure autotrophic and heterotrophic counterparts (Li et al., 2014).

Key advantages of microalgae cultivation include enhanced growth rates and biomass yields, making them highly efficient for biofuel production and other applications. Additionally, nutrient stress can improve lipid content, further boosting their potential in bioenergy production. Microalgae also exhibit greater resilience to environmental fluctuations, which is critical for maintaining consistent productivity under varying conditions. However, there are several challenges associated with microalgae cultivation. The formulation of the growth medium and process control can be complex, requiring precise management to optimise production. Furthermore, the use of organic substrates carries a risk of microbial contamination, which could compromise the culture's health and productivity. Another concern is the potential

competition between metabolic pathways, which may reduce the overall efficiency of biomass and lipid production.

Optimization involves balancing light intensity, organic carbon concentration, and nutrient supply. For instance, low glucose levels ($<10 \text{ g L}^{-1}$) combined with moderate light ($\sim 100 \text{ } \mu\text{mol photons m}^{-2} \text{ s}^{-1}$) often yield optimal results (Zhou et al., 2017). Emerging trends include fed-batch and continuous mixotrophic systems, as well as integration with wastewater treatment where organic pollutants serve as carbon sources (González et al., 2017).

2.6.4 Photoheterotrophic Cultivation: Light-Enhanced Heterotrophy

Photobeterotrophy is a specialized form of mixotrophy where light enhances heterotrophic growth without contributing significantly to carbon fixation. In other words, light acts as an energy booster rather than a carbon source (Borowitzka, 2013). This mode is particularly relevant for species that retain photosynthetic machinery but primarily rely on organic carbon. Light stimulates ATP and NADPH production via cyclic electron flow, supporting biosynthetic reactions without fixing CO_2 . For example, *Chlorella protothecoides* grown on acetate under light showed 20–30% higher biomass than in darkness, despite negligible CO_2 fixation (Chen et al., 2011). Similarly, *Schizochytrium* cultures exposed to low-intensity blue light exhibited accelerated lipid synthesis. Photoheterotrophy offers a middle ground between heterotrophy and mixotrophy, providing the speed of organic-fed systems with the metabolic boost of light. It is especially promising for high-value lipid production where rapid growth is paramount. However, defining the boundary between mixotrophy and photoheterotrophy remains ambiguous in literature. Rigorous isotopic labelling experiments (using ^{13}C -glucose and $^{14}\text{CO}_2$) are needed to distinguish true carbon assimilation pathways (Zhang et al., 2020). From an engineering perspective, photoheterotrophic systems can be operated in simpler setups than full mixotrophs,

requiring only minimal light input to augment heterotrophic metabolism. This makes them attractive for industrial scaling.

2.7 INTERACTIONS BETWEEN FACTORS: SYNERGIES AND TRADE-OFFS

The factors outlined in Figure 2.1 do not operate in isolation; they interact dynamically to shape microalgal responses. Understanding these interactions is crucial for designing efficient, resilient cultivation systems.

2.7.1 Light × Nutrient Interactions

Light and nutrients co-regulate photosynthetic capacity and carbon partitioning. Under high light, nutrient-replete cultures allocate carbon to growth-related macromolecules (proteins, nucleic acids), while nutrient-limited cultures shift toward storage lipids (Rodolfi et al., 2009). Conversely, under low light, even nutrient-sufficient cultures may accumulate lipids as a survival mechanism, conserving energy for future growth (Wang et al., 2014). Thus, the interplay between light intensity and nutrient status determines whether biomass or lipids dominate. Mathematical models incorporating light-nutrient interactions (e.g., Droop model, Monod kinetics) are widely used to predict growth and lipid accumulation under varying conditions (Huang et al., 2019).

2.7.2 Temperature × pH × Aeration

These three parameters are tightly coupled in reactor operation. For example, rising temperature increases CO₂ solubility loss, necessitating higher aeration rates to maintain CO₂ supply — which in turn lowers pH. Buffering systems must counteract this

cascade to preserve optimal conditions. Similarly, high aeration rates can cool cultures via evaporative heat loss, altering temperature-dependent enzyme kinetics. Integrated control systems using feedback loops are essential to manage these nonlinear interactions (Park et al., 2013).

2.7.3 Cultivation Mode × Nutrient Strategy

The choice of cultivation mode dictates feasible nutrient strategies. Autotrophic systems benefit from staged nutrient feeding to avoid early limitation. Heterotrophic systems can employ continuous feeding to sustain exponential growth. Mixotrophic systems require careful titration of organic carbon to prevent repression of photosynthesis. Two-stage lipid induction works best in autotrophic and mixotrophic systems, where initial biomass build-up is possible. In heterotrophic systems, lipid induction is often achieved by switching carbon sources (e.g., from glucose to acetate) or inducing stress via oxygen limitation (Zhou et al., 2017).

2.7.4 Systems Biology Approaches to Multi-Factor Optimization

Traditional “one-factor-at-a-time” experimentation is inadequate for capturing complex interactions. Modern approaches employ multivariate statistical designs (e.g., Box-Behnken, Central Composite Design) and machine learning algorithms to map response surfaces and identify global optima (Zhang et al., 2021). Transcriptomic, proteomic, and metabolomic profiling reveal how microalgae rewire their metabolism under combinatorial stresses. For instance, *Nannochloropsis* under N-starvation + high light show upregulation of TAG biosynthesis genes and downregulation of ribosomal proteins (Yan et al., 2016). Digital twins — virtual replicas of cultivation systems powered by AI — are beginning to revolutionize microalgal biotechnology by simulating thousands of scenarios before physical implementation (Huang et al., 2019).

The factors influencing microalgal growth — as summarised in Figure 2.1 — encompass a multidimensional landscape of physical, nutritional, and operational variables. Each factor exerts direct or indirect influence over cellular metabolism, ultimately determining whether microalgae prioritize biomass accumulation or lipid storage. This chapter has reviewed the state-of-the-art understanding of these factors, emphasizing their individual roles and synergistic interactions. Key takeaways include:

- i. Physical parameters (pH, temperature, aeration, light, photoperiod) must be precisely controlled to maintain physiological homeostasis and maximise photosynthetic efficiency.
- ii. Nutrient composition — particularly nitrogen and phosphorus — serves as a master switch between growth and storage metabolism, enabling strategic manipulation via two-stage cultivation.
- iii. Cultivation modes (autotrophic, heterotrophic, mixotrophic, photoheterotrophic) offer distinct advantages and trade-offs, with mixotrophy emerging as a versatile platform for high-yield, high-value production.
- iv. Interactions between factors are complex and nonlinear, necessitating systems-level approaches such as multivariate optimization, omics profiling, and digital twin modelling.

Future research should focus on developing predictive models that integrate multi-omics data with environmental variables, engineering robust strains capable of thriving under fluctuating conditions, and designing scalable, low-cost cultivation systems compatible with global deployment. Ultimately, unlocking the full potential of microalgae requires not just technological innovation, but a holistic systems perspective that recognizes the intricate web of factors shaping their biology. As we transition toward a sustainable bioeconomy, microalgae stand poised to play a central role — provided we understand and harness the very factors that govern their existence.

2.8 ALGAE DESIGN TREND IN BUILT ENVIRONMENT

In the face of accelerating climate change, urbanization, and resource depletion, the built environment is undergoing a paradigm shift from passive consumption toward active regeneration. Among the most promising bio-integrated strategies emerging at the intersection of architecture, engineering, and biotechnology is the incorporation of algae—particularly microalgae and macroalgae—into building façades, infrastructure, and urban systems. Once confined to laboratories and aquaculture ponds, algae are now being reimagined as living building materials, dynamic energy generators, and ecological mediators in the urban fabric. This section examines the evolving design trends that position algae not merely as a biological curiosity but as a functional, aesthetic, and sustainable component of next-generation architecture.

2.8.1 From Ornamental to Functional: The Evolution of Bio-Integrated Design

Historically, nature in architecture was largely ornamental—think of ivy-clad walls or rooftop gardens serving aesthetic or recreational purposes. However, the 21st century has witnessed a transition toward performative bio-design, where living organisms contribute measurable environmental services. Algae, with their rapid growth, high photosynthetic efficiency, and capacity for carbon sequestration, nutrient uptake, and biomass production, offer a compelling platform for such integration (Gruber and Schmid, 2019). Unlike static green walls or conventional solar panels, algae-based systems are dynamic, responsive, and productive. They can adapt to changing light and temperature conditions, self-replicate, and generate harvestable biomass for energy, food, or materials. This shift reflects a broader movement toward circular urban metabolism, where buildings function as nodes in a regenerative ecosystem rather than isolated energy sinks (Cheshire, 2024).

2.8.2 Key Algae Design Typologies in Architecture

Current algae integration strategies in the built environment fall into three primary typologies:

- 1. Photobioreactor (PBR) Façades**

These are transparent panels or tubes integrated into building envelopes that house microalgae cultures. Sunlight drives photosynthesis, enabling algae to absorb CO₂, release O₂, and produce biomass. Simultaneously, the dense algal suspension provides dynamic shading, reducing solar heat gain and cooling loads. The first full-scale implementation was the BIQ House in Hamburg, Germany (2013), developed by Splitterwerk Architects and Arup. Its bio-reactive façade uses *Chlorella vulgaris* in flat-panel PBRs to generate heat and biomass while modulating daylight and thermal performance (Wurm and Pauli, 2016)

- 2. Algae-Based Green Roofs and Walls**

While traditional green roofs use vascular plants, experimental systems now incorporate macroalgae (e.g., *Ulva*, *Gracilaria*) or algal mats in hydroponic or semi-aquatic setups. These systems offer enhanced stormwater retention, evaporative cooling, and air purification. In coastal cities, salt-tolerant algae can thrive without freshwater irrigation, addressing water scarcity concerns (Wong et al., 2021).

- 3. Algae-Infused Building Materials**

Researchers are embedding algae into bio-concrete, bioplastics, and hydrogels to create self-healing or carbon-negative materials. For example, cyanobacteria-infused concrete can precipitate calcium carbonate to seal cracks (Jonkers, 2011). Similarly, algae-derived biopolymers are being tested as sustainable alternatives to petroleum-based insulation or cladding (Roudbari, 2025; Alazaiza et al., 2023).

2.8.3 Performance Benefits: Beyond Aesthetics

The integration of algae into buildings offers a range of environmental and operational advantages that contribute to both sustainability and energy efficiency. One of the key benefits is carbon sequestration; a square meter of algae-based photobioreactor (PBR) can absorb up to 10 kg of CO₂ annually, akin to the carbon absorption of a mature tree, while simultaneously producing 5–10 kg of biomass (Gruber and Schmid, 2019). This contributes to reducing the carbon footprint of buildings and helps mitigate climate change. In terms of thermal regulation, algae systems can provide significant energy savings. Algal shading can reduce cooling energy demand by up to 30% during summer months, while the thermal mass of water-filled panels helps stabilize indoor temperatures, contributing to more energy-efficient buildings (Villalba et al., 2023).

Furthermore, algae can play a pivotal role in renewable energy production. Harvested algae biomass can be converted into biogas, biodiesel, or bioethanol, creating on-site energy loops. An example of this is the BIQ House, which utilizes algal biomass to power a micro-turbine for heating purposes, making it an excellent model for energy-efficient building design. Algae also provide air and water purification services. They have the ability to absorb pollutants such as NO_x, SO₂, and particulate matter from urban air, improving the quality of the surrounding environment. In hybrid systems, algae can treat greywater or blackwater by removing nitrogen, phosphorus, and heavy metals, offering an eco-friendly solution for urban wastewater management (González et al., 2017).

Finally, algae-based systems contribute to biodiversity and biophilic design by enhancing urban biodiversity. Living façades made of algae not only support local ecosystems but also offer psychological benefits by connecting building occupants to natural processes, fostering a sense of well-being and a deeper connection to the environment (Kellert et al., 2008). Through these multifaceted benefits, algae integration into building systems presents a promising avenue for sustainable, energy-efficient, and biophilic design.

2.8.4 Technological Innovations Driving Adoption

Recent advancements have significantly improved the performance and feasibility of algae-integrated systems, overcoming many of the initial challenges associated with their implementation. Strain selection has been a key area of development. Genetically optimised strains such as *Chlorella sorokiniana* and *Nannochloropsis oceanica* are now favoured for their high lipid content, thermal tolerance, and rapid growth even under variable light conditions. These improvements enable algae to thrive in a wider range of environments, enhancing their utility for building-integrated systems (Liu et al., 2018). Smart monitoring technologies have further elevated the efficiency of algae systems. The integration of IoT sensors allows real-time tracking of critical parameters such as pH, temperature, nutrient levels, and biomass density. This data enables automated adjustments for nutrient dosing, harvesting, and system maintenance, optimising algae productivity while reducing human intervention (Zhang et al., 2021).

The modular design of algae-based systems has also seen significant progress. Prefabricated photobioreactor (PBR) panels are now available, allowing for easy integration into both new and retrofitted buildings. This "plug-and-play" design simplifies installation and reduces both complexity and cost, making algae integration more accessible to a wider range of projects. In addition, the development of hybrid systems has enhanced the multifunctionality of algae-integrated façades. Combining algae PBRs with photovoltaic (PV) panels creates bio-hybrid façades capable of generating both electricity and biomass. This dual-purpose design maximises the productivity of building façades, contributing to both renewable energy generation and biomass production, further improving the sustainability of the building (Manoharan et al., 2025; Schnurr et al., 2018). These innovations have significantly advanced algae-integrated systems, making them more efficient, cost-effective, and adaptable, paving the way for wider adoption in sustainable building designs.

2.8.5 Case Studies: Pioneering Projects

Several landmark projects have marked significant milestones in the evolution of algae-based design, showcasing the potential for integrating algae into architecture while advancing sustainable building technologies. The BIQ House in Hamburg (2013) stands as the world's first algae-powered building, introducing the concept of bio-reactive façades. While its energy output was modest, the project served as a pivotal demonstration of the technical feasibility of integrating algae systems into the built environment. It catalysed global interest in living architecture, highlighting algae's potential as a renewable energy source and architectural feature. The Algae Garden Pavilion at the Milan Expo (2015), designed by ecoLogicStudio, took a more artistic approach, using microalgae in tubular reactors to visually demonstrate CO₂ consumption in real-time (Violano and Cannaviello, 2019). This installation successfully blended art, science, and public engagement, creating a powerful visual representation of algae's role in addressing climate change and contributing to a more sustainable future.

The Urban Algae Canopy in Milan (2016) took algae integration to a new level with a responsive structure made of ETFE membranes filled with algae. This canopy acted as a "living photo-bioreactor," with its opacity changing in response to sunlight intensity, making it both an environmentally interactive system and a public spectacle. The project emphasised the dynamic potential of algae in architecture, transforming a functional element into an engaging and visually stimulating urban installation. At the Algae Lab at the University of Cambridge, researchers developed a "living brick" made from cyanobacteria that generates small amounts of electrical current through photosynthesis. This breakthrough marks a significant step toward bio-photovoltaic building materials, offering the possibility of self-sustaining structures capable of generating energy directly from their environment (Sawa et al., 2017). These projects illustrate a shift from early demonstration prototypes to more scalable and user-responsive systems. They signify the growing maturity of algae-based architecture, highlighting its potential for real-world application and integration into future sustainable urban landscapes.

2.8.6 Sustainability and Circular Economy Alignment

Algae-integrated buildings are inherently aligned with the principles of a circular economy, offering a sustainable solution to urban development that emphasises resource efficiency, waste valorisation, and end-of-life recovery. Waste valorisation plays a key role in algae-based systems. Flue gas from building HVAC systems or nearby industrial sources can be harnessed to supply the necessary CO₂ for algae growth, reducing the need for additional carbon emissions. Additionally, wastewater can serve as a valuable source of nutrients, further enhancing the sustainability of the system by recycling waste products that would otherwise go unused. In terms of resource efficiency, algae offer a solution that requires minimal land area and no arable soil, thus avoiding competition with food production. This makes algae cultivation an ideal option for urban environments, where land use is at a premium and agricultural space is often limited. The ability to cultivate algae in urban settings without compromising food security is a significant advantage over other forms of bioenergy production. End-of-life recovery is another critical aspect of algae-integrated buildings. The harvested algae biomass can be anaerobically digested to produce energy, composted to enhance soil quality, or processed into bioplastics, effectively closing material loops and reducing waste. These processes contribute to a more sustainable lifecycle for algae systems, ensuring that materials are continually repurposed and not discarded.

Life cycle assessments (LCAs) further highlight the long-term environmental benefits of algae façades. Despite the higher initial embodied energy in photobioreactor (PBR) systems, LCAs suggest that algae-integrated buildings can achieve net-positive environmental performance over 20–30 years. This is largely due to the cumulative carbon savings and energy generation that algae systems provide over their lifespan, demonstrating the viability of algae as a long-term solution for sustainable urban architecture (Villalba et al., 2023). In sum, algae-integrated buildings offer a transformative approach to sustainable architecture, perfectly embodying the principles of the circular economy by turning waste into resources, minimising land use, and ensuring long-term environmental benefits.

2.8.7 Challenges and Limitations

Despite the significant promise of algae-integrated buildings, several barriers hinder their widespread adoption, posing challenges for their broader implementation in the built environment. Economic viability remains a major obstacle. The high capital costs associated with photobioreactor (PBR) systems ranging from €1,000 to €2,000 per square meter are still prohibitively expensive compared to more traditional solutions like conventional glazing or photovoltaic (PV) panels (Schnurr et al., 2018). These costs limit the appeal of algae systems for large-scale projects, especially when more affordable alternatives are readily available. Operational complexity also presents a significant challenge. Algae-based systems require specialized maintenance, including nutrient replenishment, contamination control, and harvesting. These tasks demand skilled personnel, creating operational hurdles for building managers who may lack the expertise or resources to maintain these systems effectively.

Aesthetic acceptance of algae-integrated façades can also be an issue. The natural green-to-brown colour shifts of algal cultures may not always align with architectural preferences or the desired appearance of a building. While designers are exploring solutions like colour-stable strains or artistic patterning, the inherent variability of algae cultures remains a design consideration that may not suit all projects. Regulatory gaps further complicate the adoption of algae-integrated systems. Building codes and regulations often fail to accommodate living façades, leading to permitting uncertainties. Without clear guidelines or support from regulatory bodies, architects and developers may be hesitant to incorporate algae-based systems into their designs.

Finally, the scalability of algae systems remains limited. While several high-profile projects have demonstrated the feasibility of algae integration, most are still small-scale. Integrating algae into high-rise or dense urban environments presents additional engineering challenges related to weight, pressure, and safety, making it difficult to scale these systems for large buildings or densely populated areas. While algae-integrated buildings hold great potential, addressing these economic, operational,

aesthetic, regulatory, and scalability challenges will be crucial for enabling their widespread adoption and integration into future urban development.

2.8.8 Emerging Trends and Future Directions

The next decade is poised to bring several transformative developments in the field of algae-integrated buildings, advancing both the technology and its integration into urban environments. AI-optimised cultivation will revolutionize algae farming by employing machine learning algorithms to predict optimal harvesting cycles and adjust light and nutrient inputs in real-time, maximising yield. This data-driven approach will ensure higher efficiency and productivity, addressing one of the key challenges of algae-based systems—operational complexity (Zhang et al., 2021).

Genetically engineered algae will take algae cultivation to new heights. With CRISPR-edited strains, algae could be engineered to produce specific pigments for controlled colour in façades, emit bioluminescent light for aesthetic or functional purposes, or even secrete therapeutic compounds such as antioxidants, opening the door to novel applications in architecture, health, and urban design. Decentralized urban algae hubs are another exciting possibility. Neighbourhood-scale algae farms on rooftops or vacant lots could supply local energy, food, and fertilizer, contributing to urban resilience and sustainability. This decentralized approach would reduce reliance on centralized infrastructure and support local communities, empowering cities to become more self-sufficient and less vulnerable to external disruptions (Shreya and Kshitij, 2025).

Policy incentives are likely to play a crucial role in accelerating the adoption of algae systems. Carbon credit schemes and green building certifications, such as LEED or BREEAM, may soon recognize algae-integrated systems as eligible technologies, providing the necessary financial and regulatory support to make these systems more accessible to developers and building owners. Public engagement will also be a key

component of this transformation. Interactive algae installations in schools, museums, and public plazas will raise ecological literacy, fostering greater public understanding and social acceptance of algae-based systems. These installations will help people connect with the science behind algae cultivation and the role it can play in sustainable architecture. Moreover, the concept of metabolic architecture buildings that breathe, feed, and excrete like living organisms is gaining traction. In this vision, algae serve as the metabolic engine, transforming static structures into adaptive, carbon-negative ecosystems. These buildings will be able to respond to environmental conditions and contribute to urban carbon neutrality, taking architecture from a passive element to an active, living part of the ecosystem. These developments signal a future where algae-based systems are integral to the fabric of urban life, providing sustainable solutions for energy, food, and environmental resilience, while also aligning with broader efforts to create carbon-negative, living architecture.

Algae design in the built environment represents more than a technological novelty; it embodies a philosophical reorientation toward symbiosis between human habitats and natural systems. From the pioneering BIQ House to experimental bio-bricks and responsive canopies, algae are proving their capacity to deliver tangible environmental services while redefining architectural aesthetics. Although economic, technical, and regulatory hurdles persist, ongoing innovations in biotechnology, materials science, and digital control are steadily improving feasibility. As cities strive to meet net-zero targets and enhance climate resilience, algae-integrated architecture offers a scalable, multifunctional solution that turns building surfaces into productive landscapes. The future of sustainable urbanism may well be green not just in colour, but in its very biology. By embracing algae not as an add-on but as a core design element, architects and urban planners can help cultivate a built environment that actively heals rather than merely inhabits the planet.

2.9 ALGAE TECHNOLOGY IN SOUTHEAST ASIA AND MALAYSIA

The Algae technology has seen significant growth in Southeast Asia, particularly in Malaysia, where the promising environmental conditions and strategic investments are making the country a leader in algae biotechnology. Malaysia's tropical climate, with abundant sunlight and stable temperatures, creates an ideal environment for algae cultivation. This has led to numerous initiatives focused on harnessing algae's potential for a wide range of applications, from renewable energy to health supplements. One of the most exciting projects is the Chitose Carbon Capture Central (C4) in Sarawak, Malaysia. Set to be the world's largest microalgae biomass production facility, this plant uses flat-panel photo-bioreactors to cultivate microalgae at a large scale. Supported by the Japanese government, C4 aims to produce biofuels, proteins, bioplastics, and other sustainable products. The project's potential to produce algae-based jet fuel by 2027 could play a significant role in global aviation's push toward greener energy sources (The Fish Site, 2023). In addition to large-scale production, Malaysia is becoming a hub for algae research and innovation. The Algae Biotechnology Consortium (ABC), launched by the University of Nottingham Malaysia, brings together global researchers and institutions to explore algae cultivation and commercialization. This initiative focuses on developing algae as a renewable source for food, bioenergy, and even cosmetics, positioning Malaysia as a critical player in the green industrial revolution (Hazim, 2022). Local companies like Algaetech International are also contributing to the algae boom in Southeast Asia. Specializing in *Haematococcus pluvialis*, an algae known for producing astaxanthin, a powerful antioxidant, Algaetech is the first company in the region to produce this high-value product. The company's products range from health supplements to functional foods, helping to expand the commercial potential of algae (Algaetech International Sdn Bhd 2024). These advancements highlight the versatility of algae as a sustainable resource. With continued investment in research and technology, Malaysia is ready to lead the way in algae innovation, offering solutions to global challenges in energy, food security, and environmental sustainability.

2.10 ALGAE-BASED MATERIALS AS A SUSTAINABLE SOLUTION IN BUILT ENVIRONMENT

Microalgae are chlorophyll-containing eukaryotic organisms found in freshwater and marine water habitats. The main composition of microalgae are proteins, lipids, carotenoids (i.e., astaxanthin), and nucleic acids (Khoo et al., 2020). Algae-based materials have gained attention as sustainable solutions for mitigating carbon emissions due to their high photosynthetic efficiency and capacity for carbon sequestration. Microalgae can fix atmospheric CO₂ at rates significantly higher than terrestrial plants, transforming it into biomass that can be further processed into biopolymers, construction composites, and biochar (Chew et al., 2022). The integration of algae cultivation systems into the built environment, such as photobioreactor façades, not only reduces greenhouse gas concentrations but also provides functional materials that contribute to sustainable urban development (Zhou et al., 2022). This dual role positions algae-based materials as viable contributors to both carbon mitigation and green building initiatives.

Beyond carbon capture, algae-based systems offer considerable potential for energy savings in urban contexts. Algae façades and panels act as dynamic shading devices, reducing solar heat gain in buildings while simultaneously producing oxygen and biomass. These biological façades absorb light for photosynthesis, thereby lowering indoor cooling loads and reducing reliance on air conditioning systems—a major contributor to energy consumption in cities. Additionally, the harvested algal biomass can be converted into bioenergy, further supporting renewable energy integration in urban infrastructures (Chisti, 2007). Such applications highlight the versatility of algae-based systems as multifunctional technologies for energy-efficient building design.

The relevance of algae-based materials to Urban Heat Island (UHI) mitigation lies in their combined ecological and architectural functions. By lowering building surface temperatures and providing localized carbon sinks, algae systems directly address the drivers of UHI, such as excess anthropogenic heat and poor carbon balance (Perini and Rosasco, 2013). When deployed across urban landscapes, these materials

not only help reduce urban energy demand but also create cooler microclimates through carbon absorption and shading effects. Consequently, algae-based innovations represent a promising nature-based solution to the UHI problem, bridging climate adaptation and mitigation strategies within sustainable urban planning.

One of the most cited examples is the BIQ House in Hamburg, Germany, which features a bioreactor (PBR) façade integrated into a five-storey passive house design (Table 2.2). The algae panels are installed on the south-east and south-west facades, where they serve multiple functions: generating biomass, producing heat via solar absorption, providing shading, and capturing carbon dioxide. The façade removes up to ~6 tonnes of CO₂ annually. Excess heat from the PBR façade is used to pre-heat domestic hot water or for central heating. The system also uses energy storage (through geothermal boreholes) to smooth out supply. While the measured solar-to-heat conversion ($\approx 21\%$) and into biomass ($\approx 4\%$) were lower than originally modelled, the building still show significant reductions in energy demand, particularly for heating and cooling. Because the algae panels afford shading and reduce direct solar gain, they contribute to lowered cooling loads in summer—which is directly relevant to reducing the UHI effect at micro-scale.

The AlgaePARC Pilot Facility at Wageningen University in the Netherlands is one of Europe's foremost platforms for advancing algae cultivation technologies from laboratory to semi-industrial scale (Table 2.2). The facility combines tubular photobioreactors (PBRs) and open raceway ponds to test productivity, energy efficiency, and environmental performance under controlled yet scalable conditions. Reported productivity levels at AlgaePARC reach up to 20–25 g dry weight/m²/day, with CO₂ fixation rates of approximately 1.8–2.0 kg CO₂ per kg of dry biomass produced, depending on reactor type and environmental parameters (Wijffels and Barbosa, 2010). Compared with open ponds, PBR systems at AlgaePARC achieve higher yields with reduced contamination risk, while also lowering water and nutrient inputs. Life-cycle assessments conducted at the facility highlight the potential to reduce energy demand for biomass production by optimising reactor design and integrating waste heat or flue gas as resource inputs. These findings position AlgaePARC as a

crucial testbed for demonstrating how algae-based systems can be scaled for both industrial applications and urban integration. By improving carbon capture efficiency and supporting renewable biomass production, the lessons from AlgaePARC offer pathways for incorporating algae façades into buildings, where they could reduce energy consumption and contribute to Urban Heat Island (UHI) mitigation through shading and localized carbon sequestration.

The SYMBIO2 project, developed in 2016 in Nantes, France, by XTU Architects, represents a speculative yet highly influential demonstration of integrating microalgae-based photobioreactor (PBR) façades into building design (Table 2.2). Conceived as a research centre, the project employed flat-panel PBRs covering an area of approximately 300 m², designed not only to cultivate microalgae for medical research but also to provide functional energy and environmental benefits. The system could produce about 10 kWh/year of usable biomass energy while sequestering between 1 and 1.8 tons of CO₂ annually, showcasing its potential role in urban carbon mitigation strategies. Beyond carbon capture, the heat generated by the PBRs was recovered and used to supply domestic hot water and contribute to space heating, thereby reducing the building's reliance on conventional energy systems. The SYMBIO2 project thus exemplifies the multifunctionality of algae-based façades simultaneously supporting biomedical research, contributing to renewable energy generation, enhancing building energy performance, and reducing greenhouse gas emissions. As such, it offers a valuable precedent for exploring how algae-integrated architectural systems can be scaled and adapted to address urban sustainability challenges, including mitigating the Urban Heat Island effect through shading, localized cooling, and reduced fossil energy dependency.

Collectively, the BIQ House in Hamburg, the AlgaePARC facility in the Netherlands, and the SYMBIO2 project in Nantes demonstrate the versatility and transformative potential of algae-based systems in both architectural and industrial contexts. The BIQ House illustrates the feasibility of full-scale residential integration, where façade mounted photobioreactors provide shading, capture up to 6 tons of CO₂ annually, and reduce building energy demand through biomass and heat recovery. At

the industrial research scale, AlgaePARC provides quantitative evidence of high productivity, achieving 20–25 g/m²/day of biomass with CO₂ fixation rates of 1.8–2.0 kg CO₂ per kg of biomass, thereby establishing scalable pathways for energy-efficient carbon capture and resource recovery. Meanwhile, SYMBIO2 highlights speculative architectural applications in research infrastructure, integrating a 300 m² flat-panel PBR façade that sequesters 1–1.8 tons of CO₂ per year while supplying domestic hot water and heating. Taken together, these cases underline the dual contributions of algae façades: (i) as active agents in carbon mitigation through sequestration and biomass valorisation, and (ii) as energy-saving systems that reduce cooling and heating loads in buildings. Importantly, they also point to algae’s emerging role in mitigating urban sustainability challenges such as the Urban Heat Island effect by lowering surface temperatures, enhancing shading, and creating localized carbon sinks within dense urban environments.

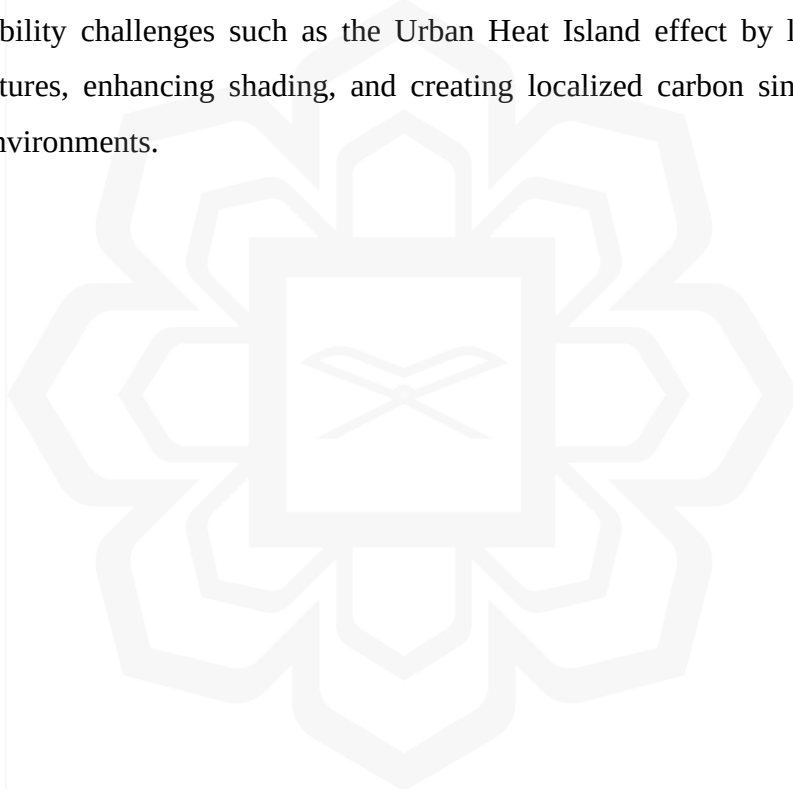


Table 2.2 The existing project with objective and design data

PROJECT	LOCATION	OBJECTIVE AND DESIGN DATA	REF.
	The Bio Intelligent Quotient, BIQ Building Hamburg, Germany	The system operates year-round, converting 10% of light into biomass and 38% into heat. In comparison, photovoltaic systems achieve 12-15% efficiency, while solar thermal systems reach 60-65%. Photobioreactor PBR Type: Flat panel (24-L capacity) Number of PBR modules: 129(2.5-0.7 m) PBR façade area: 232 sqm Sequestered CO ₂ : 16 kg/day Biomass production: 30 kWh/sqm/year Heat production: 150 kWh/sqm/year.	The RIBA Journal September 2013
	SYMBIO2 2016 Nantes, France	A speculative building integrating a microalgae producing PBR bio-façade for medical research. The heat collected by the PBRs is used for domestic hot water and heating. Building type: Research Centre PBR type: Flat panel PBR PBR façade area: 300 sqm Biomass production: 10 kWh/year Sequestered CO ₂ : 1–1.8 ton/year.	XTU Architects. 2016
	School of Architecture, University of North Carolina at Charlotte	The microalgae facade in the creativity study is composed of a network of interlocking bioreactors filled with spirulina, blue-green microalgae. Using the carbon sequestration rate of 1.8 kg of CO ₂ removed for 1 kg of dry algal biomass	Kathryn et al., 2023
	AlgaePARC Pilot Facility, Wageningen, Netherlands	Multiple PBR types; ~24 m ² footprint (tubular, plate, film reactors). 20–25 g dry weight/m ² /day, with CO ₂ fixation rates of approximately 1.8–2.0 kg CO ₂ per kg of dry biomass produce	van Beilen et al., 2017

2.11 APPLICATION OF MICROALGAE AS CARBON SEQUESTRATION IN THE BUILT ENVIRONMENT

The built environment—comprising buildings, infrastructure, and urban systems—is responsible for nearly 40% of global energy-related CO₂ emissions (IEA, 2023). As cities strive to meet net-zero targets under the Paris Agreement, innovative carbon mitigation strategies are urgently needed. Among the most promising biological solutions is the integration of microalgae into architectural and urban systems for active carbon sequestration. Unlike passive carbon storage methods (e.g., afforestation or geological sequestration), microalgae offer a dynamic, productive, and scalable approach that transforms buildings from carbon emitters into carbon sinks. This chapter explores how microalgae are being deployed in the built environment to capture, utilize, and store atmospheric and point-source CO₂, contributing to climate-resilient urban futures.

2.11.1 The Carbon Sequestration Potential of Microalgae

Microalgae are unicellular photosynthetic organisms capable of fixing CO₂ at rates 10–50 times higher than terrestrial plants due to their high surface-to-volume ratio, rapid growth (doubling times of 3–24 hours), and efficient photosynthetic machinery (Chisti, 2007). Through the Calvin cycle, they convert CO₂ and sunlight into biomass, with carbon accounting for approximately 50% of their dry weight (Wang et al., 2008). Globally, microalgae are estimated to fix 10–20 billion tons of CO₂ annually, representing nearly half of Earth's photosynthetic carbon fixation (Field et al., 1998).

Crucially, microalgal carbon sequestration is not merely temporary. When biomass is harvested and converted into stable end-products such as biochar, bioplastics, or construction materials the carbon can be stored for decades or centuries, achieving long-term carbon removal (Mata et al., 2010). This distinguishes microalgae

from conventional green infrastructure (e.g., trees), where carbon is re-released upon decomposition or combustion.

2.11.2 Integration Strategies in the Built Environment

The application of microalgae for carbon sequestration in urban settings centres on three primary integration strategies:

2.11.2.1 Photobioreactor (PBR) Façades

The most advanced application involves embedding closed loop photobioreactors into building envelopes. These transparent panels or tubes contain dense microalgal cultures (e.g., *Chlorella vulgaris*, *Scenedesmus obliquus*) that absorb CO₂ from ambient air or flue gas while generating biomass. Sunlight drives photosynthesis, and the system provides simultaneous shading, thermal regulation, and carbon capture. The landmark BIQ House in Hamburg, Germany (2013), developed by Arup and Splitterwerk Architects, demonstrated this concept at full scale. Its south-facing bio-reactive façade uses flat-panel PBRs to sequester an estimated 6–10 kg of CO₂ per m² annually while producing 5–8 kg of harvestable biomass (Wurm and Pauli, 2016). The biomass is processed into biogas for heating, closing the energy loop. Recent innovations include modular PBR systems that can be retrofitted onto existing buildings. For example, the Algae Solar Collector by Colt International combines thermal energy collection with algal cultivation, capturing CO₂ while preheating water for building use (Manoharan et al., 2025; Schnurr et al., 2018).

2.11.2.2 Urban Algae Farms on Rooftops and Vacant Lots

Decentralized microalgal cultivation on underutilised urban spaces rooftops, parking structures, brownfields offers a scalable model for community-level carbon management. These systems can be fed with flue gas from nearby buildings, data centres, or small-scale industrial sources, turning waste CO₂ into valuable biomass. In Singapore, the Algae Urban Farming Initiative explores rooftop PBRs integrated with HVAC exhaust streams to capture CO₂ while producing feedstock for nutraceuticals (Wong et al., 2021). Similarly, in Barcelona, the Green Urban Algae Project uses vertical PBR towers in public plazas to offset local emissions while engaging citizens in climate action. Such systems align with the circular city paradigm, where urban metabolism is optimised through localized resource loops. A 1,000 m² rooftop algae farm can sequester 5–10 tons of CO₂ per year—equivalent to removing 2–4 cars from the road (Villalba et al., 2023).

2.11.2.3 Hybrid Systems with Wastewater and Flue Gas

Microalgae thrive on nutrients (N, P) and CO₂, making them ideal for co-treatment of wastewater and flue gas. In the built environment, this synergy is harnessed through integrated biorefineries attached to buildings or districts. For instance, a commercial office building can channel its HVAC exhaust (containing 400–1,000 ppm CO₂) and greywater into a microalgal bioreactor. The algae consume CO₂ and nutrients, purifying water while growing biomass. The treated water can be reused for irrigation or cooling, and the biomass processed into biogas or bioplastics (González et al., 2017). Pilot projects in California and the Netherlands have shown that such hybrid systems can achieve >90% CO₂ removal efficiency from diluted gas streams and >80% nutrient removal from wastewater (Chen et al., 2021a).

2.11.3 Performance Metrics and Carbon Accountings

Quantifying the carbon sequestration potential of microalgal systems is crucial for understanding their contribution to reducing greenhouse gas emissions. This requires the use of life cycle assessment (LCA) and carbon accountings frameworks to measure the system's environmental impact across all stages of its life. CO₂ fixation rate is a key metric, with microalgae typically fixing 1.8–2.0 kg of CO₂ per kilogram of biomass produced (Chisti, 2007). This figure helps estimate the amount of carbon that can be captured by algae in each system. Areal productivity is another important factor. In optimised photobioreactor (PBR) systems, algae can produce 20–30 g of dry biomass per square meter per day. This translates to approximately 6–10 kg of CO₂ captured per square meter per year (Gruber and Schmid, 2019), making it a highly efficient method of carbon sequestration in urban environments. The net carbon balance is a more comprehensive measure that accounts for the embodied energy required to produce, maintain, and operate the PBR system, including energy for pumping, harvesting, and material use. Studies indicate that, despite the initial energy input, these systems can achieve net-negative emissions over a 20-year lifespan, meaning they remove more carbon from the atmosphere than is consumed in their operation (Villalba et al., 2023). For context, a typical office building emits approximately 50 kg of CO₂ per square meter per year. By integrating algae façades on 30% of the building's envelope, it could offset 15–20% of its operational emissions. This represents a significant contribution toward achieving net-zero carbon goals, showcasing the potential of algae systems to play a vital role in sustainable building design and urban carbon management.

When microalgal biomass is converted into long-lived products, the carbon removal effect becomes permanent, creating a lasting environmental benefit. For example:

- i. Biochar is a highly stable form of carbon sequestration, as it remains stable for centuries. It can be used as a soil amendment, improving soil fertility, or incorporated into construction composites, locking carbon into building materials for long periods.

- ii. Algae-based bioplastics offer a sustainable alternative to petroleum-based plastics, effectively locking carbon into consumer goods and reducing reliance on fossil fuels.
- iii. Algae-infused concrete represents a carbon-negative building material with additional benefits, such as self-healing properties. This innovation not only captures carbon during its production but also enhances the longevity and sustainability of building structures (Roudbari, 2025; Alazaiza et al., 2023).

Compared to conventional carbon mitigation strategies, microalgal carbon sequestration offers several distinct advantages:

- i. High efficiency: Algae can fix CO₂ faster than trees and require significantly less land to do so. This makes algae cultivation a more efficient solution for carbon capture, especially in urban environments where land availability is limited.
- ii. Dual functionality: Algae systems provide multiple benefits simultaneously. They can generate energy, produce materials, treat water, and offer thermal regulation, making them a versatile addition to building systems.
- iii. Urban compatibility: Algae can be integrated vertically, making them suitable for deployment in dense, urban environments where land is scarce. This allows cities to harness the benefits of algae without needing vast open spaces.
- iv. Circularity: Algae systems convert waste streams, such as CO₂ and wastewater, into valuable resources. This aligns perfectly with the principles of a circular economy, reducing waste and promoting sustainability.
- v. Scalability: Modular algae systems are highly scalable, allowing for incremental deployment from individual buildings to district-scale networks. This flexibility enables widespread adoption and adaptation to various urban contexts.

These advantages make algae-integrated systems an attractive solution for urban carbon mitigation, sustainability, and resource management, offering an innovative path toward achieving long-term environmental goals. In contrast, afforestation requires large land areas and decades to mature, while direct air capture (DAC) technologies remain energy-intensive and costly (~\$600/ton CO₂) (Fasihi et al., 2019). Microalgae systems, by comparison, can achieve carbon removal at \$100–300/ton CO₂ when co-producing valuable biomass (Sedighi et al., 2023; Schnurr et al., 2018).

2.11.4 Challenges and Limitations

Despite the promising potential of algae-integrated systems, several barriers continue to impede their widespread adoption:

- i. High capital costs: Photobioreactor (PBR) systems are expensive, with costs ranging from €1,000 to €2,000 per square meter, significantly higher than conventional solutions like glazing or solar panels (Wurm and Pauli, 2016). This price disparity makes it challenging for developers to justify the investment in algae systems, particularly in the context of cost-effective alternatives.
- ii. Operational complexity: Algae systems require ongoing monitoring of variables such as pH, nutrient levels, temperature, and contamination. The maintenance of these systems is specialized, demanding skilled personnel and leading to higher operational costs and complexity for building managers who may lack the necessary expertise.
- iii. Energy input: Although algae systems can offer carbon sequestration benefits, pumping, mixing, and harvesting processes consume significant amounts of energy. To ensure that these systems have a net-positive carbon benefit, renewable power sources must be used. Without the integration of renewable energy, the carbon footprint of algae systems may be offset by the energy demands of their operation.
- iv. Aesthetic and social acceptance: The green-brown colouration of algal cultures may not align with the aesthetic preferences of architects and

building owners. Additionally, public perception of "slimy" or "unattractive" algae façades remains a social hurdle, potentially deterring acceptance and integration into mainstream architecture.

- v. Regulatory gaps: Building codes and regulations typically do not accommodate living façades, creating uncertainty around permitting and compliance. This lack of regulatory support adds another layer of complexity for those seeking to integrate algae systems into building designs.
- vi. Biomass valorisation: The economic viability of algae-integrated systems depends on the ability to find markets for algae-derived products. Without established demand for algae-based products such as biofuels, bioplastics, or other materials, the economic incentives to scale up algae systems remain limited, impacting their long-term feasibility.

While algae-based systems offer immense potential, overcoming these barriers will be critical for unlocking their full capabilities and achieving their widespread adoption in sustainable building practices. Several pioneering projects demonstrate the feasibility of algae-integrated systems in real-world applications. The BIQ House in Hamburg, Germany, is the world's first algae-powered building, capturing approximately 150 kg of CO₂ per year from its 200 m² façade while supplying 30% of its heating needs through biogas production (Wurm and Pauli, 2016). The Algae Canopy at the Milan Expo 2016, an ETFE-membrane structure filled with microalgae, not only sequestered CO₂ but also served as a dynamic public art installation, blending environmental function with aesthetic appeal (ecoLogicStudio, 2016). Algenhaus, located in Germany, is a research facility testing algae façades for residential use, demonstrating a 25% reduction in heating demand and continuous CO₂ uptake (Fraunhofer IBP, 2018). In Singapore, the Urban Algae Farm is a pilot rooftop system that uses building exhaust to cultivate *Chlorella*, aiming to sequester 5 tons of CO₂ per year per 1,000 m² (Wong et al., 2021). These case studies validate the technical performance of algae systems while underscoring the need for cost reduction and policy support to enable broader adoption and integration into urban environments.

2.11.5 Policy, Economics and Future Outlook

The future of microalgal carbon sequestration in cities hinges on three critical enablers: policy incentives, technological innovation, and market development. Policy incentives will play a pivotal role in accelerating adoption. Carbon pricing, green building certifications like LEED v5 and BREEAM, and municipal mandates could drive the widespread integration of algae systems into urban development. For instance, Hamburg already offers subsidies for bio-reactive façades, setting a precedent for other cities to follow. Technological innovation will further reduce the costs and increase the reliability of algae systems. Advances in strain engineering, such as CRISPR-edited high-CO₂-fixing strains, and the use of low-cost materials like recycled polymers for photobioreactors (PBRs) will make algae systems more affordable and efficient. Additionally, AI-driven automation will streamline maintenance and monitoring, enhancing system performance and lowering operational complexity (Zhang et al., 2021). Market development is essential for ensuring the economic sustainability of algae-integrated systems. Creating demand for algae-derived products such as biofuels, bioplastics, and food supplements will generate revenue streams that can offset the initial investment costs. The global algae market is projected to reach \$1.8 billion by 2027 (Grand View Research, 2022), signalling growing commercial viability and encouraging further investment in algae-based technologies. Emerging concepts such as carbon-positive buildings—which sequester more CO₂ than they emit over their lifecycle—and district-scale algae biorefineries that serve multiple buildings, represent the next frontier in algae integration. In the long term, microalgae could become standard components of regenerative urban infrastructure, much like solar panels are today, contributing to the creation of carbon-neutral and resilient cities.

The integration of microalgae into the built environment represents a paradigm shift in urban carbon management—from passive reduction to active sequestration. By transforming building surfaces into living carbon sinks, microalgae offer a multifunctional, scalable, and circular solution to one of the defining challenges of our time. While economic and technical hurdles remain, the convergence of biotechnology, sustainable architecture, and climate policy is creating fertile ground for rapid advancement. As cities evolve into metabolic ecosystems, microalgae will likely play a

central role—not just as a tool for carbon capture, but as a symbol of a new architectural ethos: one that embraces biology as infrastructure, and buildings as agents of planetary healing. With continued innovation and supportive frameworks, microalgal carbon sequestration could become a cornerstone of net-zero urbanism in the 21st century.

2.12 ALGAE AS THERMAL INSULATION IN BUILDINGS: LIGHT INTENSITY IN HEAT REGULATION

Algae-based thermal insulation for buildings presents a novel approach to energy efficiency by harnessing the natural properties of algae to regulate temperature through light intensity management. Algae panels, integrated into building facades, absorb sunlight and convert it into biomass while providing insulation. The effectiveness of these panels can be calculated by measuring the light intensity they receive and the corresponding heat absorption rate. Light intensity, often measured in lux or watts per square meter, directly impacts the rate of photosynthesis, influencing the thermal regulation capacity of the algae. By adjusting the algae layer thickness and optimising the light intensity levels through shading or reflective materials, the system can effectively maintain indoor temperatures. Microalgae facades represent a cutting-edge innovation in architectural design. Research shows they can significantly lower a building's carbon footprint by reducing energy consumption and offer the added benefit of improving indoor air quality by helping to reduce air pollution (Othman et al., 2024; Warren et al., 2023).

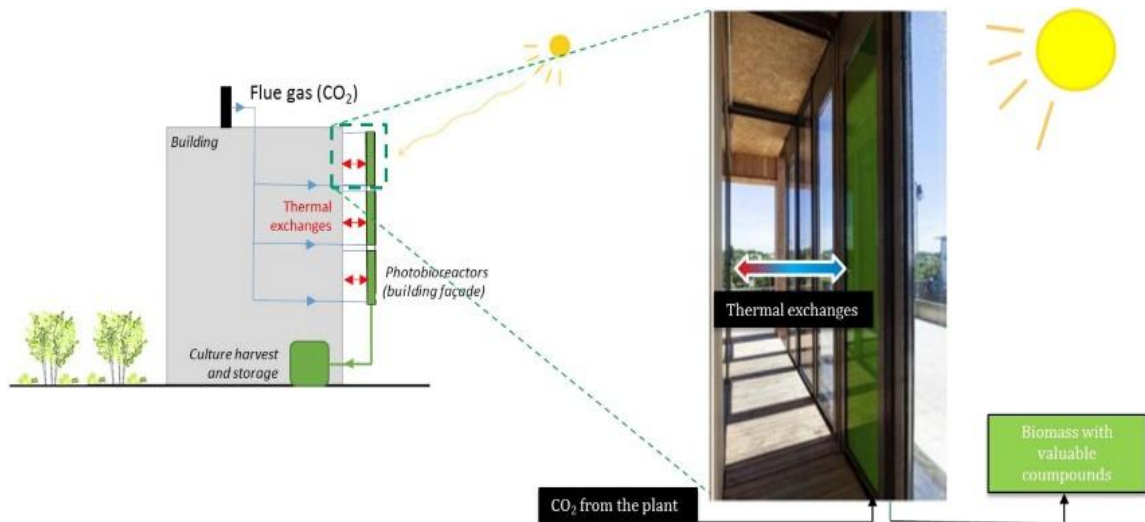


Figure 2.2 Microalgae culture in building-integrated Algae Panel (Pruvost et al., 2016)

Certain algae species possess insulating properties. Incorporating algae-based materials in building construction can enhance thermal insulation, thereby lowering the energy needed for heating and cooling. Algae panel can meet a building's thermal needs by functioning as solar thermal collectors, photosynthetic biomass converters for biofuel production, thermal insulation materials, and adaptable shading devices (Casini, 2016). The design of panel should be cultivated to make it properly function as Figure 2.2. Research indicates that energy exchange between algae panel and buildings aids in regulating thermal load. This symbiotic relationship prevents algae panel from overheating by filtering and shading thermal loads in hot weather, while also supporting microalgal biomass growth in cold weather (Pruvost et al., 2016). Integrating the algae panel with solar collection and PV-integrated shading mechanisms allows the system to simultaneously generate electricity and provide shading (Al Dakheel and Tabet Aoul, 2017). Additionally, the algae panel enhances the building's thermal insulation, contributing to the occupants' thermal comfort (Öncel et al., 2016). Additionally, temperature reduction results from shading, solar absorption, and the parasol effect generated during microalgal photosynthesis (Cervera Sardá and Vicente, 2016). The best light intensity measurement for cooling a building focuses on reducing excess heat generated by sunlight, which can lead to increased cooling loads (Białek et al., 2022). To manage this effectively, architects and engineers often consider light intensity in

terms of illuminance (measured in lux or lumens per square meter), and it is balanced with natural ventilation and shading strategies.

Algae-based panels ranging from enclosed algae façade panels to dried microalgae bio composites and foams have been investigated both as active building skins (dynamic shading + biomass production) and as passive bio-based insulating materials. Early applied demonstrations, such as the BIQ House in Hamburg, framed algae panels as a “second skin” that shades façades while producing biomass, sparking interest in their thermal and energy benefits at whole-building scale (Shepherd, 2012; Prieto et al., 2021). Moreover, material-level thermal performance laboratory and prototype studies report that algae-derived bio composites and insulation boards can reach thermal conductivity values competitive with conventional bio-insulators. Thermal conductivity values around $0.09\text{--}0.10\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ have been measured for algae-based boards and *Chlorella*-based bio composites prepared as dried panels, i.e., in the range of many conventional insulating bricks/boards and markedly lower than denser construction materials (Kumar et al., 2019; Lim et al., 2020). These numbers indicate clear potential for passive thermal resistance when algae biomass is immobilised in low-density matrices. Façade-scale thermal reduction and U-value findings studies of integrated PBR façades show measurable reductions in heat transfer into conditioned spaces. Experimental and modelling work found that adding an algae PBR layer or double-skin with microalgae can reduce overall thermal transmittance (U-value) of a wall assembly. Prototype reports include U-values on the order of $0.36\text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ for PBR double façades in certain configurations, and researchers have documented that PBR façades reduce solar heat gains through shading and by creating an air/water buffer layer (Yin et al., 2020; Han et al., 2023). Several simulation and experimental studies also report annual cooling energy savings or peak load reductions when PBR façades are properly oriented and operated, though percentage savings depend strongly on climate, façade geometry, and operational choices (Prieto et al., 2021; Lim et al., 2020).

Thermal mechanisms and measured thermal-reduction data: the observed thermal benefits arise from (1) reduced solar irradiance transmitted through the skin

(dynamic shading by algal biomass), (2) increased thermal resistance of the envelope when panels are low-conductivity bio composites, and (3) boundary-layer effects and fluid thermal inertia in PBR systems that damp peak heat fluxes. Quantitative experiments and building simulations in temperate climates have reported reductions in peak solar heat gain and modelled annual HVAC energy demand decreases varying across studies—some case studies estimate reductions in cooling loads and CO₂ emissions, although payback times are long (Zhao et al., 2019; Prieto et al., 2021). In summary as per Table 2.3, synthesis and recommendations current literature demonstrates that algae panels whether as dried bio composite boards ($\lambda \approx 0.09\text{--}0.10 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) or as algae façades panel that add a low-conductivity/air buffer layer (measured façade U-values lowered to $\sim 0.36 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ in prototypes)—can deliver meaningful reductions in heat transfer and cooling demand when properly designed and maintained. Future work should standardise thermal testing for algae-derived insulators, report complete sample properties (density, moisture, thickness), quantify long-term ageing and fire/safety properties, and perform integrated techno-economic and lifecycle assessments to determine where algae panels are most advantageous (Kumar et al., 2019; Yin et al., 2020).

Table 2.3 Thermal reduction application and case study

Author(s), Year	Type of Algae Panel	Measured Thermal Conductivity (λ) / U-value	Key Findings on Thermal Reduction	Climate Context
Kumar et al., 2019	Dried microalgae bio composite boards	$\lambda \approx 0.09\text{--}0.10 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$	Demonstrated low thermal conductivity comparable to conventional bio-insulators; performance sensitive to moisture content.	Laboratory-controlled (general applicability, no specific climate)
Lim et al., 2020	Algae façade panels	U-value reduction observed compared to single glazing	Reduced solar heat gain and improved indoor thermal comfort, lowering cooling demand.	Tropical (Singapore/Malaysia)
Yin et al., 2020	Photobioreactor (PBR) façade	U-value $\approx 0.36 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$	Reduced overall heat transfer into building envelope; acted as dynamic shading and thermal buffer.	Temperate (China)
Han et al., 2023	PBR double-skin façade	U-value improved by $\sim 25\text{--}35\%$ compared to conventional façade	Reduced solar heat gain, peak indoor temperature, and cooling energy demand; algal density critical.	Temperate (China)
Zhao et al., 2019	Simulated algae façade (modelling study)	(simulation-based)	Predicted reduction in cooling load and CO ₂ emissions; performance varied with climate and orientation.	Multiple climates (simulation: temperate & subtropical)
Prieto et al., 2021	Algae Building Integration Systems (review + BIQ House case study)	Reported operational U-value improvements in practice	Documented annual cooling energy savings, though long payback time noted; highlighted optimisation needs.	Temperate (Hamburg, Germany)
Shepherd, 2012	BIQ House (Hamburg, prototype project)	Photovoltaic systems achieve 12-15% efficiency, while solar thermal systems reach 60-65%.	Proof-of-concept algae façade as “second skin”; highlighted biomass + shading function with thermal comfort improvement.	Temperate (Hamburg, Germany)

2.13 ENERGY SAVING IN THE BUILT ENVIRONMENT

Energy saving in Malaysia's built environment has become more important as the country continues to grow and urbanize. With rising energy demands and the need for sustainable practices, buildings whether residential, commercial, or industrial—are responsible for a large portion of the country's energy consumption. To tackle this, Malaysia has introduced various initiatives aimed at making buildings more energy-efficient and environmentally friendly. One such initiative is the Green Building Index (GBI), a national certification system launched in 2009 that encourages developers and building owners to incorporate energy-saving technologies and sustainable practices into their designs and operations.

DETAIL ASSESSMENT CRITERIA SUMMARY OF FINAL SCORE			
PART	ITEM	MAXIMUM POINTS	SCORE
1	Energy Efficiency	38	
2	Indoor Environmental Quality	21	
3	Sustainable Site Planning & Management	10	
4	Material & Resources	9	
5	Water Efficiency	12	
6	Innovation	10	
TOTAL SCORE		100	

GREEN BUILDING INDEX CLASSIFICATION	
POINTS	GBI RATING
86 to 100 points	Platinum
76 to 85 points	Gold
66 to 75 points	Silver
50 to 65 points	Certified

Figure 2.3 GBI Malaysia Assessment Criteria 2016

The GBI plays a key role in driving energy efficiency in Malaysia's built environment (Figure 2.3). The certification assesses buildings on a range of criteria, including energy and water efficiency, indoor air quality, and the use of eco-friendly materials. By following GBI guidelines, developers and building owners can reduce energy usage, lower carbon emissions, and improve the overall efficiency of their properties. The GBI program also offers incentives like tax exemptions and grants, making it easier for developers to adopt greener practices. As a result, more and more buildings are being designed with energy-saving technologies, from solar panels to smart building systems, helping to create more sustainable communities across the country.

Energy-efficient buildings help reduce electricity bills for occupants, providing long-term savings for homeowners and businesses alike. They also improve indoor air quality, which can lead to better health and productivity for those who live and work in these spaces. In Malaysia, the push for energy efficiency through initiatives like the GBI is helping to build a more sustainable future for its cities. By focusing on energy savings, Malaysia is addressing its energy challenges while also contributing to global efforts to reduce carbon emissions and create healthier, greener environments for future generations.

According to Ahmad et al., 2022, benefits of green buildings which can be categorized into three main dimensions: economic, health and society, and environmental. From an economic perspective, green buildings increase overall building and rental value, reduce operating costs, and enhance employee satisfaction by providing a healthier workplace. In terms of health and societal benefits, they contribute to improved indoor air quality, better thermal comfort, higher quality of living, and an increased ratio of green spaces, which collectively support human well-being. On the environmental side, green buildings play a crucial role in decreasing waste generation, reducing freshwater consumption, lowering greenhouse gas (GHG) emissions, and minimising overall energy and material usage. Altogether, these dimensions highlight how green buildings integrate sustainability into the built environment while delivering economic returns, social improvements, and ecological conservation.

2.14 CHAPTER SUMMARY

Algae are versatile organisms with many applications in sustainable building design. They can grow in three ways—autotrophic, mixotrophic, and heterotrophic—each suited for different conditions. Recent trends in architecture incorporate algae into building systems for carbon capture and energy efficiency. In Southeast Asia and Malaysia, research on algae technology is growing, focusing on their ability to absorb CO₂ and improve urban air quality. Understanding how microalgae perform under different environmental conditions helps measure their efficiency as a carbon sequestration tool

Algae-based materials offer a sustainable solution for construction, especially in energy-saving applications. These materials can reduce light intensity and regulate heat, helping to lower indoor temperatures and cut energy use. By adjusting colour saturation and light absorption, algae can improve thermal insulation, making them valuable for buildings in hot climates. As cities seek greener solutions, algae technology presents a promising way to create energy-efficient and eco-friendly urban spaces. Moreover, to cultivate microalgae, there are significant parameters that can influence microalgal growth mainly pH, temperature, light and photoperiod. On the hands, the impact of energy-saving measures goes beyond just environmental benefits; it also brings economic and health advantages (Figure 2.4). Energy-efficient buildings help reduce electricity bills for occupants, providing long-term savings for homeowners and businesses alike. They also improve indoor air quality, which can lead to better health and productivity for those who live and work in these spaces.

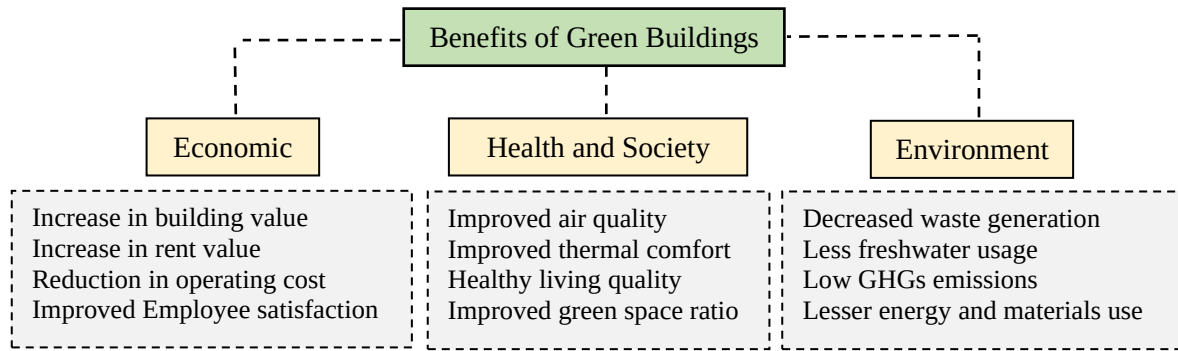


Figure 2.4 The benefit of green buildings.



CHAPTER THREE

METHODOLOGY

3.1 INTRODUCTION

In this study, two cyanobacteria species (*P. amphigranulata* and *Alkalinema sp.*) and two green algae species (*C. radiosa* and *D. brasiliensis*) were explored. The experimental design examined the effects of nutrient composition, pH, and light cycles on their growth performance, biochemical properties, and pigmentation. The aim was to evaluate how these environmental variables influenced biomass productivity, carbon absorption capacity, and colouration intensity—factors that are essential for energy efficiency and sustainability applications in the built environment. The findings from this study are expected to identify the optimal medium, pH range, and light conditions necessary to maximise biomass yield while maintaining consistent pigmentation (Figure 3.1).

3.2 METHODOLOGY

3.2.1 Sample Collection and Inoculation of Microalgae

The selection of microalgae species was based on their potential for optimization within controlled environmental conditions to maximise growth and viability as indicated in Table 3.1. The microalgae samples were purchased from USM Algae Culture Collection (USMACC), School of Biological Sciences, Penang. The stock culture was preserved in Bold's Basal Medium (BBM) at 25 °C– 28°C with an initial pH value of 6.8 (Kanz and Bold et al., 1969). The seed culture was continuously illuminated with cool-white, fluorescent light (Philip TL-D 36 W/965) with a light intensity ranging from 60 to 70 $\mu\text{mol m}^{-2} \text{s}^{-1}$ with 16:8 light: dark cycle (Tan et al., 2018).

Table 3.1 Selection of microalgae

Species	Taxonomic Classification	Characteristics	Reference
<i>Pseudanabaena amphigranulata</i>	Phylum: Cyanobacteria; Class: Cyanophyceae; Family: Pseudanabaenaceae; Genus: <i>Pseudanabaena</i>	High photosynthetic efficiency and rapid growth; tolerates high CO ₂ concentrations; suitable for carbon capture and urban air quality improvement.	Ram and Tessy (2024)
<i>Alkalinema</i> sp.	Phylum: Cyanobacteria; Class: Cyanophyceae; Family: Coleofasciculaceae; Genus: <i>Alkalinema</i>	Resilient to extreme environments, including high pH and nutrient-poor conditions; suitable for building applications with fluctuating environmental factors.	Fiore (2015)
<i>Chlamydomonas radiosa</i>	Phylum: Chlorophyta; Class: Chlorophyceae; Family: Chlamydomonadaceae; Genus: <i>Chlamydomonas</i>	Highly adaptable to different media; efficient light absorption; rapid growth; suitable for energy-saving and scalable building-integrated systems.	Nozaki et al. (2002)
<i>Desmodesmus brasiliensis</i>	Phylum: Chlorophyta; Class: Chlorophyceae; Family: Scenedesmaceae; Genus: <i>Desmodesmus</i>	High biomass productivity and efficient carbon fixation; strong photosynthetic capacity; suitable for carbon sequestration and algae-based building materials.	Hegewald (2000)

The rationale for selecting algae can be summarised as follows:

a. Cyanobacteria Characteristics

Pseudanabaena amphigranulata: This species is known for its high photosynthetic efficiency and rapid growth, making it an ideal candidate for carbon capture in building-integrated applications. Its ability to thrive under varying environmental conditions and high carbon dioxide concentrations enhances its suitability for urban settings, where air quality improvement and carbon sequestration are key priorities.

Alkalinema sp.: This cyanobacterium is chosen for its resilience to extreme environmental conditions, such as high pH levels, and its proven ability to perform well

in nutrient-poor environments. These traits make *Alkalinema* sp. a strong candidate for building applications where environmental factors like fluctuating pH and limited nutrient availability may affect algae-based materials.

b. Green Algae Characteristics

Chlamydomonas radiosa: This species is selected for its high adaptability to different growth media and its effective light absorption properties, which are critical for energy-saving applications in buildings. *C. radiosa* also possesses a fast growth rate, making it suitable for scalable applications in building-integrated systems.

Desmodesmus brasiliensis: Chosen for its high biomass productivity and efficient carbon fixation, *D. brasiliensis* has demonstrated excellent potential for both carbon sequestration and sustainable biomass production. Additionally, its ability to thrive in different environmental conditions and its strong capacity for photosynthesis make it an ideal species for integration into algae-based materials for building design.

3.2.2 Preparation of Media Solutions

Stock solutions for the different culture media (BBM, Bristol, BG11, and Chu 10) were prepared according to standard recipes for freshwater algae culture, adapted from media formulations widely used in recent microalgae studies (Martínez-Ruiz et al., 2022; Buitrago et al., 2023). These media were specifically selected based on their nutrient profiles, which were optimal for supporting microalgae growth. The ingredients for each medium are listed in Table 3.2. To prepare the medium, the salts were measured according to the recipe, and the pH was adjusted to 6.8 using potassium hydroxide (KOH) or hydrochloric acid (HCl). The medium was then autoclaved for 15 minutes at 121°C for sterilisation. The algae cultures were maintained indoors in growth chambers under Philips fluorescent lights with light intensity ranging from 60 to 70 $\mu\text{mol m}^{-2} \text{s}^{-1}$

and kept at a room temperature at 25°C– 28°C. After two weeks, the algae reached optimal growth and were ready to be subcultured for the next experiment.

Table 3.2 Medium ingredients

Chemical Component	CHU 10	BG 11	BBM	Bristol
Calcium nitrate ($\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$)	0.04 g	-	-	-
Sodium nitrate (NaNO_3)	-	1.5 g	0.25 g	0.25 g
Potassium phosphate monobasic (KH_2PO_4)	-	-	0.175 g	0.175 g
Potassium phosphate dibasic (K_2HPO_4)	-	0.04 g	0.075 g	0.075 g
Magnesium sulphate (MgSO_4)	0.05 g	0.075 g	0.075 g	0.075 g
Calcium chloride dihydrate ($\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$)	-	-	0.025 g	0.025 g
Sodium chloride (NaCl)	-	-	0.025 g	0.025 g
Sodium carbonate (Na_2CO_3)	0.02 g	0.02 g	-	-
Sodium silicate (Na_2SiO_3)	0.025 g	-	-	-
Disodium ethylenediaminetetraacetate dihydrate (Na_2EDTA)	-	0.001 g	0.1 g	-
Ferric chloride (FeCl_3)	0.0008 g	-	-	-
Potassium hydroxide (KOH)	-	0.062 g	-	-
Boric acid (H_3BO_3)	-	-	0.12 g	-
Ferrous sulphate heptahydrate ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$)	-	-	0.05 g	0.05 g
Manganese (II) chloride tetrahydrate ($\text{MnCl}_2 \cdot 4\text{H}_2\text{O}$)	-	-	-	-
Ammonium molybdate tetrahydrate ($(\text{NH}_4)_6\text{Mo}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$)	0.1 mg	-	-	-
Citric acid ($\text{H}_3\text{C}_6\text{H}_5\text{O}_7$)	-	0.006 g	-	-
Ferric ammonium citrate	-	0.006 g	-	-
pH	6.8	6.8	6.8	6.8
*Trace metal mix A	-	1 mL	1 mL	-
**Trace metal mix B	-	1 mL	1 mL	-
Total volume	1 L	1 L	1 L	1 L

*Trace Metal Mix A		**Trace Metal Mix B	
Boric acid (H_3BO_3)	2.86 g	Ammonium nitrate (NH_4NO_3)	22.96 g
Manganese(II) chloride tetrahydrate ($\text{MnCl}_2 \cdot 4\text{H}_2\text{O}$)	1.81 g	Potassium dichromate ($\text{K}_2\text{Cr}_2(\text{SO}_4)_4 \cdot 24\text{H}_2\text{O}$)	96.00 g
Zinc sulphate ($\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$)	0.222 g	Nickel sulphate heptahydrate ($\text{NiSO}_4 \cdot 7\text{H}_2\text{O}$)	47.85 g
Molybdic acid sodium salt dihydrate ($\text{NaMoO}_4 \cdot 2\text{H}_2\text{O}$)	0.39 g	Sodium molybdate ($\text{Na}_2\text{SO}_4 \cdot 2\text{H}_2\text{O}$)	17.94 g
Copper(II) sulphate pentahydrate ($\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$)	0.079 g	Titanium sulphate ($\text{Ti}(\text{SO}_4)_3$)	40.00 g
Cobalt(II) nitrate hexahydrate ($\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$)	49.4 g	Distilled water	1.0 L
Distilled water	1.0 L		

The following experimental parameters were systematically tested as showed in Figure 3.1:

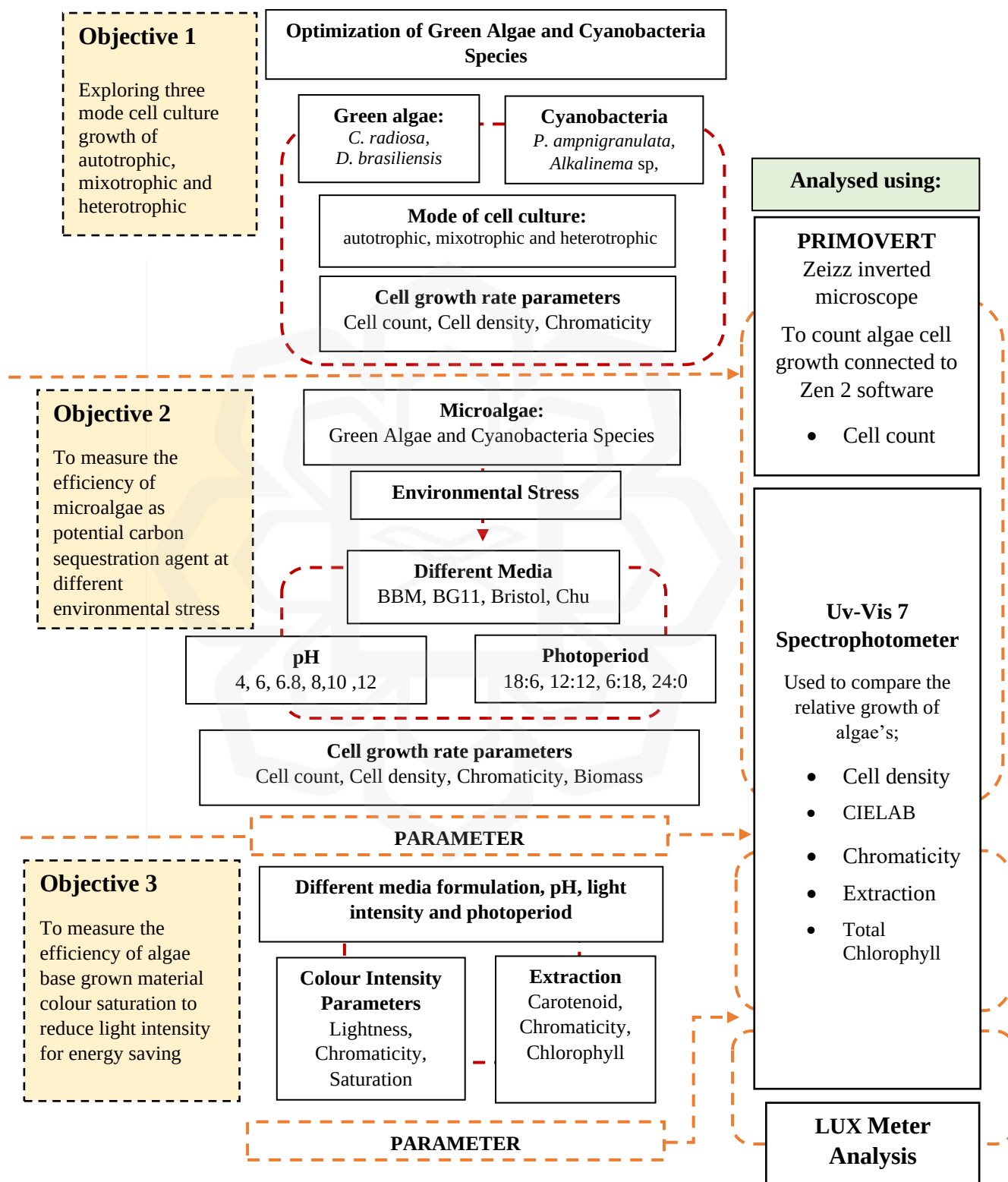


Figure 3.1 Experimental Design

3.2.3 Determination of Microalgae Cell Counts

Once in 2 days, microalgae cell was counted using Zeiss Primovert inverted cell culture microscope that connected using ZEN 2 software application in the computer. Haemocytometer was placed under the inverted microscope. It was captured and saved in the computer. The cells were counted manually.

3.2.4 Determination of Microalgae Growth Rate

The concentration of 1×10^5 cells/ml isolated strains were cultured in the 48-well microplate for 15 days set at $25 \pm 1^\circ\text{C}$ with light intensity ranging from 60 to $70 \mu\text{mol m}^{-2} \text{s}^{-1}$ with different medium formulations, pH and photoperiods. The growth absorbance was determined every day according to an optical density at 750 nm wavelength ($\text{OD}_{750 \text{ nm}}$) using Metler-Toledo UV7 spectrophotometer (Kasan et al., 2020).

3.2.5 Determination of Microalgae Biomass and Carbon Sequestration Rate

The dry weight (DW) of harvested biomass of microalgae species cultured in different medium formulation, pH and photoperiod was measured after 14 days of culture period. The dewatered biomass was freeze-dried for 3 days, after which the samples were weighed and stored at -80°C until further analysis (Böpple et al., 2024). The carbon sequestered by the microalgae species was estimated on the basis of total carbon content in the dry weight biomass (Kumari et al., 2023). The total carbon sequestered was calculated by multiplying the dry weight biomass with the conversion factor 0.427. The quantity of total CO_2 sequestered was calculated by multiplying the carbon content with 3.67 (ratio of molecular weight of carbon dioxide and carbon).

Based on the provided information, the carbon sequestration rate can be calculated as follows:

- **Total Carbon Sequestered (kg): Dry Weight Biomass (g) x 0.427**
- **Total CO₂ Sequestered (kg): Total Carbon Sequestered (kg) x 3.67**

3.2.6 CIELAB Colour Analysis

The colour intensity of microalgae was measured by using a Metler-Toledo UV7 spectrophotometer. CIE refers to the Commission Internationale de l'Éclairage (International Commission on Illumination) or in the CIE 1976 (L*, a*, b*) colour system, abbreviated CIELAB, the lightness coefficient, L*, ranges from black (0) to white (100), positive a* indicates a hue of red purple and negative a*, of bluish green. Whereas positive b* indicates yellow and negative b* blue. The colour of achromatic or gray is when a* and b* = 0 (Othman, 2009).

3.2.7 Determination of Microalgae Chlorophyll Content

Analysis of chlorophyll content was measured using Metler-Toledo UV7 spectrophotometer. The dried microalgae biomass sample was resuspended with 300 uL ethyl acetate. Then, 50 uL of sample was pipetted and transferred into 2000 uL Eppendorf tube. After that, 950 uL of chloroform was added into the sample. The mixture was gently shaken in order to mix them well. Three different wavelength were used to measure the chlorophyll content, which were 480 nm, 648 nm and 666 nm (Raven, 2016; Othman, 2009).

3.2.8 Light Intensity Analysis

To evaluate the microalgae's effectiveness in reducing light intensity, a lux meter was utilized to measure the light levels transmitted through a microalgae-filled panel as showed in Figure 3.2. Selected species that show high potential was tested under a controlled 2000 lux light source, simulating standard outdoor lighting conditions.

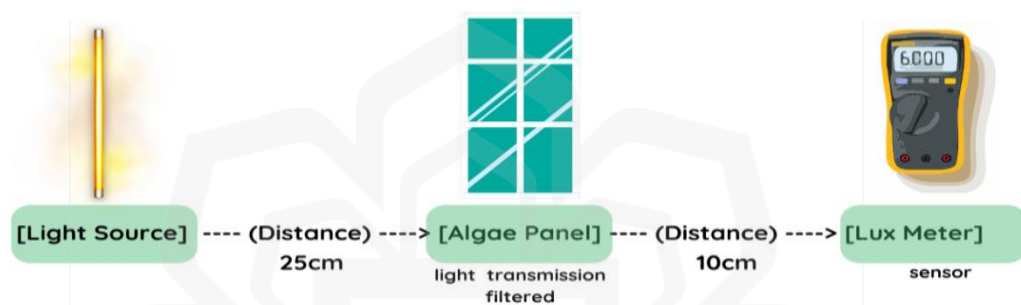


Figure 3.2 Schematic diagram for light intensity method using Lux Meter

Light intensity was measured both with and without the algae layer to determine the reduction efficiency. This data was essential for assessing how well each species could attenuate light, contributing to a framework for microalgae use in energy-efficient building designs (Kim et al., 2023).

3.2.9 Statistical Analysis

The dataset was processed using XLSTAT-Basic+ (2024) for outlier treatment, transformation, and the Kaiser-Meyer-Olkin (KMO) test. Standardization and outlier detection were performed at a significance level of 0.05. Outliers were identified using the Grubbs test and Dixon's approach. The Tukey ANOVA test assessed significant differences between dataset means. Various transformation methods, including

standardization and Pareto, ensured normal distribution. The KMO test evaluated dataset adequacy for Multivariate Data Analysis. Principal Component Analysis (PCA) with Pearson correlation identified correlations and factor loadings (FL) of variables, which were then clustered to assess their contributions to algae cell culture growth treatments.

3.3 CHAPTER SUMMARY

The study evaluated Cyanobacteria (*P. amphigranulata* and *Alkalinema sp.*) and Green Algae (*C. radiosa*, *D. brasileensis*) under specific culture conditions. The media used for cultivation included BBM, BG11, Chu 10, and Bristol, with pH levels set at 3.0, 5.0, 7.0, 9.0, and 11.0. Different photoperiods (18:6, 12:12, 6:18, 24:0) were also tested for each medium, including BBM, BG11, Bristol, and Chu 10. The efficiency of the algae as potential carbon sequestration agents was analysed using the UV-Vis spectrophotometer, which provided a comparative analysis of relative growth and absorbance. The study also examined the potential of these algae as material for light intensity reduction and energy saving.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 INTRODUCTION

This section revealed the behaviour of blue green (*P. amphigranulata* and *Alkalinema* sp,) and green algae (*C. radiosa* and *D. brasileensis*) cell culture growth in four different mediums of BBM, BG11, Bristol and Chu under different pH (4.0, 6.0, 6.8, 8.0, 10.0 and 12.0) and photoperiod (24:0, 18:6, 12:12 and 6:18). The parameter will include:

1. Cell counts and Absorbance (750nm)
2. Assessment of cell culture biomass as Carbon Sequestration Agent
3. Effects of pH and photoperiod on UV-vis spectra absorbance values for chlorophyll content
4. The Green Intensity (a^*) of cell culture growth
5. The lightness (L^*) of cell culture growth

Therefore, the main objectives of this specific chapter were:

1. To investigate the cell culture growth of cyanobacteria and green algae species behaviour at different medium formulation, pH condition and photoperiod
2. To evaluate the potential of green algae species as carbon sequestration agent
3. To assess the potential of cyanobacteria and green algae ability to reduce light intensity and enhance energy efficiency.

4.2 PSEUDANABAENA AMPHIGRANULATA

4.2.1 Effect of BBM Medium Formulation, pH and Photoperiod on *P. amphigranulata* Cell Culture Growth

The relationship between BBM (Bold's Basal Medium) media and algae cell counts is that BBM provides essential nutrients that support the growth and proliferation of algae, leading to an increase in cell counts under optimal conditions Andersen (2005). Figure 4.1 present cell counts data for *P. amphigranulata* in BBM medium over a 14-day. For the 24:0 condition, cell counts showed a consistent increase across all pH levels, with optimal growth observed at pH 8 and 10. The 18:6 condition also demonstrated similar trends, though cell counts were slightly lower compared to the continuous light condition. Under the 12:12 photoperiod, growth rates were moderate, with the most favourable growth again occurring around pH 8 and 10. In contrast, the 6:18 photoperiod resulted in significantly reduced cell counts, indicating limited growth across all pH levels, with minimal variation between conditions. With a peak of 3678×10^6 cells/mL at pH 6.8 over an 18-hours photoperiod, Table 4.1 showed the highest cell counts under BBM media. This was followed by impressive increase during a 24-hours photoperiod, reaching 3435×10^6 cells/mL at pH 10 and 2435×10^6 cells/mL at pH 8. In contrast, the lowest growth was observed under a 6-hours photoperiod, with a maximum of only 170×10^6 cells/mL at pH 6.8.

Overall, growth trends indicate that the optimal conditions at photoperiods of 18–24 hours and pH levels between 6.8 and 8 that showed longer photoperiods strong positive impact, particularly within the mid-range pH levels. The absorbance graphs at 750 nm in BBM media throughout a 14-day period suggests that pH and light exposure have an impact on growth patterns. Absorbance increases gradually at all pH levels throughout the 24:0 photoperiod, with pH 8 and pH 10 showing the highest results. The 18:6 photoperiod show a similar trend, but the absorbance values are slightly lower, reflecting reduced light exposure. For the 12:12 photoperiod, absorbance increases moderately, with pH 8 and 10 still supporting the highest growth but to a lesser extent than the previous conditions. The 6:18 photoperiod exhibits minimal absorbance increases, indicating limited growth under this light-dark cycle, regardless of pH. These

results emphasise the importance of both continuous light and an optimal pH range of 8 to 10 for maximising *P. amphigranulata* growth.

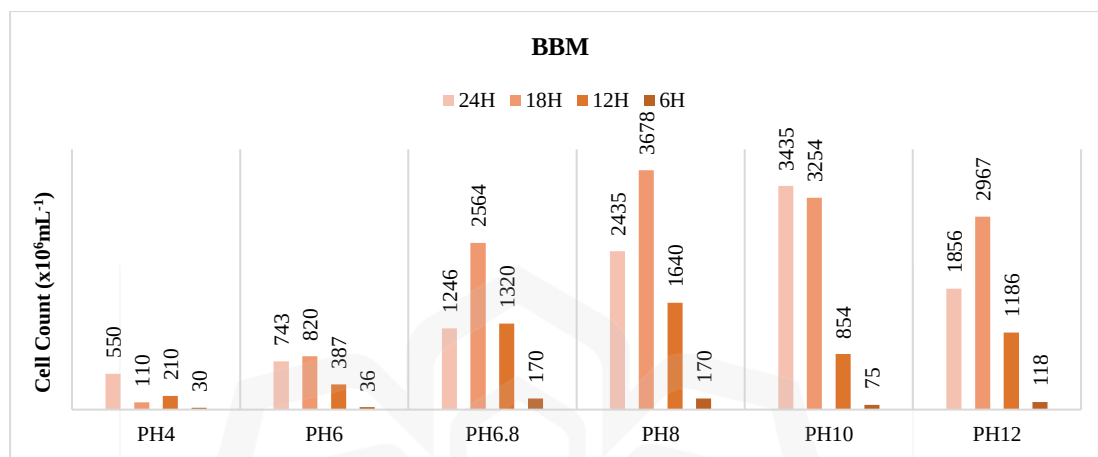


Figure 4.1 Cell counts of *P. amphigranulata* cultured in BBM medium at different pH and photoperiod after 2 weeks

Table 4.1 The optimum cell counts distribution of *P. amphigranulata* cultured in BBM medium at different pH and photoperiod after 2 weeks

Species	Photoperiod	pH	Cell Counts (x10 ⁶ mL ⁻¹)
<i>P. amphigranulata</i>	24:0	pH 10	3435
	18:6	pH 8	3678
	12:12	pH 8	1640
	6:18	pH 8	190

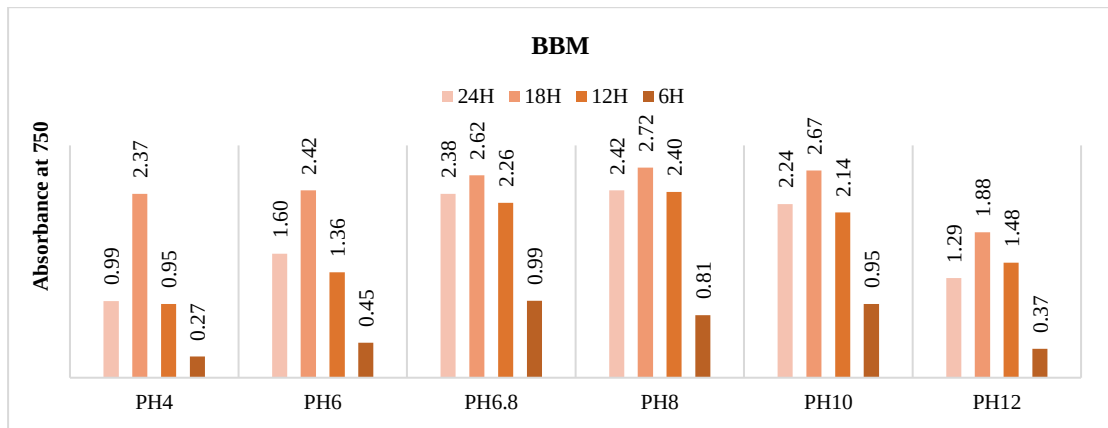


Figure 4.2 The effect of different photoperiod and pH on cell density measured at 750 nm (OD₇₅₀) of *P. amphigranulata* cultured in BBM medium after 2 weeks

Table 4.2 The optimum cell density distribution measured at OD₇₅₀ of *P. amphigranulata* in BBM medium at different pH and photoperiod after 2 weeks

Species	Photoperiod	pH	Abs
<i>P. amphigranulata</i>	24:0	pH 8	2.42
	18:6	pH 8	2.72
	12:12	pH 12	1.48
	6:18	pH 6.8	0.99

The absorbance cell growth is highest at pH 10 for both the 24-hours (3.58) and 18-hours (3.59) photoperiods (Table 4.2), suggesting that pH 8 and 10 are higher. In contrast, the 6-hours photoperiod achieves its peak growth at pH 4 (2.2) but records the lowest absorbance at pH 6.8 (1.60). Overall, longer photoperiods 24 and 18 hours consistently support higher absorbance refer to Figure 4.2.

4.2.2 Effect of BBM Medium Formulation, pH and Photoperiod on *P. amphigranulata* Biomass and Carbon Sequestration Rate (CSR)

Biomass and CO₂ sequestration in *P. amphigranulata* involves the organism's ability to grow and accumulate organic matter while capturing and storing atmospheric carbon dioxide through photosynthesis, making it a potential tool for carbon mitigation and sustainable bioresource production (Tounsi et al., 2023). Figure 4.3 highlights that the optimal conditions for biomass and CO₂ sequestration in *P. amphigranulata* occur at pH 8 with a 12-hours light cycle, resulting the highest values of 0.87 g/L biomass and 1.36 g/L CO₂e for carbon sequestration, indicating that moderate pH and balanced light exposure foster efficient growth and carbon fixation. Under continuous light (24 hours), biomass and CO₂ sequestration remain substantial at 0.72 g/L and 1.13 g/L CO₂e, respectively, demonstrating that extended light exposure can support growth, although less efficiently than balanced cycles. In contrast, extreme pH levels (4 and 12) combined with limited light (6 hours) yield the lowest outputs, with biomass at 0.01 g/L and CO₂ sequestration at 0.02 g/L CO₂e, emphasizing the damaging effects of strict conditions. Table 4.3 reflects this trend, emphasizing that moderate conditions, particularly pH 8 with 12-hours photoperiods, are essential for maximising biomass production and carbon sequestration efficiency.

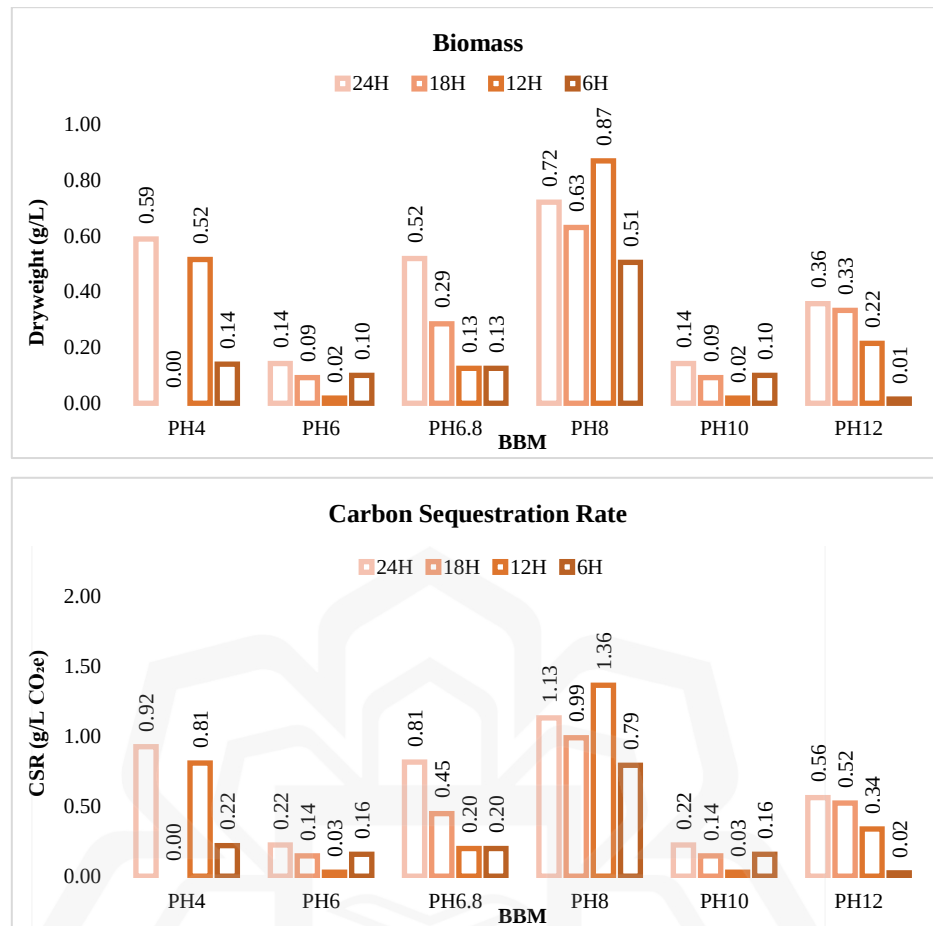


Figure 4.3 Biomass and CSR of of *P. amphigranulata* cultured in BBM medium at different pH and photoperiod after 2 weeks

Table 4.3 The optimum biomass and CSR distribution of *P. amphigranulata* cultured in BBM medium at different pH and photoperiod after 2 weeks

Species	pH	Photoperiod	Biomass (g/L)	CSR (CO ₂ e)
<i>P. amphigranulata</i>	pH 4	24:0	0.59	0.92
	pH 6	24:0	0.14	0.22
	pH 6.8	24:0	0.52	0.81
	pH 8	12:12	0.87	1.36
	pH 10	24:0	0.14	0.22

4.2.3 Effect of BBM Medium Formulation, pH and Photoperiod on *P. amphigranulata* Chlorophyll Content

Chlorophyll content is influenced by light exposure, which enhances its synthesis and stability and pH levels. Figure 4.4 display distinct patterns in the 600–700 nm wavelength range, indicating variations in chlorophyll content influenced by light exposure and pH. The 24:0 graph show a pronounced peak at ~680 nm for pH 6.8, with lower absorbance at extreme pH levels. Similarly, the 18:6, 12:12 and 6:18 photoperiod maintain high absorbance at ~680 nm, particularly at pH 6.8, 8 and 10, reflecting adaptability to moderate light-dark cycles. The green intensity colouration is directly linked to its absorbance values, suggesting that greener samples generally reflect higher chlorophyll content and enhanced light absorption efficiency demonstrated in Figure 4.4.

The optimal chlorophyll production occurs at pH 8 (4.02), closely followed by pH 6.8 (4.01), with peaks achieved under 18-hours and 12-hours photoperiods as showed in Figure 4.4. These results emphasise the significance of balanced pH and moderate light-dark cycles in enhancing chlorophyll activity. In contrast, extreme pH levels, such as acidic pH 4 and highly alkaline pH 12, exhibit significantly lower absorbance values of 0.18 and 0.17, respectively, across all photoperiods, indicating limited photosynthetic efficiency. This highlights that near-neutral pH conditions (6.8–8.0) combined with moderate light exposure optimise chlorophyll synthesis.

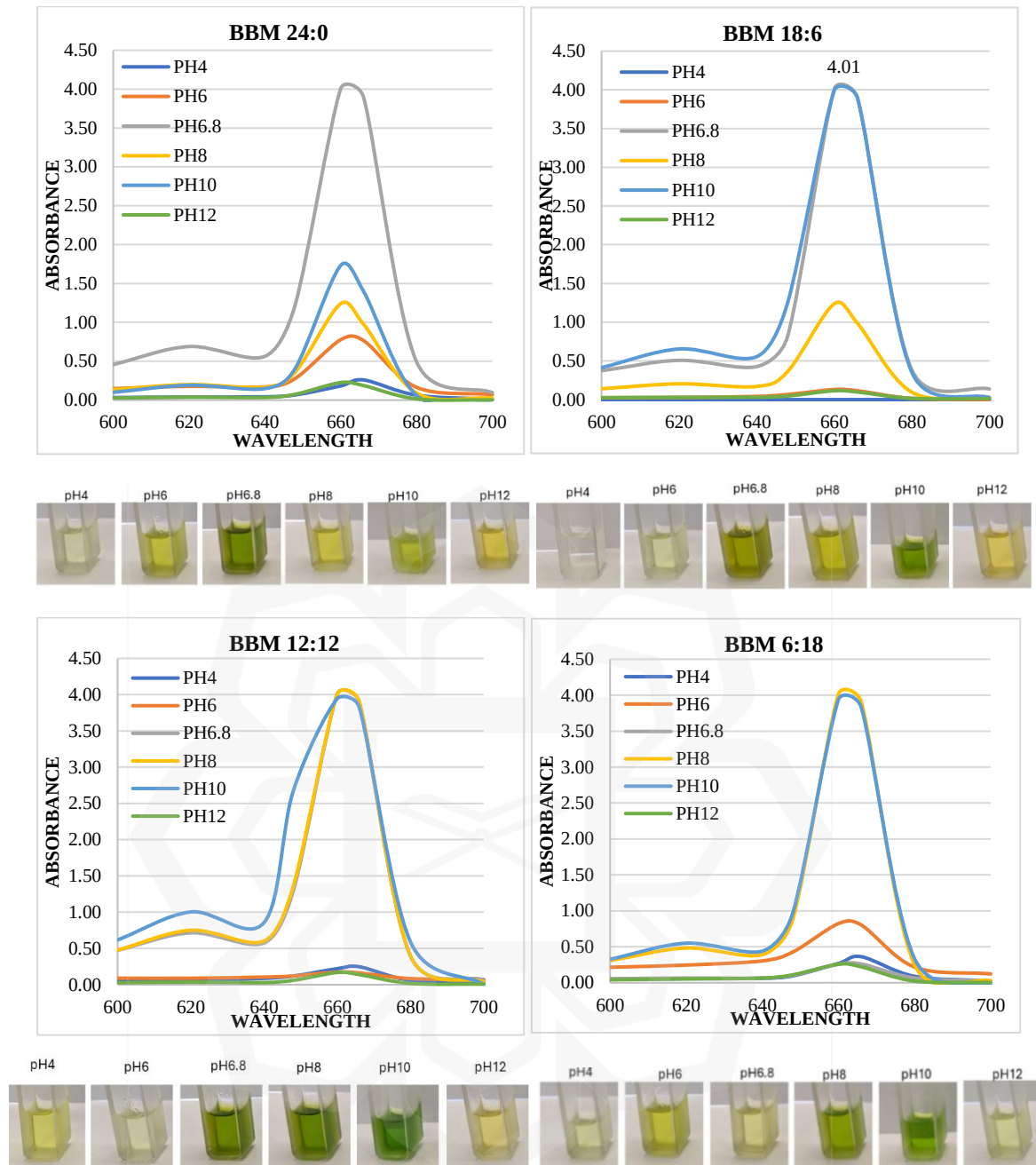


Figure 4.4 Effects of pH and photoperiod on chlorophyll content of *P. amphigranulata* cell culture in BBM medium after 2 weeks

4.2.4 Effect of BBM Medium Formulation, pH and Photoperiod on *P. amphigranulata* Cell Culture Chromaticity

The chromaticity of *P. amphigranulata* can vary depending on its growth conditions. The 12-hours cycle consistently showed the highest values, indicating that it is the most compromising for green intensity, while the 18-hours cycle had the lowest values overall, especially at pH 4. Figure 4.5 and Table 4.4 show that the highest green intensity (a^*) was recorded at a 12-hours photoperiod with pH 10, reaching 52.27, and the lowest was observed at an 18-hours photoperiod with pH 12, at 7.21. Under an 18-hours photoperiod, the maximum lightness value ($L^* = 97.36$) was recorded at pH 6, indicating reduced light absorption (Figure 4.6 and Table 4.5). Under a 12-hours photoperiod, the lightness value with the lowest value ($L^* = 65.43$) was at pH 6.8, suggesting more light absorption. Overall, shorter photoperiods (especially 12 hours) with pH levels between 6 and 6.8 are better for maximising light absorption by the algae.

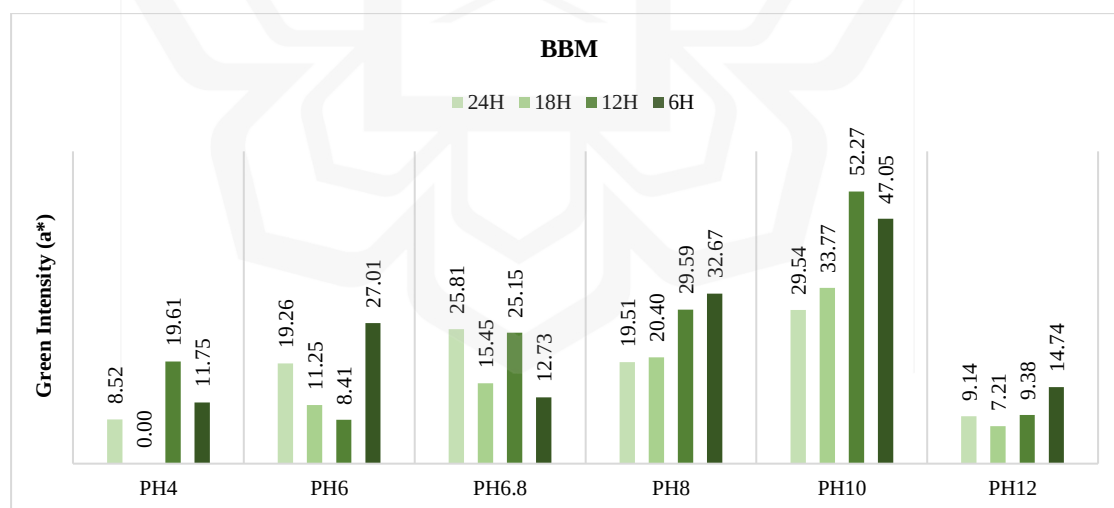


Figure 4.5 Effects of pH and photoperiod on green intensity values (a^*) of *P. amphigranulata* cell culture in BBM medium after 2 weeks

Table 4.4 Green intensity (a^*) distribution of *P. amphigranulata* cell culture in BBM medium at different pH and photoperiod after 2 weeks

Species	Photoperiod	Peak pH	a^*
<i>P. amphigranulata</i>	24:0	pH10	29.54
	18:6	pH10	33.77
	12:12	pH10	52.27
	6:18	pH10	47.05
a^* , ranges from white (0) to green (100)			

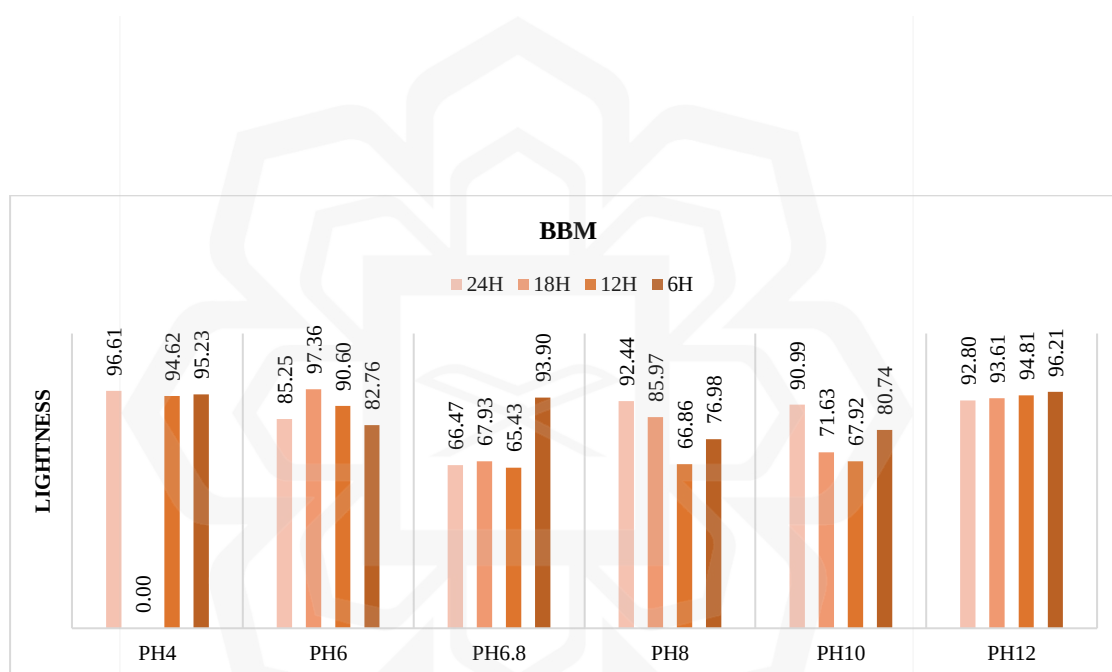


Figure 4.6 Effects of pH and photoperiod on lightness values (L^*) of *P. amphigranulata* cell culture in BBM medium after 2 weeks

Table 4.5 Lightness (L*) values distribution of *P. amphigranulata* cell culture in BBM medium at different pH and photoperiod after 2 weeks

Cynobacteria	Photoperiod	Peak pH	L*
<i>P. amphigranulata</i>	24:0	pH 6.8	66.47
	18:6	pH 6.8	67.93
	12:12	pH 6.8	65.43
	6:18	pH 8	76.98
<i>L*</i> , ranges from black (0) to white (100)			

In conclusion the result on *P. ampnigranulata* cultured in BBM medium demonstrates its optimal performance under 18–12-hours photoperiods and mid-range pH levels (6.8–8). These conditions support peak cell growth, achieving a biomass of 0.87 g/L and CO₂ sequestration of 1.36 g/L CO₂e, indicating its potential for sustainable applications. Chlorophyll absorbance (3.94 ± 4.02) and light absorption are maximised at pH 6.8–8 with 12–18-hours photoperiods, emphasizing the importance of balanced light cycles and moderate pH for photosynthetic efficiency. In contrast, extreme pH levels and shorter photoperiods significantly reduce growth, biomass, and CO₂ sequestration.

4.2.5 Effect of pH, BG11 Medium Formulation and Photoperiod on *P. amphigranulata* Cell Culture Growth

The BG11 medium formulation and photoperiod significantly influence the growth of *P. amphigranulata* cultures, impacting nutrient availability, light-dependent metabolic processes, and overall production. Figure 4.7 reveals that cell counts in BG11 medium experience a significant increase after Day 6, with peak growth observed by Day 14. Continuous light (24:0) promotes the fastest and highest cell growth, making it the most

effective photoperiod for growth. In contrast, the 12:12 and 6:18 cycles with reduced light exposure result in noticeably slower growth rates and much lower peak cell counts.

With a peak of 5570×10^6 cells/mL at pH 8 and substantial increase over the course of 18 hours, reaching 4750×10^6 cells/mL at pH 8, Figure 4.7 show the maximum cell counts under BG11 media during 12-hours photoperiod. In contrast, the lowest growth was observed under pH 4 and 6 at 6hours photoperiod, with a maximum of only $12 \pm 20 \times 10^6$ cells/mL. Overall, growth trends indicate that the optimal conditions at photoperiods of 18–24 hours and pH levels between 6.8 and 10 that showed longer photoperiods strong positive impact, particularly within the mid-range pH levels.

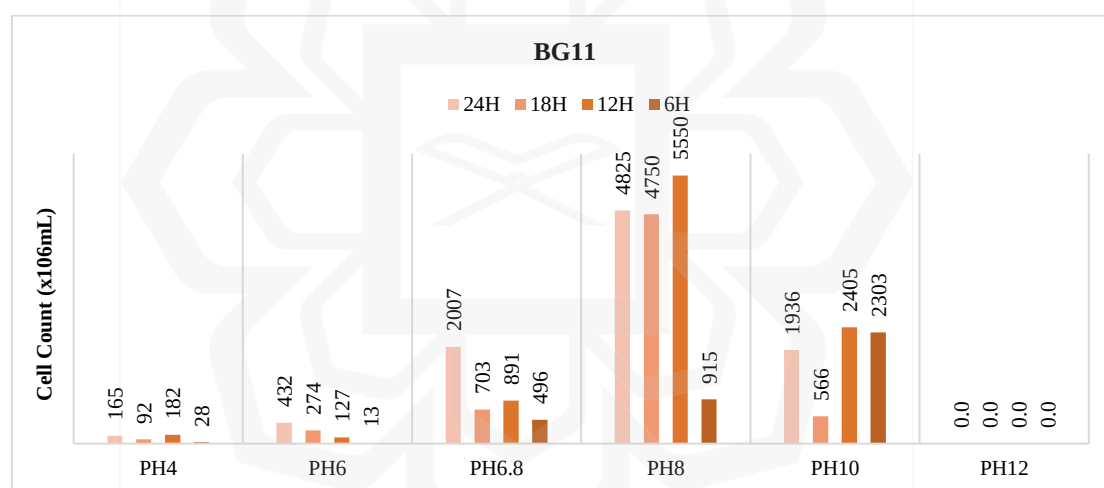


Figure 4.7 Cell counts of *P. amphigranulata* cultured in BG11 medium at different pH and photoperiod after 2 weeks

Table 4.6 The optimum cell counts distribution of *P. amphigranulata* cultured in BG11 medium at different pH and photoperiod after 2 weeks

Cynobacteria	Photoperiod	Peak pH (day)	Cell Counts (x10 ⁶ mL ⁻¹)
<i>P. amphigranulata</i>	24:0	pH 8	4825
	18:6	pH 8	4750
	12:12	pH 8	5550
	6:18	pH 10	2303

With a peak of 5570×10^6 cells/mL at pH 8 and substantial increase over the course of 18 hours, reaching 4750×10^6 cells/mL at pH 8, Table 4.6 show the maximum cell counts under BG11 media during 12-hours photoperiod. In contrast, the lowest growth was observed under pH 4 and 6 at 6hours photoperiod, with a maximum of only $12 \pm 20 \times 10^6$ cells/mL. Overall, growth trends indicate that the optimal conditions at photoperiods of 18–24 hours and pH levels between 6.8 and 10 that showed longer photoperiods strong positive impact, particularly within the mid-range pH levels.

The absorbance graphs at 750 nm in BG11 media over a 14-day period are shown in Figure 4.8, which suggests that pH and light exposure have an impact on growth trends. Absorbance increases gradually at all pH levels during the 24:0 and 18:6 photoperiod, with pH 8 and 10 showing the highest values. Absorbance rises somewhat during the 12:12 photoperiod, with pH 8 and 10 continuing to sustain the greatest development, but less so than under the earlier circumstances. Regardless of pH, the 6:18 photoperiod show little absorbance increases, suggesting restricted growth under this light-dark cycle.

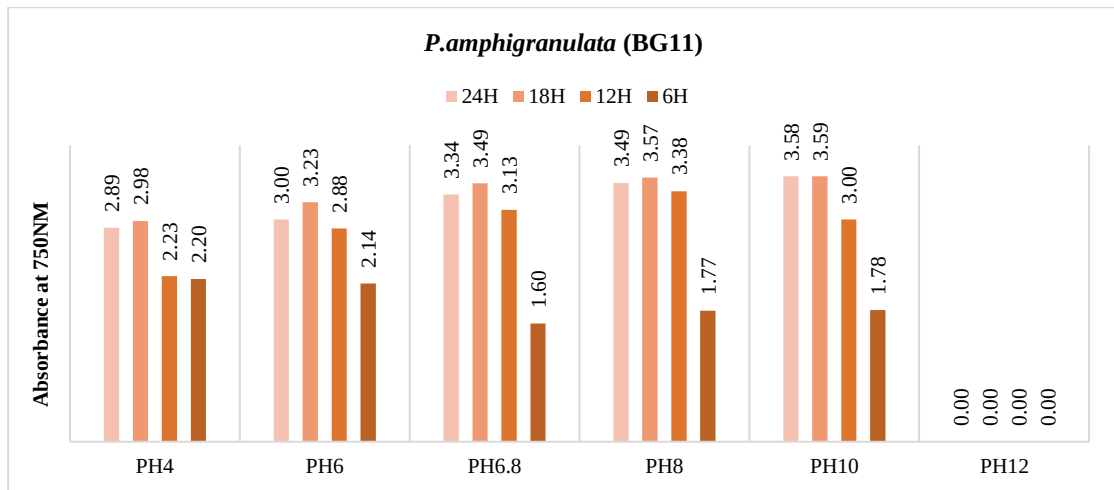


Figure 4.8 The effect of different photoperiod and pH on cell density measured at 750 nm (OD_{750}) of *P. amphigranulata* cultured in BG11 medium after 2 weeks

Table 4.7 The optimum cell density distribution measured at (OD_{750}) of *P. amphigranulata* in BG11 medium at different pH and photoperiod after 2 weeks

Cynobacteria	Photoperiod	Peak pH	Abs
<i>P. amphigranulata</i>	24:0	pH 10	3.58
	18:6	pH 10	3.59
	12:12	pH 8	3.38
	6:18	pH 10	1.78

The optimal absorbance, peaking at pH 10 under an 18H photoperiod on Day 14 (3.59). The lowest value is at pH 6.8 under a 6H photoperiod on Day 14 (1.60) as displayed in Table 4.7. Longer photoperiods (24H, 18H) support higher growth rates, while shorter ones (12H, 6H) show limited growth. pH 6.8–10 generally promotes better absorbance.

4.2.6 Effect of BG11 Medium Formulation, pH and Photoperiod on *P. amphigranulata* Biomass and Carbon Sequestration Rate (CSR)

According to Table 4.8, an 18-hours photoperiod at pH 8 results in the best biomass (0.61 g/L) and carbon sequestration (0.96 g/L CO₂e). The lowest results (biomass 0.07 g/L, carbon sequestration 0.10 g/L CO₂e) under 6H are obtained at pH 6.8. Continuous light (24H) supports growth but is less effective than 12H, with biomass and CO₂ sequestration peaking at pH 8 (0.49 g/L and 0.77 g/L CO₂e). Moderate conditions like pH 6 with an 18H photoperiod yield outstanding performance (biomass 0.37 g/L, CO₂ 0.57 g/L CO₂e), while extreme pH levels and shorter photoperiods limit results. As per show in Figure 4.9.

Table 4.8 The optimum biomass and CSR distribution of *P. amphigranulata* cultured in BG11 medium at different pH and photoperiod after 2 weeks

Green Algae	pH	Photoperiod	Biomass (g/L)	CSR (CO ₂ e)
<i>P. amphigranulata</i>	pH 4	12:12	0.45	0.70
	pH 6	6:18	0.51	0.79
	pH 6.8	18:6	0.35	0.55
	pH 8	18:6	0.61	0.96
	pH 10	6:18	0.28	0.44

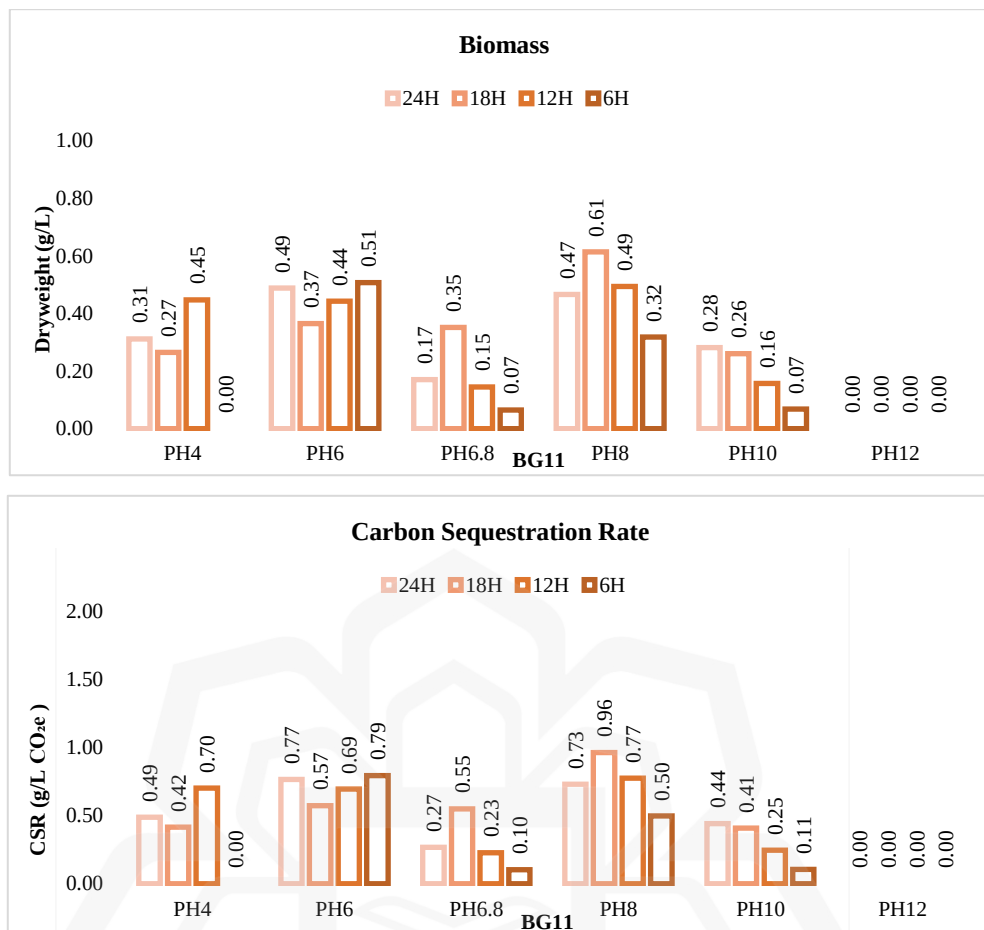


Figure 4.9 Biomass and CSR of of *P. amphigranulata* cultured in BG11 medium at different pH and photoperiod after 2 weeks

4.2.7 Effect of BG11 Medium Formulation, pH and Photoperiod on *P. amphigranulata* Chlorophyll Content

Figure 4.10 show clear patterns in the 600–700 nm wavelength region, showing how pH and light exposure affect the amount of chlorophyll. The graphic also demonstrated how the absorbance result is impacted by vegetation colours. With decreased absorbance at extreme pH values, the 24:0 and 18:6 graph displays a noticeable peak at about 680 nm at pH 10. The graphs at 12:12 and 6:18, on the other hand, show decreased absorption.

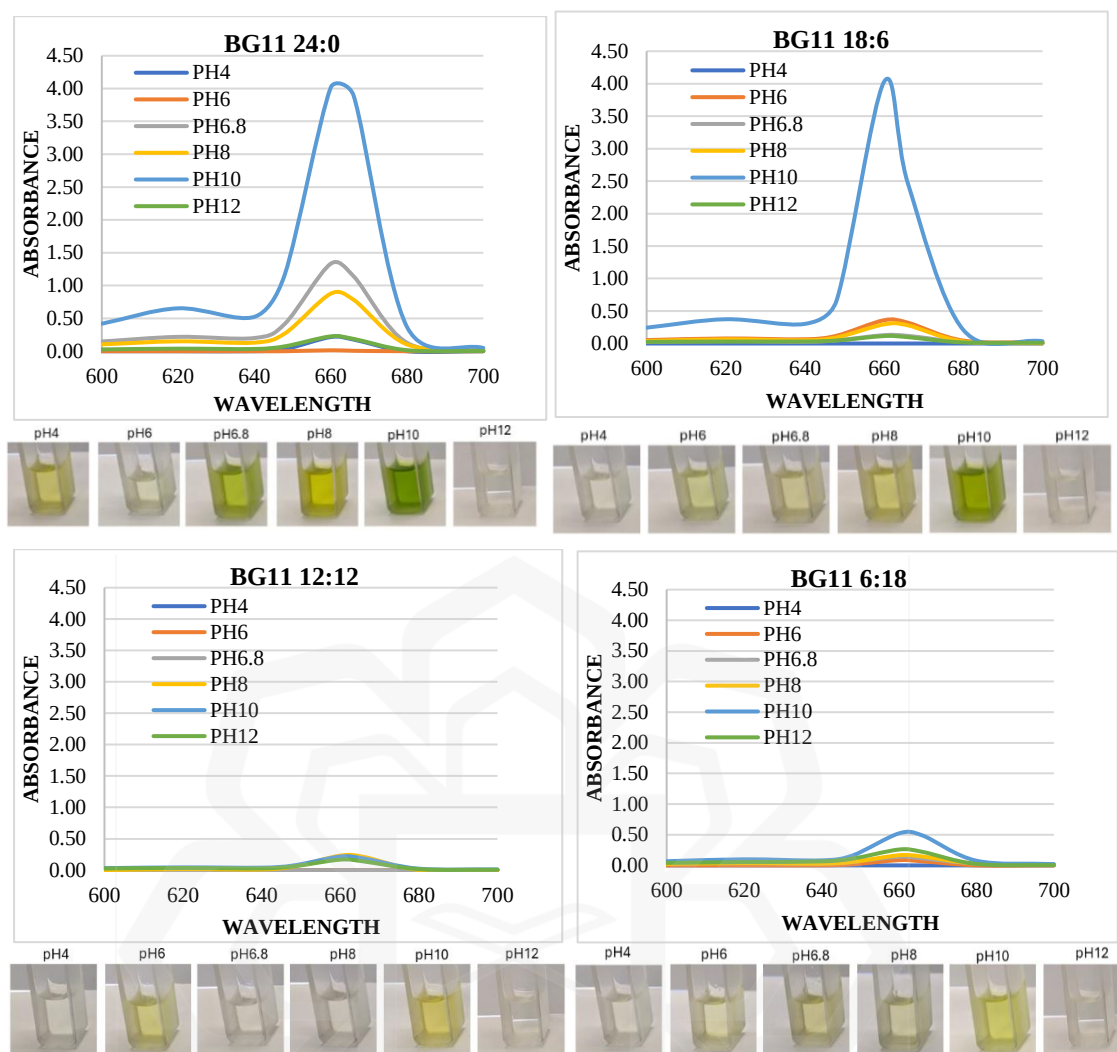


Figure 4.10 Effects of pH and photoperiod on chlorophyll content of *P. amphigranulata* cell culture in BBM medium after 2 weeks

4.2.8 Effect of BG11 Medium Formulation, pH and Photoperiod on *P. amphigranulata* Cell Culture Chromaticity

Chlorophyll production of *P. amphigranulata* cultured in BG11 show a distinct peak at pH 10, with absorbance values (4.02 ± 4.03), indicating strong pigment synthesis under alkaline conditions as showed in Figure 4.11. This peak is most prominent under continuous light (24:0) and extended light periods (18:6), where consistent illumination enhances photosynthetic activity and pigment production. In contrast, limited light

exposure (6-hours photoperiod) and extreme pH levels (6 and 6.8) significantly reduce chlorophyll synthesis, with pH 6 yielding only (0.9), highlighting suboptimal conditions. The 24:0 and 18:6 photoperiods are particularly effective in driving pigment production, while acidic pH levels (pH 4 and 6) exhibit the lowest pigment synthesis.

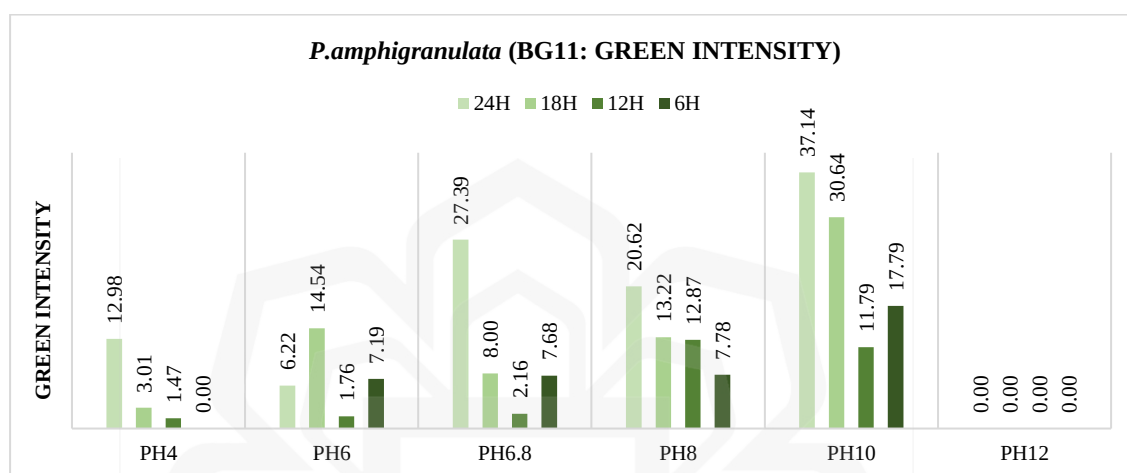


Figure 4.11 Effects of pH and photoperiod on green intensity values (a*) of *P. amphigranulata* cell culture in BG11 medium after 2 weeks

Table 4.9 Green intensity (a*) distribution of *P. amphigranulata* cell culture in BG11 medium at different pH and photoperiod after 2 weeks

Cynobacteria	Photoperiod	Peak pH (day)	a*
<i>P. amphigranulata</i>	24:0	pH 10	37.14
	18:6	pH 10	30.64
	12:12	pH 8	12.87
	6:18	pH 10	17.79
<i>a*</i> , ranges from white (0) to green (100)			

According to Table 4.9, Green intensity (a^*) peaks at pH 10 under a 24H photoperiod (37.14), while the lowest values occur at pH 4 and 6 under a 12H photoperiod (1.47 ± 1.76). The 18H cycle consistently yields the highest intensity, while the 12H cycle produces the lowest. Moderate values are observed under 24H and 6H, with pH 10 consistently showing the highest intensity.

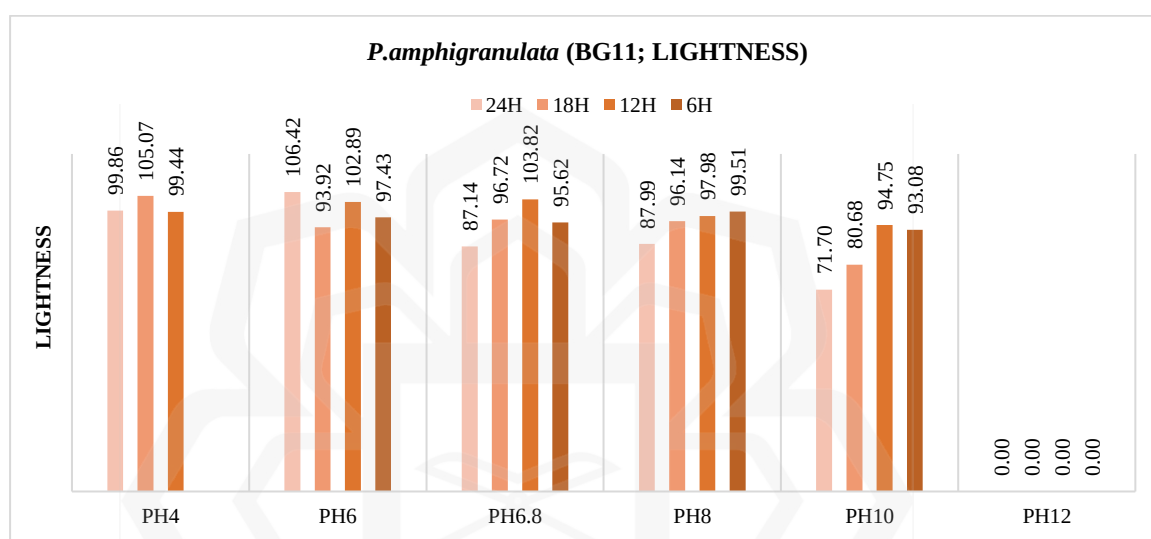


Figure 4.12 Effects of pH and photoperiod on lightness values (L^*) of *P. amphigranulata* cell culture in BG11 medium after 2 weeks

Table 4.10 Lightness (L^*) values distribution of *P. amphigranulata* cell culture in BG11 medium at different pH and photoperiod after 2 weeks

Cynobacteria	Photoperiod	Peak pH	L^*
<i>P. amphigranulata</i>	24:0	pH 10	71.70
	18:6	pH 10	80.68
	12:12	pH 10	94.75
	6:18	pH 10	93.08
<i>L*</i> , ranges from black (0) to white (100)			

Lightness (L*) lowest at pH 10 under a 24H photoperiod (71.70) and highest at pH 6 under the same photoperiod (106.42), indicating reduced light absorption under these conditions. Longer photoperiods (24H, 18H) with pH 10 enhance light absorption, while shorter light exposure and acidic conditions reduce efficiency. As showed in Figure 4.12 and Table 4.10, cell culture grown in BG11 medium varies with different photoperiods, reflecting changes in cell density and pigment concentration influenced by light exposure duration.

In conclusion, the study identifies pH 8 under 12-hours and 18-hours photoperiods as the most efficient conditions for optimal growth cultured in BG11, with absorbance values peaking under these settings (3.38 ± 3.59), indicating enhanced biomass production (0.51 ± 0.6 g/L) and Carbon sequestration (0.79 ± 0.96 g/L CO_{2e}). Chlorophyll absorbance (4.02) and light intensity (71.10), however, show a different trend, with the highest values achieved at pH 10 under continuous light (24-hours) and 18-hours photoperiods, suggesting that alkaline conditions combined with extended light exposure are optimal for photosynthetic pigment production. In contrast, acidic pH levels (4 and 6) and shorter photoperiods (6-hours) significantly limit growth, absorbance, and chlorophyll production, demonstrating the importance of balanced pH and sufficient light exposure for achieving optimal outcomes in algal cultivation.

4.2.9 Effect of BRISTOL Medium Formulation, pH and Photoperiod on *P. amphigranulata* Cell Culture Growth

P. Ampnigranulata cell counts increasing significantly after Day 6 and peaking by Day 14 in Bristol medium. Figure 4.13 showed, overall result leads to the lower growth, under 24:0 light followed by the 18:6 light cycle. Less light in the 12:12 which still supports good growth but at a slightly slower rate and 6:18 cycles slow growth visibly.

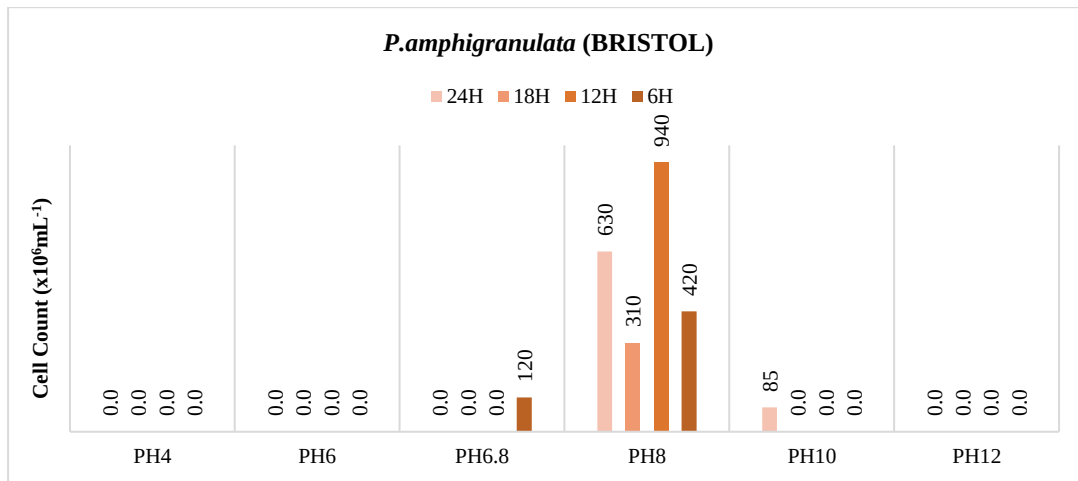


Figure 4.13 Cell counts of *P. amphigranulata* cultured in BRISTOL medium at different pH and photoperiod after 2 weeks

Table 4.11 The optimum cell counts distribution of *P. amphigranulata* cultured in BRISTOL medium at different pH and photoperiod after 2 weeks

Cynobacteria	Photoperiod	Peak pH	Cell Counts (x10 ⁶ mL ⁻¹)
<i>P. amphigranulata</i> .	24:0	pH 8	630
	18:6	pH 8	310
	12:12	pH 8	940
	6:18	pH 8	420

Data from Bristol medium reveals the optimal conditions for cell growth, with the highest cell counts of $940 \times 10^6 \text{ mL}^{-1}$ observed under a 12-hours photoperiod at pH 8, followed by $630 \times 10^6 \text{ mL}^{-1}$ under a 24-hours photoperiod. In contrast, minimal growth occurred under a 6-hours photoperiod at pH 10, with just $35 \times 10^6 \text{ mL}^{-1}$ recorded as indicated in Figure 4.13 and Table 4.11 These findings highlight the influence of photoperiod and pH on cell proliferation, indicating that moderate photoperiods and

neutral to slightly alkaline pH levels promote better growth compared to shorter periods and higher pH levels. Continuous light exposure (24:0) produces the steady and slow growth conditions, followed by the 18:6 photoperiod with slightly reduced growth as per showed in Figure 4.14. The 12:12 photoperiod results in highest growth at peak of Ph 6.8, while the 6:18 photoperiod show the lowest absorbance, reflecting minimal growth due to limited light exposure.

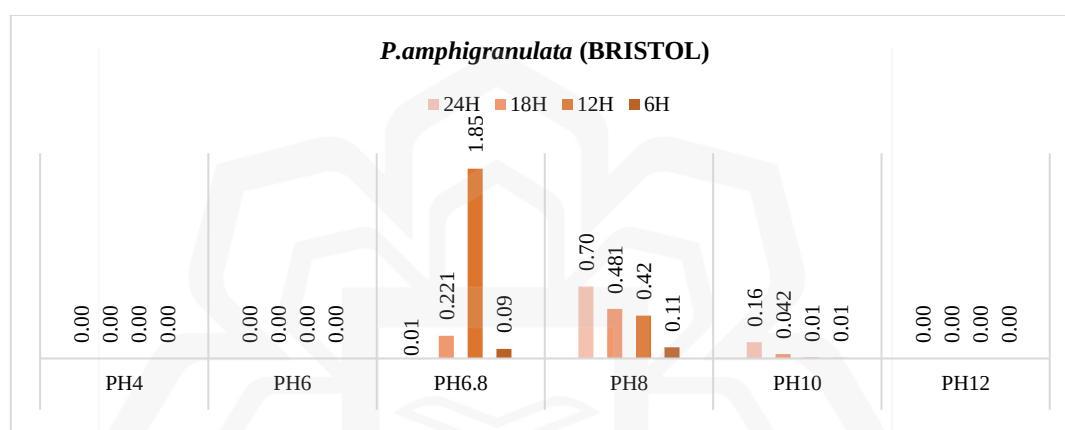


Figure 4.14 The effect of different photoperiod and pH on cell density measured at 750 nm (OD₇₅₀) of *P. amphigranulata* cultured in BRISTOL medium after 2 weeks

Table 4.12 The optimum cell density distribution measured at (OD₇₅₀) of *P. amphigranulata* in BBM medium at different pH and photoperiod after 2 weeks

Cynobacteria	Photoperiod	Peak pH	Abs
<i>P. amphigranulata</i>	24:0	pH 8	0.70
	18:6	pH 8	0.481
	12:12	pH 6.	1.85
	6:18	pH 8	0.11

Optimal growth was influenced by the pH range and duration of light exposure, with significant variations observed across treatments. Table 4.12 show, the highest absorbance is recorded at pH 6.8 with a 12-hours photoperiod on Day 14 (1.85), while the lowest is at pH 10 with a 6-hours photoperiod (0.01). Longer photoperiods (24 and 18 hours) and pH levels near neutral to slightly alkaline (6.8–8) support better growth.

4.2.10 Effect of BRISTOL Medium Formulation, pH and Photoperiod on *P. amphigranulata* Biomass and Carbon Sequestration Rate (CSR)

Table 4.13 and Figure 4.15 highlight the results for biomass and CO₂ sequestration of *P. amphigranulata* grown in Bristol medium under varying pH levels and photoperiods. The highest biomass production, reaching 0.28 g/L, was observed at pH 8 with a 12-hours photoperiod, alongside the peak CO₂ sequestration of 0.44 g/L CO₂e. Conversely, the lowest values were recorded at pH 6.8 under a 6-hours photoperiod, with biomass at just 0.03 g/L and carbon sequestration at 0.05 g/L CO₂e. This data underscores the optimum conditions for biomass production and carbon sequestration in cell culture growth.

Table 4.13 The optimum biomass and CSR distribution of *P. amphigranulata* cultured in BRISTOL medium at different pH and photoperiod after 2 weeks

Green Algae	pH	Photoperiod	Biomass (g/L)	CSR (CO ₂ e)
<i>P. amphigranulata</i>	pH 6.8	6:18	0.03	0.05
	pH 8	12:12	0.28	0.44
	pH 10	24:0	0.03	0.04

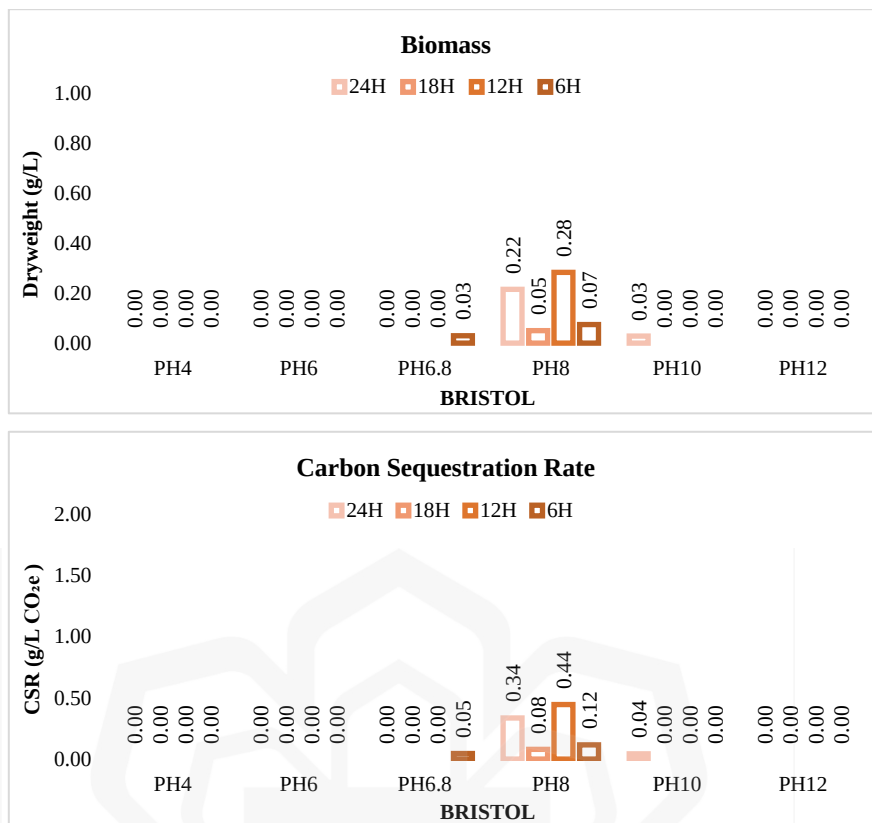


Figure 4.15 Biomass and CSR of *P. amphigranulata* cultured in BRISTOL medium at different pH and photoperiod after 2 weeks

4.2.11 Effect of BRISTOL Medium Formulation, pH and Photoperiod on *P. amphigranulata* Chlorophyll Content

Clear patterns in the 600–700 nm wavelength region that show how pH and light exposure affect the amount of chlorophyll as showed in Figure 4.16. The 24:0 and 18:6 graph show a pronounced peak at ~680 nm for pH 10 and pH 8, with lower absorbance at extreme pH levels. In contrast, 12:12 and 6:18 graphs with lower absorbance result. It showed that greenery coloured will affect the absorbance result refer to Figure 4.16.

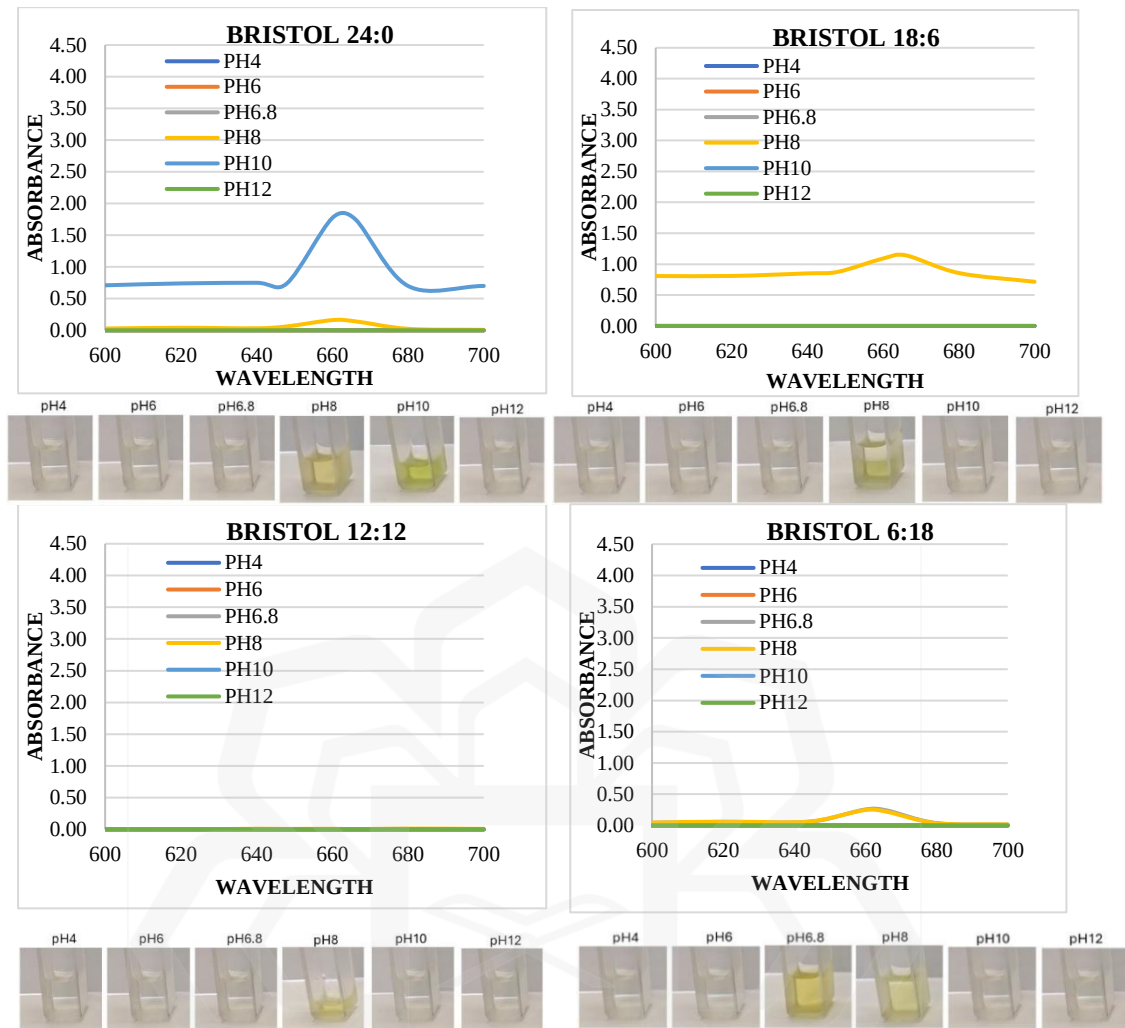


Figure 4.16 Effects of pH and photoperiod on chlorophyll content of *P. amphigranulata* cell culture in BRISTOL medium after 2 weeks

4.2.12 Effect of BRISTOL Medium Formulation, pH and Photoperiod on *P. amphigranulata* Cell Culture Chromaticity

The highest green intensity (a^*) is observed at pH 8 with a 6-hours photoperiod (11.76), while the lowest is at pH 8 with a 12-hours photoperiod (0.16). Green intensity generally peaks at pH 8 across all photoperiods refer to Figure 4.17 and Table 4.14. The lowest lightness value (L^*), indicating better light absorption, is 45.81 at pH 8 under an 18-hours photoperiod. The highest lightness, indicating reduced absorption, is 94.78 at pH 8 with a 6-hours photoperiod as per showed in Figure 4.18 and Table 4.15.

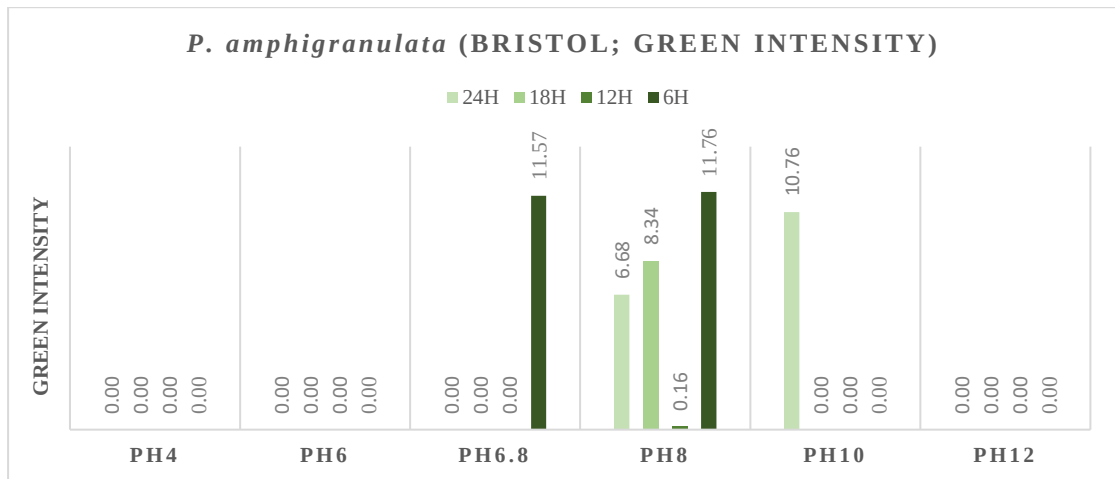


Figure 4.17 Effects of pH and photoperiod on green intensity values (a^*) of *P. amphigranulata* cell culture in BRISTOL medium after 2 weeks

Table 4.14 Green intensity (a^*) distribution of *P. amphigranulata* cell culture in BRISTOL medium at different pH and photoperiod after 2 weeks

Cynobacteria	Photoperiod	Peak pH	a^*
<i>P. amphigranulata</i>	24:0	pH 10	10.72
	18:6	pH 8	8.34
	12:12	pH 8	0.16
	6:18	pH 8	11.76
<i>a*</i> , ranges from white (0) to green (100)			

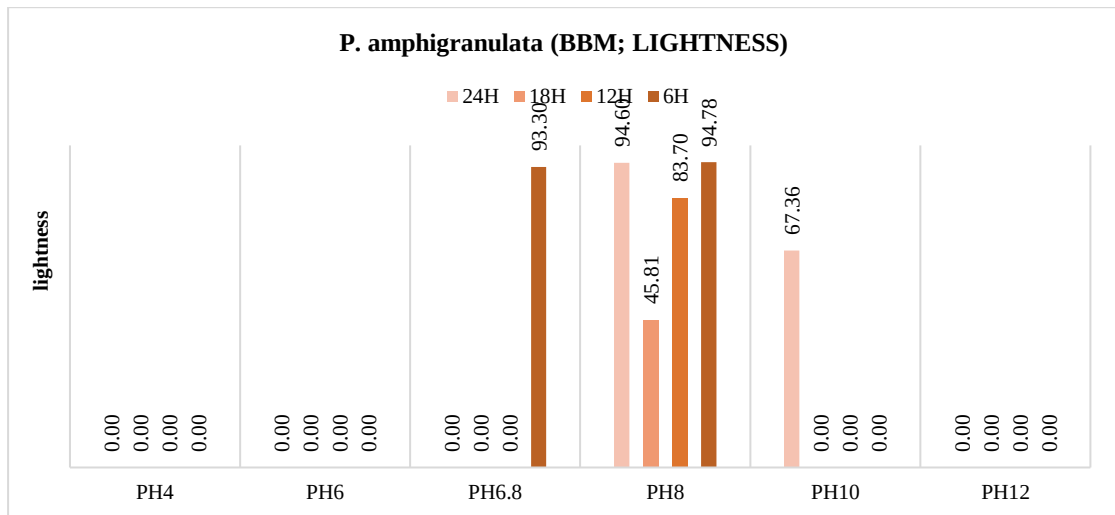


Figure 4.18 Effects of pH and photoperiod on lightness values (L*) of *P. amphigranulata* cell culture in BISTOL medium after 2 weeks

Table 4.15 Lightness (L*) values distribution of *P. amphigranulata* cell culture in BRISTOL medium at different pH and photoperiod after 2 weeks

Cynobacteria	Photoperiod	Peak pH	L*
<i>P. amphigranulata</i>	24:0	pH 10	67.36
	18:6	pH 8	45.81
	12:12	pH 8	83.70
	6:18	pH 8	94.78

*L**, ranges from black (0) to white (100)

In conclusion, the optimal growth at pH 8 with 24-hours light exposure, enhancing biomass (0.22 g/L), CO₂ sequestration (0.34 g/L CO₂e, and growth rates, highlighting a preference for slightly alkaline, continuous light conditions. Absorbance and chlorophyll production peak under pH 10 with 24-hours light (1.77), suggesting

stress-induced pigment synthesis. While lightness increases under longer photoperiods 18 hours (45.81) at slightly acidic to neutral pH, improving growth efficiency.

4.2.13 Effect of Chu Medium Formulation, pH and Photoperiod on *P. amphigranulata* Cell Culture Growth

P. amphigranulata cell counts increasing significantly after Day 6 and peaking by Day 14 in Chu medium. Overall result leads to the lower growth, under 24:0 light followed by the 18:6 light cycle. Less light in the 6:18 which still supports good growth but at a slightly slower rate and 12:12 cycles slow growth visibly according to Figure 4.19.

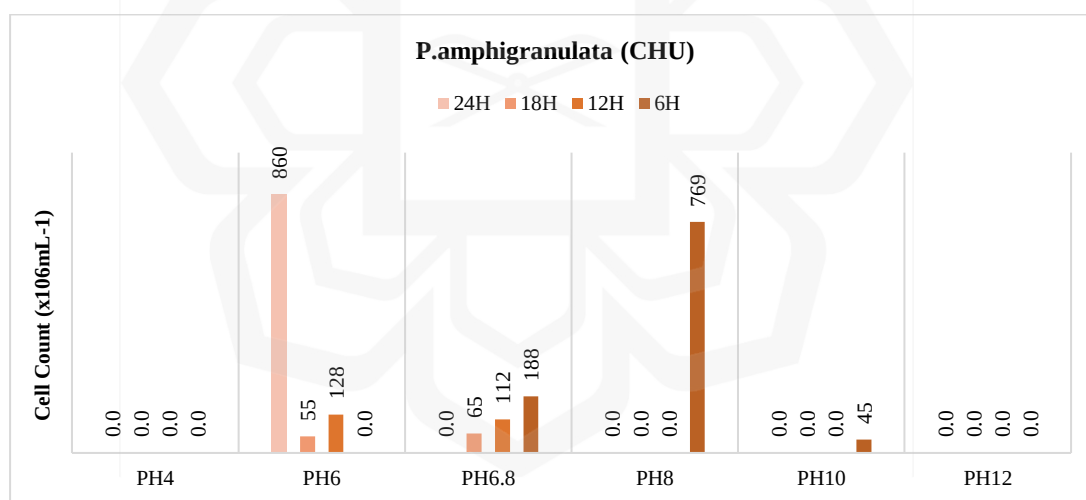


Figure 4.19 Cell counts of *P. amphigranulata* cultured in Chu medium at different pH and photoperiod after 2 weeks

Table 4.16 The optimum cell counts distribution of *P. amphigranulata* cultured in Chu medium at different pH and photoperiod after 2 weeks

Cynobacteria	Photoperiod	Peak pH (day)	Cell Counts (x10 ⁶ mL ⁻¹)
<i>P. amphigranulata</i>	24:0	pH 6	860
	18:6	pH 6.8	65
	12:12	pH 6.8	112
	6:18	pH 8	769

The data collected using Chu medium show the highest cell counts recorded under a 24-hours photoperiod at pH 6 ($860 \times 10^6 \text{ mL}^{-1}$) and followed by 6 hours ($769 \times 10^6 \text{ mL}^{-1}$), The least growth occurs under a 6-hours photoperiod at pH 10 ($45 \times 10^6 \text{ mL}^{-1}$) refer to Table 4.16.

The absorbance analysis of *P. ampnigranulata* cultured in CHU medium reveals that pH 6 consistently supports optimal growth across all photoperiods, followed by pH 6.8, while pH 10 and pH 12 exhibit minimal growth as per Figure 4.20. Continuous light (24:0) and extended light exposure (18:6) result in higher absorbance values and faster growth compared to shorter light periods (12:12 and 6:18). Growth peaks are generally observed between days 6 and 10 under encouraging conditions, with reduced light exposure (6:18) leading to the lowest absorbance and growth.

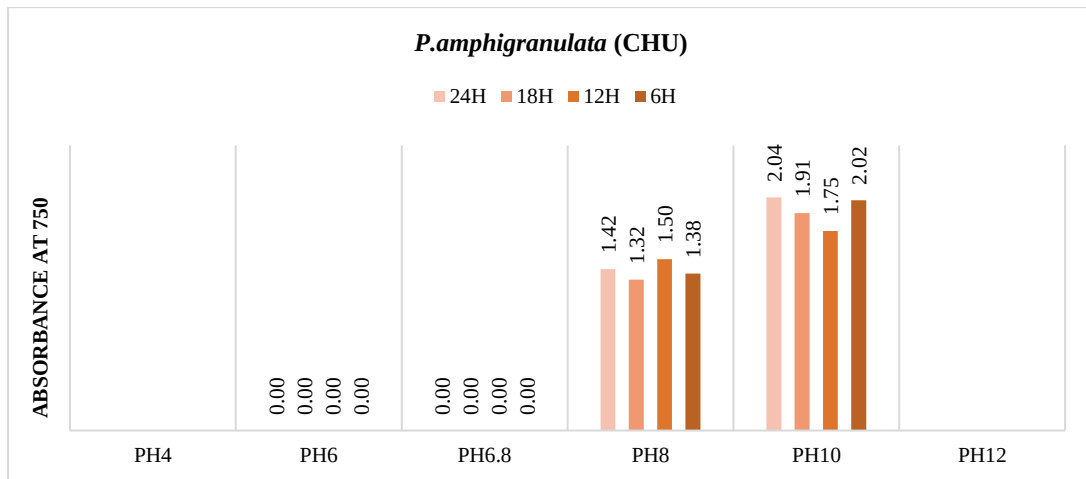


Figure 4.20 The effect of different photoperiod and pH on cell density measured at 750 nm (OD_{750}) of *P. amphigranulata* cultured in Chu medium after 2 weeks

Table 4.17 The optimum cell density distribution measured at (OD_{750}) of *P. amphigranulata* in Chu medium at different pH and photoperiod after 2 weeks

Cynobacteria	Photoperiod	Peak pH	Abs
<i>P. amphigranulata</i>	24:0	pH 10	2.04
	18:6	pH 10	1.91
	12:12	pH 10	1.75
	6:18	pH 10	2.02

Figure 4.20 show the highest absorbance is recorded at pH 10 with a 24-hours photoperiod on Day 14 (2.04), followed by 6 hours by 2.02 at same ph. While the lowest is at pH 8 with a 12-hours photoperiod (1.32). Longer photoperiods (24H) and pH levels near neutral to slightly alkaline (8-10) support consistent and better growth refer to Table 4.17.

4.2.14 Effect of Chu Medium Formulation, pH and Photoperiod on *P. amphigranulata* Biomass and Carbon Sequestration Rate (CSR)

The highest biomass results under a 24-hours photoperiod at pH 6, show biomass peaks at 0.28 g/L and CO₂ sequestration at 0.44 g/L CO₂e. The lowest values are at pH 10 with a 6-hours photoperiod: biomass (0.02 g/L) and CO₂ sequestration (0.02 g/L CO₂e) refer to Figure 4.21 and Table 4.18.

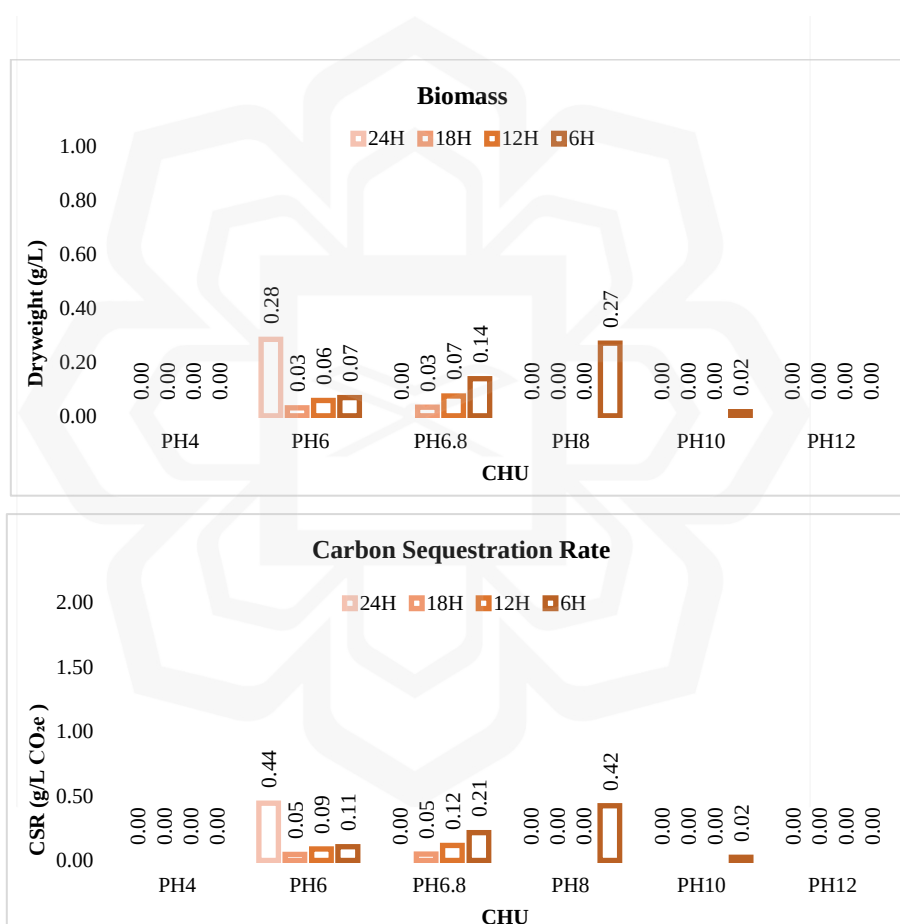


Figure 4.21 Biomass and CSR of *P. amphigranulata* cultured in Chu medium at different pH and photoperiod after 2 weeks

Table 4.18 The optimum biomass and CSR distribution of *P. amphigranulata* cultured in Chu medium at different pH and photoperiod after 2 weeks

Green Algae	pH	Biomass (g/L)	CSR (CO ₂ e)
<i>P. amphigranulata</i>	pH 6 (24H)	0.28	0.44
	pH 6.8 (6H)	0.14	0.21
	pH 8 (6H)	0.27	0.42
	pH 10 (6H)	0.02	0.02

4.2.15 Effect of Chu Medium Formulation, pH and Photoperiod on *P. amphigranulata* Chlorophyll Content

Figure 4.22 display distinct patterns in the 600–700 nm wavelength range, indicating variations in chlorophyll content influenced by light exposure and pH. The 24:0 and 12:12 graph show a pronounced peak at ~680 nm for pH 6 and 6.8 and overall trend almost flat to the lowers. Followed by 18:6 and 6:18 graphs with lower absorbance result.

The optimal chlorophyll production occurs at pH 6.8 under a 6-hours photoperiod, reaching the highest value of (0.15), indicating that a short light exposure combined with near-neutral pH promotes effective chlorophyll synthesis. This is followed by pH 6 under 24-hours (continuous light) and 12-hours photoperiods, compromise slightly lower chlorophyll concentrations of (0.13 ± 0.11), respectively. According to Figure 4.22, these results suggest that pH 6 is generally good for chlorophyll production, especially under extended light exposure. However, the lowest chlorophyll production is observed at pH 6 under a 12-hours photoperiod, with a significant drop to 0.02, indicating that specific combinations of pH and light exposure can negatively affect chlorophyll synthesis. Interestingly, pH 6–6.8 consistently enhances chlorophyll synthesis across various photoperiods, highlighting these pH levels as optimal for supporting photosynthetic activity in Chu medium.

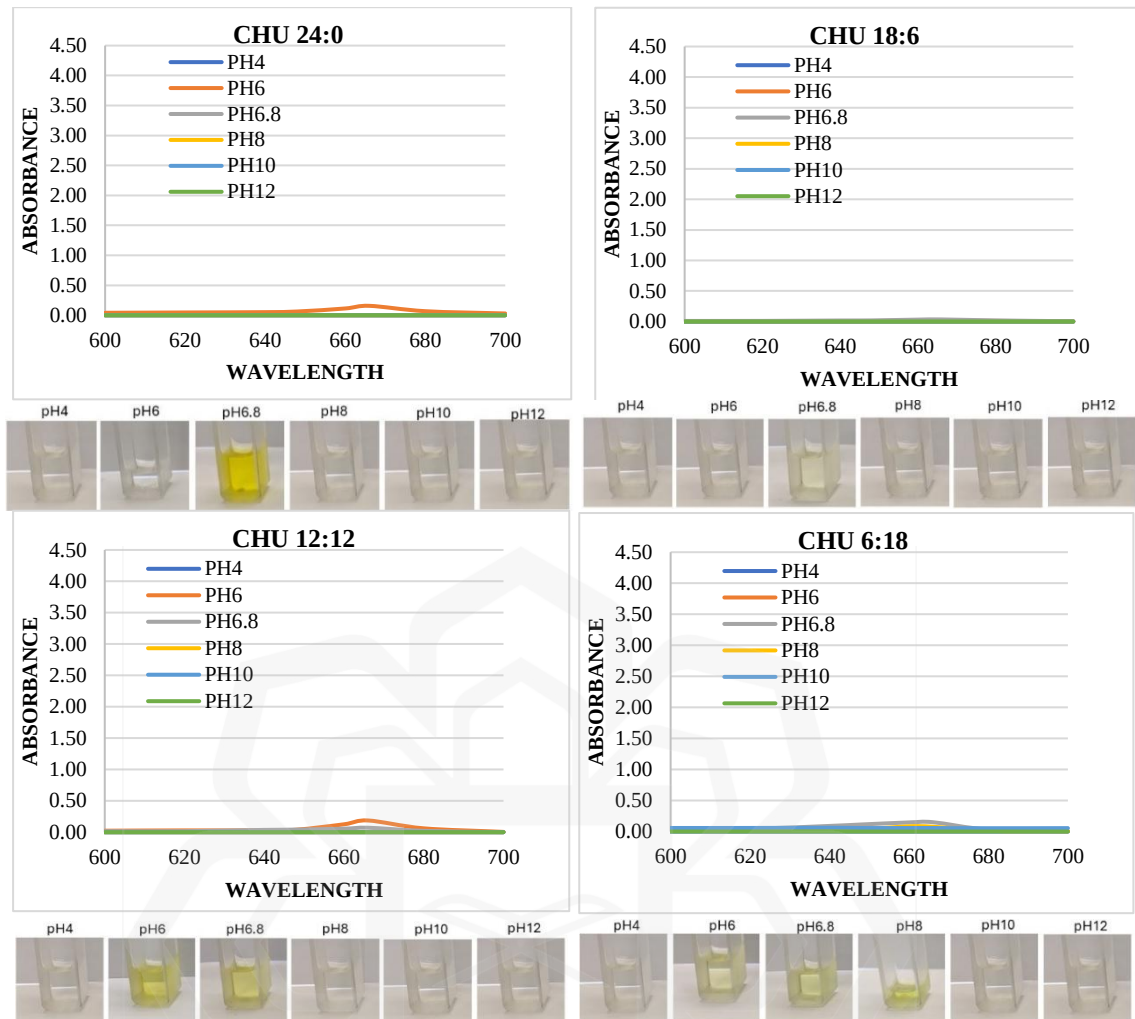


Figure 4.22 Effects of pH and photoperiod on chlorophyll content of *P. amphigranulata* cell culture in Chu medium after 2 weeks

4.2.16 Effect of Chu Medium Formulation, pH and Photoperiod on *P. amphigranulata* Cell Culture Chromaticity

As shown in Figure 4.23 Table 4.19, the highest green intensity (a^*) is recorded at pH 6 with a 24-hours photoperiod (35.02), while the lowest is observed at pH 6 with an 18-hours photoperiod (1.88). Overall, green intensity tends to peak at pH levels of 6 and 6.8 across all photoperiods. The lowest lightness value (L^*), indicating optimal light absorption, is (85.37) at pH 6 under a 24-hours photoperiod (Table 4.20). In contrast,

the highest lightness value, representing reduced light absorption, is 99.32 at pH 6 under an 18-hours photoperiod, as shown in Figure 4.24.

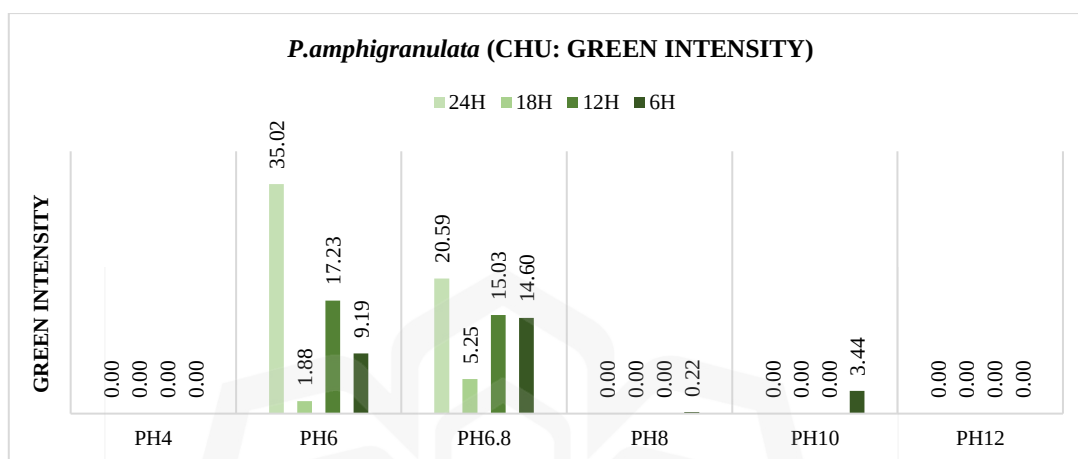


Figure 4.23 Effects of pH and photoperiod on green intensity values (a^*) of *P. amphigranulata* cell culture in Chu medium after 2 weeks

Table 4.19 Green intensity (a^*) distribution of *P. amphigranulata* cell culture in Chu medium at different pH and photoperiod after 2 weeks

Cynobacteria	Photoperiod	Peak pH	a^*
<i>P. amphigranulata</i>	24:0	pH 6	35.02
	18:6	pH 6.8	5.25
	12:12	pH 6	17.23
	6:18	pH 6.8	14.60
<i>a*</i> , ranges from white (0) to green (100)			

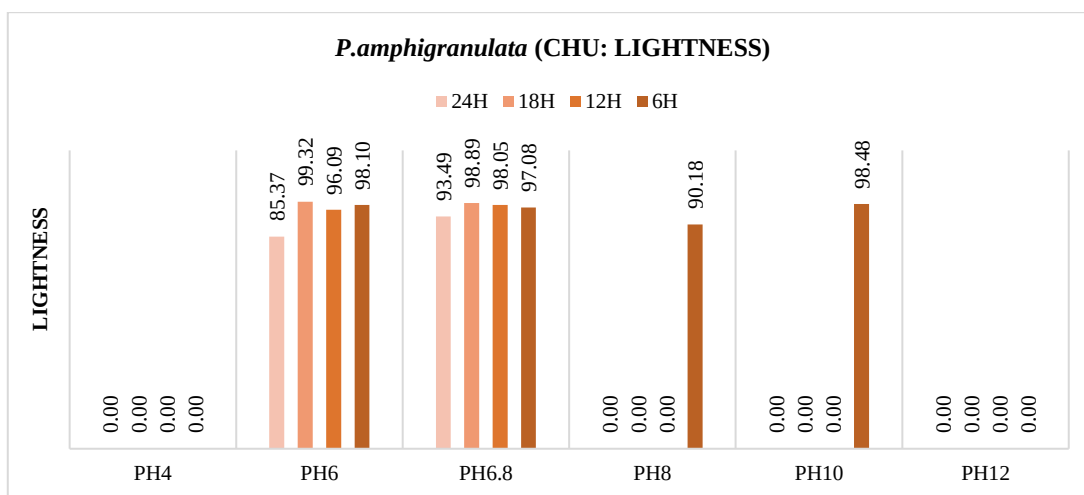


Figure 4.24 Effects of pH and photoperiod on lightness values (L*) of *P. amphigranulata* cell culture in Chu medium after 2 weeks

Table 4.20 Lightness (L*) values distribution of *P. amphigranulata* cell culture in Chu medium at different pH and photoperiod after 2 weeks

Cynobacteria	Photoperiod	Peak pH	L*
<i>P. amphigranulata</i>	24:0	pH 6	85.37
	18:6	pH 6.8	98.89
	12:12	pH 6	96.09
	6:18	pH 6.8	90.18
<i>a*</i> , ranges from white (0) to green (100)			

In conclusion, the optimal growth in Chu medium occurs under a 24-hours photoperiod at pH 6, with peak cell counts (860), biomass (0.28 g/L), CO₂ sequestration (0.44 g/L CO₂e), and green intensity (35.02). Chlorophyll synthesis is enhanced at pH 6–6.8, peaking at (0.15) under a 6-hours photoperiod. Absorbance and light absorption are highest at pH 10 and pH 6, respectively, with extended photoperiods supporting better growth across parameters.

4.2.17 Multivariate Data Analysis

4.2.17.1 Multivariate Analysis

The analysis of 10 variables was conducted using Multivariate Data Analysis to identify the key factors influencing *P. amphigranulata* cell growth, carbon sequestration, and chromaticity datasets. The sampling adequacy for *P. amphigranulata* data on cell growth, carbon sequestration, and chromaticity datasets was assessed using the Kaiser-Meyer-Olkin (KMO) test, which requires a value greater than 0.5, followed by Bartlett's Test of Sphericity ($p < 0.05$), and the Pearson Correlation Matrix, where values must be equal to or greater than 0.01 (Atiqah et al., 2023). The KMO test was performed at a significance level of $\alpha = 0.05$ to confirm that the dataset was suitable for multivariate data analysis. The average KMO values were classified according to the ranking criteria outlined by Ismail et al. (2021), as detailed below.

KMO < 0.5	inadequate
0.5 < KMO < 0.7	mediocre
0.7 < KMO < 0.8	good
0.8 < KMO < 0.9	very good
KMO > 0.9	excellent

The KMO values for the 288 datasets yielded a score of 0.755 (Table 4.21), indicating that the dataset falls within the "good" category and is suitable for PCA analysis. Bartlett's Test of Sphericity was conducted to verify that the R-matrix is not equivalent to the identity matrix. The p -value for the *P. amphigranulata* datasets on cell growth, carbon sequestration, and chromaticity showed highly significant differences at 0.0001.

Table 4.21 Kaiser-Meyer-Olkin and Bartlett's test for *P. amphigranulata* Cell Culture Growth, Carbon Sequestration, and Chromaticity

Kaiser-Meyer-Olkin Measure of Sampling Adequacy		0.755
Bartlett's Test of Sphericity	Chi-square (Observed value)	5357.59
	DF	45
	<i>p</i> -value (Two-tailed)	< 0.0001

Correlation coefficient matrix (r^2) in Table 4.22 revealed a positive and negative correlations strength between two variables among *P. amphigranulata* cell growth, carbon sequestration, and chromaticity datasets. A very high positive correlation was observed among biomass and CSR ($r^2 = 1$). A perfect positive correlation indicates that increases in biomass are directly proportional to carbon sequestration rate. High positive correlations were observed in Chlorophyll content, green intensity, lightness, biomass and CSR ($r^2 = 0.712$ to 0.800).

Table 4.22 Correlation coefficient matrix for the *P. amphigranulata* Cell Culture Growth, Carbon Sequestration, and Chromaticity

Variables	L*	a*	Chl	CCt	CDt	BM	CSR	PH	PHPD	Day
L*	1									
a*	0.712	1								
Chl	0.397	0.800	1							
CCt	0.526	0.522	0.407	1						
CDt	0.597	0.508	0.442	0.639	1					
BM	0.730	0.577	0.453	0.614	0.628	1				
CSR	0.730	0.577	0.453	0.614	0.628	1.000	1			
pH	-0.071	0.015	0.059	0.089	-0.042	-0.076	-0.076	1		
PHPD	-0.033	0.018	0.038	0.137	0.142	0.069	0.069	0.000	1	
Day	0.604	0.472	0.314	0.358	0.525	0.451	0.451	0.000	0.000	1

Values in bold are different from 0 with a significance level $\alpha=0.01$

4.2.17.2 Principal Component Analysis (PCA)

The next step involved analysing the dataset using Principal Component Analysis (PCA) to identify variables with high factor loadings that significantly explain the principal components. Factor loadings were categorized as follows: strong (>0.75), moderate ($0.50-0.75$), weak ($0.30-0.49$), and negligible (<0.30), as described by Rani et al. (2017). Eigenvalues were utilized to determine the principal components that accounted for more cumulative variations in the dataset, with an eigenvalue of 1 or greater considered significant for PCA (Le et al., 2017; Zubir et al., 2016; Yang et al., 2020). The PCA was applied to 10 variables derived from *P. amphigranulata*'s cell growth, carbon sequestration, and chromaticity parameters dataset to identify the variables contributing significantly to *P. amphigranulata* pigment stability. The analysis revealed two principal components (PCs) encompassing the 10 variables, which together accounted for a cumulative variability of 60.80%. The eigenvalues for F1 and F2 were 4.9 and 1.0, respectively, as shown in Table 4.23. In principle, variables far away from the axes F1 and F2 had a strong factor loading (FL). Referring to the Table 4.23, L^* , a^* , cell density, biomass, CSR and pH had strong FL ($FL > 0.75$) whereas chlorophyll, cell counts and day had moderate FL ($0.500 < FL < 0.749$) and pH and photoperiod had a weak FL ($FL < 0.499$).

Table 4.23 The principal components factor loading and eigenvalues of the correlation matrix for *P. amphigranulata* Cell Growth, Carbon Sequestration, and Chromaticity

Variables	F1	F2
L^* (Lightness)	0.849	-0.150
a^* (green intensity)	0.814	0.221
Chl (Chlorophyll content)	0.663	0.365
CCt (Cell counts)	0.745	0.145
CDt (Cell Density)	0.790	-0.033
BM (Biomass)	0.884	-0.185
CSR	0.884	-0.185
pH	-0.028	0.878
PHPD (Photoperiod)	0.087	0.138
Day	0.647	-0.056
Eigenvalue	4.991	1.089
Variability (%)	49.915	10.887
Cumulative (%)	49.915	60.802

The first principal component (F1) explained 49.91% of the total variance, with strong factor loadings observed for L*, a*, CDt, BM, and CSR. In contrast, the second principal component (F2) accounted for 10.88% of the total variance, with pH identified as the only variable showing a strong association. The PCA analysis highlights key factors and provides valuable insights into *P. amphigranulata* cell growth, carbon sequestration, and chromaticity parameters dataset. Consequently, factor loadings can be used to assess the strength of the relationships between variables in these aspects.

4.2.18 Summary of results

1. There is a strong relationship between the cell growth, biomass, carbon sequestration, lightness and green intensity of the *P. amphigranulata* with time exposure in response to light and dark condition
2. BBM medium is the optimal choice for cultivating *P. amphigranulata*, achieving the highest overall growth, biomass production, CO₂ sequestration, and chlorophyll content.
3. The best performance was observed at pH 8 under 12-hours photoperiod and pH 10 under a 24-hours photoperiod.
4. BBM medium is a strong alternative for applications focused on carbon capture, with the highest CO₂ sequestration (1.36 g/L CO₂e) and robust biomass production (0.87 g/L).
5. *P. amphigranulata* show optimal under 12 hours at pH 8 in Chlorophyll content with absorbance (4.01) that significantly to Chromaticity values on Lightness (L*) 66.86 and Green Intensity (a*) 29.59.
6. The findings revealed strong correlations among variables with high positive relationships, including Chlorophyll content, green intensity, lightness, biomass and CSR, which are key parameters for the application algae model system.

4.3 ALKALINEMA SP.

4.3.1 Effect of BBM Medium Formulation, pH and Photoperiod on *Alkalinema* sp. Cell Culture Growth

The formulation of Bold's Basal Medium (BBM) and the regulation of light exposure (photoperiod) play a crucial role in optimising the growth and metabolic activities of the *Alkalinema* sp. cultured. Figure 4.25 present cell counts data for *Alkalinema* sp. in BBM medium over a 14-day. For the 24:0 condition, cell counts showed a consistent increase across all pH levels, with optimal growth observed at pH 6.8 and 8. The 18:6 condition also demonstrated similar trends, though cell counts were slightly lower compared to the continuous light condition. Under the 12:12 photoperiod, growth rates were moderate, with the most favourable growth again occurring around pH 6.8 and 8. In contrast, the 6:18 photoperiod resulted in significantly reduced cell counts, indicating limited growth across all pH levels, with minimal variation between conditions.

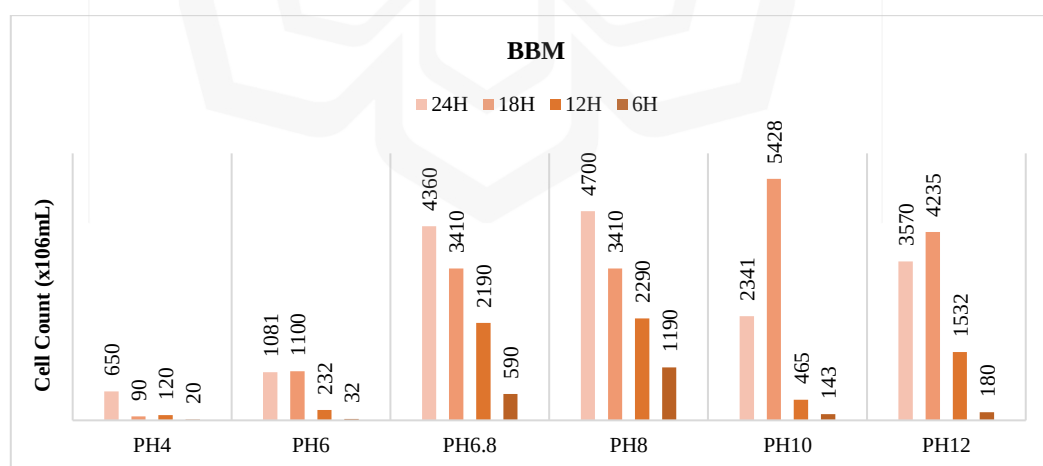


Figure 4.25 Cell counts of *Alkalinema* sp. cultured in BBM medium at different pH and photoperiod after 2 weeks

Table 4.24 The optimum cell counts distribution of *Alkalinema sp.* cultured in BBM medium at different pH and photoperiod after 2 weeks

Cynobacteria	Photoperiod	Peak pH	Cell Counts (x10 ⁶ mL ⁻¹)
<i>Alkalinema sp.</i>	24:0	pH 8	4700
	18:6	pH 10	5428
	12:12	pH 8	2980
	6:18	pH 8	970

The highest cell counts of *Alkalinema sp.* under BBM medium with an 18-hours photoperiod, peaking at 5428×10^6 cells/mL at pH 10. Significant growth was also observed at pH 12 under the same 18-hours photoperiod, reaching 4235×10^6 cells/mL, while pH 8 supported 4700×10^6 cells/mL. In contrast, the lowest growth was recorded under a 6-hours photoperiod at pH 6, with only 32 cells counted as showed in Table 4.24. Overall, the growth trends indicate that photoperiods of 18–24 hours, coupled with pH levels between 8 and 12, have a strong positive impact on growth, particularly within mid-range pH levels.

The absorbance graphs at 750 nm in BBM medium over 14 days, as shown in Figure 4.26, demonstrate that growth trends are influenced by light exposure and pH conditions. Under the 24:0, 18:6, and 12:12 photoperiods, absorbance steadily increases across all pH levels, with the highest readings observed at pH 8 and 10. For the 6:18 photoperiod, absorbance increases moderately, with pH 8 and 10 still supporting the highest growth but to a lesser extent than the previous conditions. These results emphasise the importance of both continuous light and an optimal pH range of 8 to 10 for maximising *Alkalinema sp.* growth.

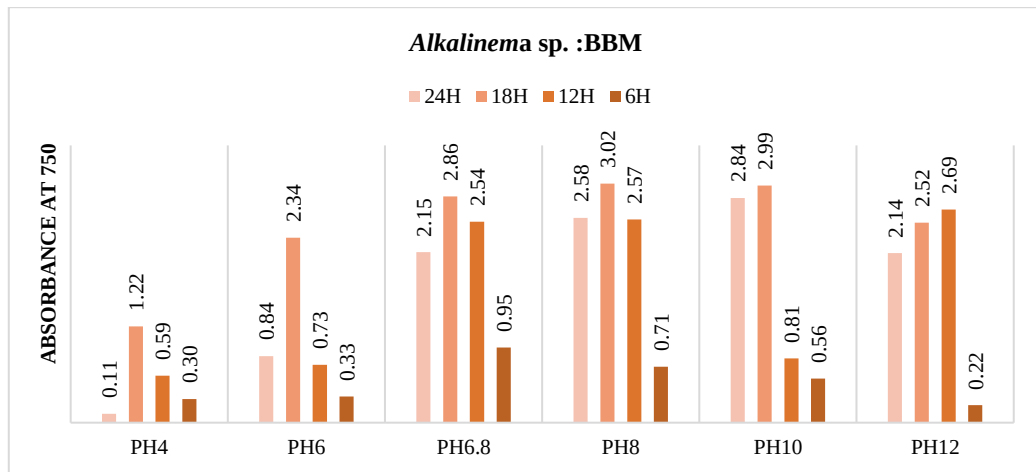


Figure 4.26 The effect of different photoperiod and pH on cell density measured at 750 nm (OD_{750}) of *Alkalinema sp.* cultured in BBM medium after 2 weeks

Table 4.25 The optimum cell density distribution measured at (OD_{750}) of *Alkalinema sp.* in BBM medium at different pH and photoperiod after 2 weeks

Cynobacteria	Photoperiod	Peak pH	Abs
<i>Alkalinema sp.</i>	24:0	pH 10	2.84
	18:6	pH 8	3.02
	12:12	pH 12	2.69
	6:18	pH 12	1.56

The highest absorbance for cell growth was observed at pH 8 with an 18-hours photoperiod (3.02). In comparison, a 24-hours photoperiod showed its peak growth at pH 10 (2.84), but also recorded the lowest absorbance at pH 4 (0.11). According to Table 4.25, overall balanced photoperiods of 24 and 18 hours consistently supported higher absorbance values with pH range 6.8 to 10.

4.3.2 Effect of BBM Medium Formulation, pH and Photoperiod on *Alkalinema* sp. Biomass and Carbon Sequestration Rate (CSR)

The optimal biomass production (0.76 g/L) and CO₂ sequestration (1.19 g/L CO₂e) occurred at pH 8 under an 18-hours photoperiod as per display in Figure 4.27 and Table 4.26. Similarly, a 24-hours photoperiod also supported significant growth, yielding biomass of (0.61 g/L) and CO₂ sequestration of (0.95 g/L CO₂e). In contrast, pH levels of 6 and 10, combined with shorter light cycles of 6 and 12 hours, resulted in the lowest values, with biomass at (0.05 g/L) and CO₂ sequestration at (0.08 g/L CO₂e). These findings highlight those moderate conditions—particularly pH 8 and a balanced light cycle maximise both growth and carbon sequestration.

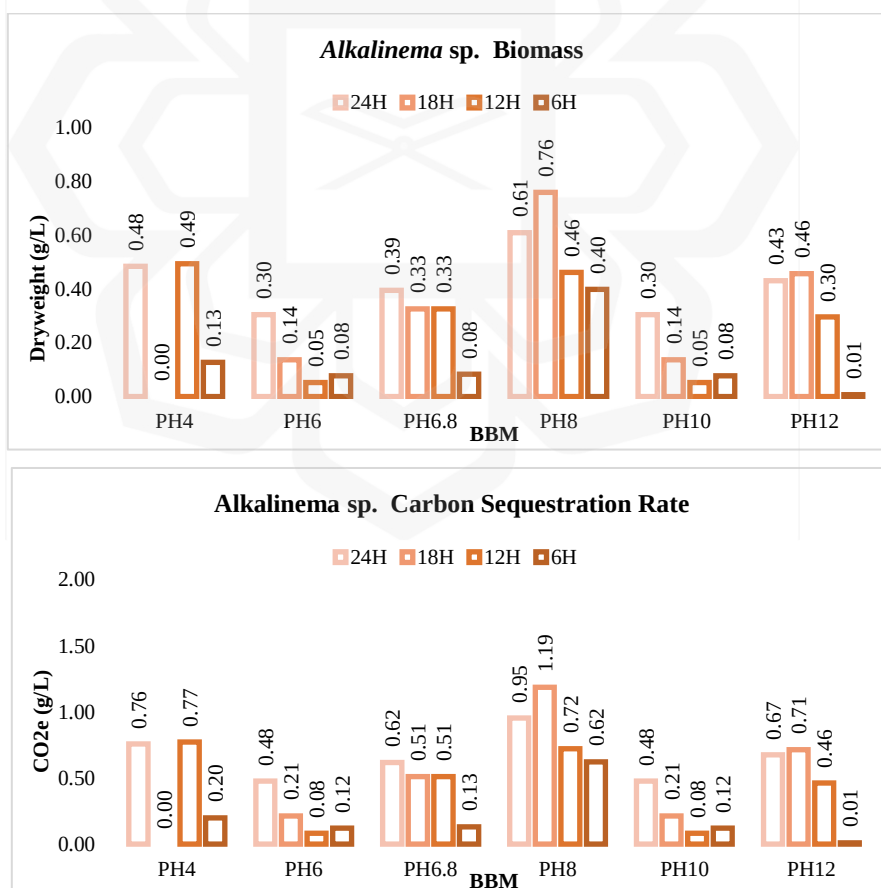


Figure 4.27 Biomass and CSR of *Alkalinema* sp. cultured in BBM medium at different pH and photoperiod after 2 weeks

Table 4.26 The optimum biomass and CSR distribution of *Alkalinema* sp. cultured in BBM medium at different pH and photoperiod after 2 weeks

Cynobacteria	pH	Photoperiod	Biomass (g/L)	CSR (CO ₂ e)
<i>Alkalinema</i> sp	pH 4	12:12	0.49	0.77
	pH 6	24:0	0.30	0.48
	pH 6.8	24:0	0.39	0.62
	pH 8	18:6	0.76	1.19
	Ph 10	24:0	0.30	0.48
	pH 12	18:6	0.46	0.71

4.3.3 Effect of BBM Medium Formulation, pH and Photoperiod on *Alkalinema* sp. Chlorophyll Content

Figure 4.28 display distinct patterns in the 600–700 nm wavelength range, indicating variations in chlorophyll content influenced by light exposure and pH. The 24:0 graph show a pronounced peak at ~680 nm for pH 10, with lower absorbance at extreme pH levels. Similarly, the 18:6, 12:12 and 6:18 graphs maintain high absorbance at ~680 nm, particularly at pH 6.8, 8 and 10, reflecting adaptability to moderate light-dark cycles. Figure 4.28 also demonstrates that the intensity of green colouration is directly linked to its absorbance values, suggesting that greener samples generally reflect higher chlorophyll content and enhanced light absorption efficiency.

The absorbance data indicate that chlorophyll production peaks under alkaline conditions, with pH 8 showing the highest value of 4.021, closely followed by pH 10 at 2.15, both under a 24-hours photoperiod as showed in Figure 4.28. These findings suggest that alkaline environments, combined with continuous light exposure, are ideal for maximising chlorophyll synthesis. Conversely, acidic conditions at pH 4 and 6 significantly suppressed chlorophyll activity, recording minimal absorbance values of 0.04 and 0.09, respectively, across all photoperiods. This highlights the critical role of

maintaining balanced pH levels to support algal metabolic processes. Additionally, moderate light-dark cycles may offer further potential for optimising chlorophyll activity while mitigating stress in microalgae.

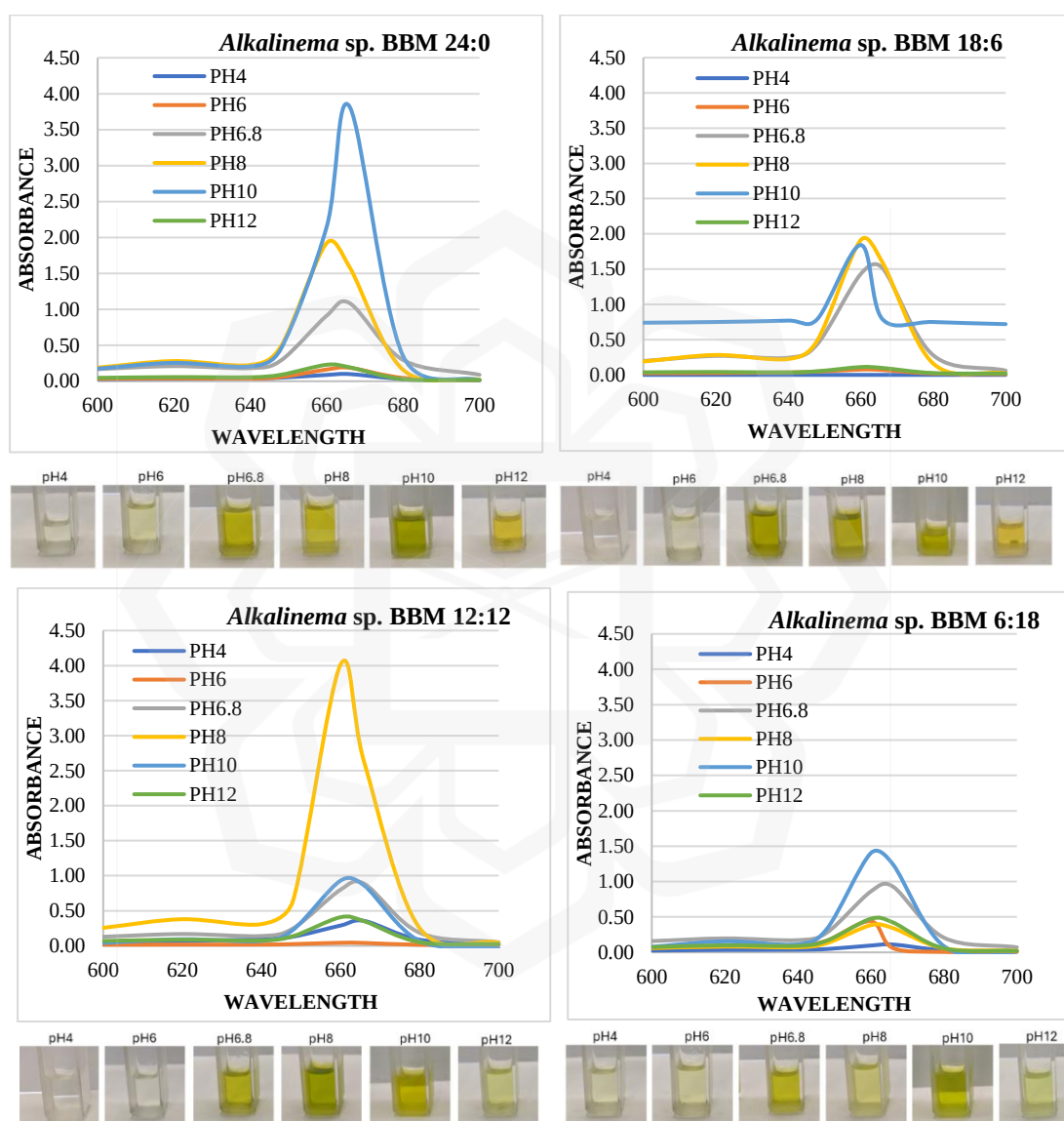


Figure 4.28 Effects of pH and photoperiod on chlorophyll content of *Alkalinema* sp. cell culture in BBM medium after 2 weeks

4.3.4 Effect of BBM Medium Formulation, pH and Photoperiod on *Alkalinema* sp. Cell Culture Chromaticity

According to Figure 4.29 and Table 4.27, the highest green intensity (a^*) value was recorded at pH 10 under a 6-hours photoperiod, reaching 47.05.

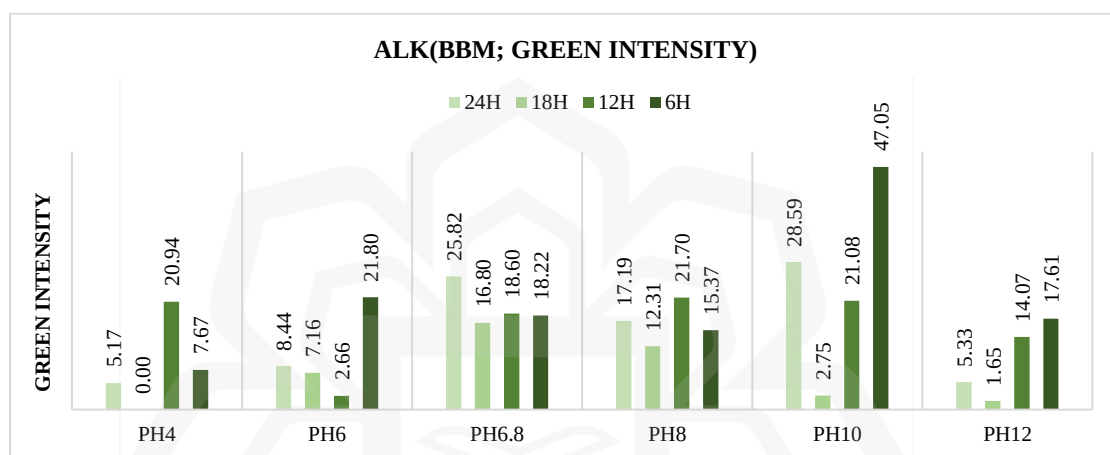


Figure 4.29 Effects of pH and photoperiod on green intensity values (a^*) of *Alkalinema* sp. cell culture in BBM medium after 2 weeks

Table 4.27 Green intensity (a^*) distribution of *Alkalinema* sp. cell culture in BBM medium at different pH and photoperiod after 2 weeks

Cynobacteria	Photoperiod	Peak pH (day)	a^*
<i>Alkalinema</i> sp.	24:0	pH 10	28.59
	18:6	pH 6.8	16.80
	12:12	pH 8	21.70
	6:18	pH 10	47.05

a^* , ranges from white (0) to green (100)

In contrast, the lowest green intensity occurred at pH 12 under an 18-hours photoperiod, with a value of 1.65. Among photoperiods, the 6-hours cycle consistently exhibited mid-range green intensity values, indicating it as the most favourable condition, while the 18-hours photoperiod generally resulted in the lowest values, particularly at pH 4.

For lightness (L^*), the highest value of 77.23 was observed at pH 8 under a 12-hours photoperiod, indicating reduced light absorption. Conversely, the lowest lightness value (98.77) was recorded at pH 6 under the same 12-hours photoperiod. Overall, shorter photoperiods, especially 12 hours, combined with moderately acidic to neutral pH levels (pH 6.8–8), appear to enhance light absorption efficiency in algae refer Figure 4.30 and Table 4.28.

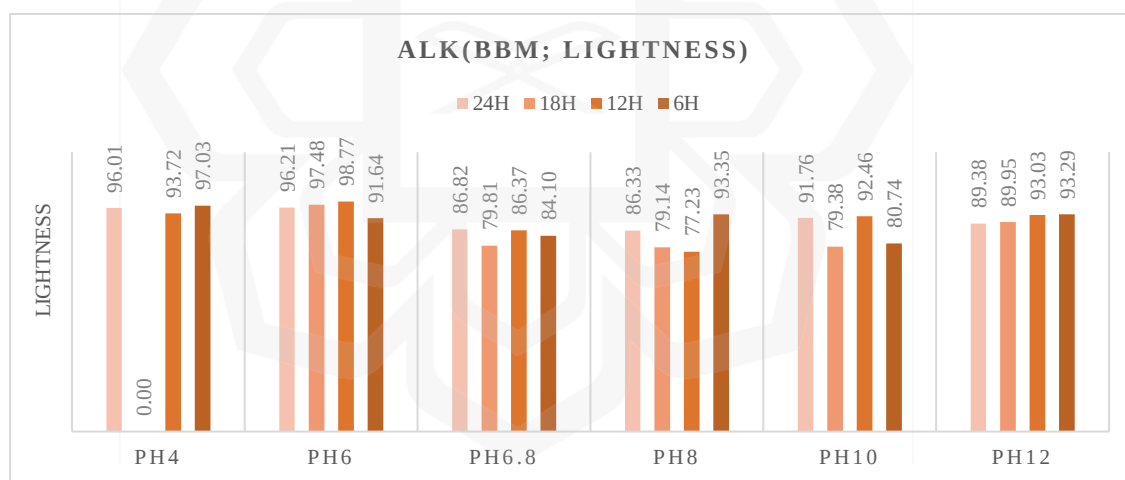


Figure 4.30 Effects of pH and photoperiod on lightness values (L^*) of *Alkalinema sp.* cell culture in BBM medium after 2 weeks

Table 4.28 Lightness (L*) values distribution of *Alkalinema* sp. cell culture in BBM medium at different pH and photoperiod after 2 weeks

Cynobacteria	Photoperiod	Peak pH	L*
<i>Alkalinema</i> sp.	24:0	pH 8	86.33
	18:6	pH 8	79.14
	12:12	pH 8	77.23
	6:18	pH 10	80.74
<i>L*</i> , ranges from black (0) to white (100)			

In conclusion, *Alkalinema* sp. achieved optimal growth, biomass production (0.76 g/L), and CO₂ sequestration (1.19 g/L CO₂e) at pH 8 under an 18-hours photoperiod. Balanced photoperiods of 12–18 hours and pH levels between 8 and 12 promoted maximum cell counts, chlorophyll production (4.01), and light intensity (77.32). While shorter photoperiods (6 hours) favored higher green intensity (47.05). Acidic pH levels (4–6) and shorter photoperiods consistently yielded the lowest values across all parameters. Moderate pH and balanced light cycles are therefore essential for maximising the performance of *Alkalinema* sp.

4.3.5 Effect of BG11 Medium Formulation, pH and Photoperiod on *Alkalinema* sp. Cell Culture Growth

Alkalinema sp. cell counts in BG11 medium experience a significant increase after Day 6, with peak growth observed by Day 14. Continuous light 24:0 and 18:6 promotes the fastest and highest cell growth, making it the most effective photoperiod for growth. In contrast, the 12:12 and 6:18 cycles with reduced light exposure result in noticeably slower growth rates and much lower peak cell counts refer to Figure 4.31.

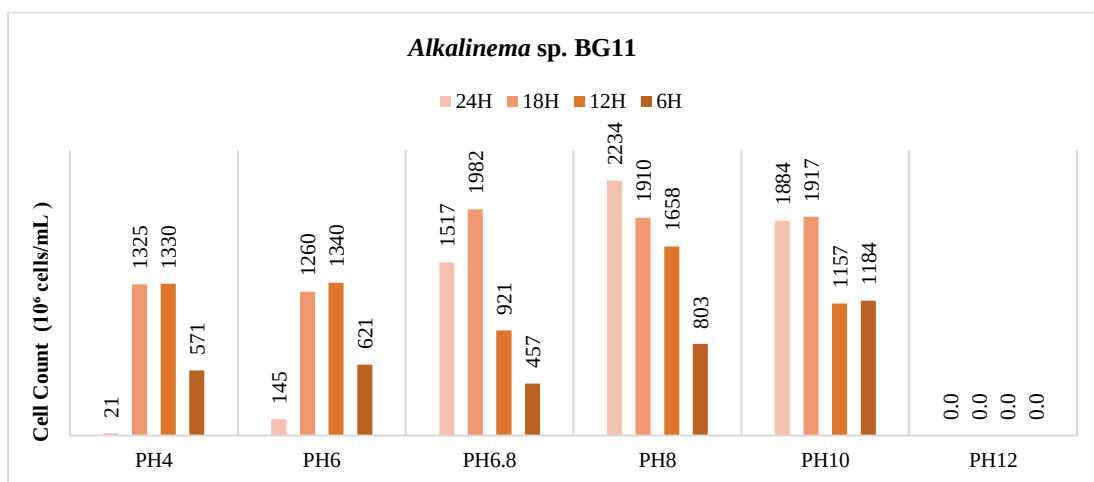


Figure 4.31 Cell counts of *Alkalinema sp.* cultured in BG11 medium at different pH and photoperiod after 2 weeks

Table 4.29 The optimum cell counts distribution of *Alkalinema sp.* cultured in BG11 medium at different pH and photoperiod after 2 weeks

Cynobacteria	Photoperiod	Peak pH	Cell Counts (x10 ⁶ mL ⁻¹)
<i>Alkalinema sp.</i>	24:0	pH 8	2234
	18:6	pH 10	1917
	12:12	pH 10	1658
	6:18	pH 10	1184

The study revealed that the highest cell counts occurred under BG11 medium at a 24-hours photoperiod, with a peak of 2234×10^6 cells/mL at pH 8 as per showed in Table 4.29. Significant growth was also observed during the 18-hours photoperiod, reaching 1962×10^6 cells/mL at pH 6.8. In contrast, minimal growth was recorded at pH levels 4 and 6, where cell counts ranged between 21 to 145×10^6 cells/mL under the

24-hours photoperiod. Overall, the results indicate that longer photoperiods (18–24 hours) combined with mid-range pH levels (6.8–10) significantly promote growth.

Absorbance graphs at 750 nm in BG11 medium over 14 days indicate that growth trends are influenced by light exposure and pH conditions as exhibit in Figure 4.32. In the 24:0, 8:6 and 12:12 photoperiod, absorbance steadily increases across all pH levels, with the highest readings observed for all pH. The 6:18 photoperiod exhibits minimal absorbance increases, indicating limited growth under this light-dark cycle, regardless of pH.

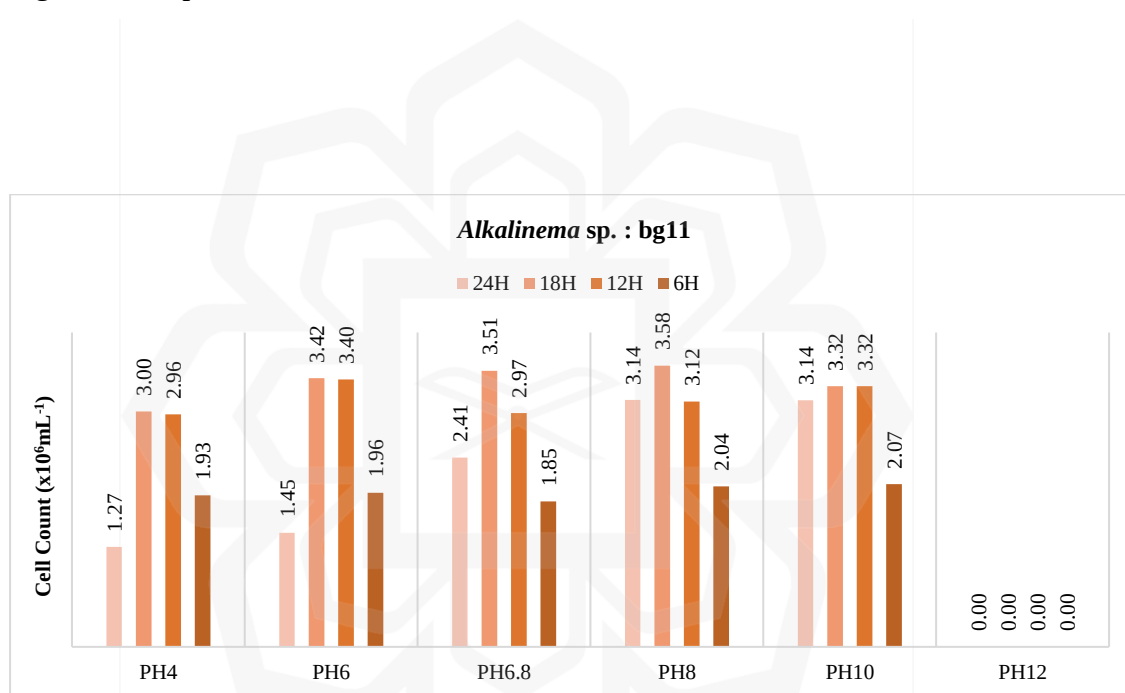


Figure 4.32 The effect of different photoperiod and pH on cell density measured at 750 nm (OD_{750}) of *Alkalinema* sp. cultured in BG11 medium after 2 weeks

Table 4.30 The optimum cell density distribution measured at (OD₇₅₀) of *Alkalinema* sp. in BG11 medium at different pH and photoperiod after 2 weeks

Cynobacteria	Photoperiod	Peak pH	Abs
<i>Alkalinema</i> sp.	24:0	pH 6	3.53
	18:6	pH 8	3.58
	12:12	pH 6	3.40
	6:18	pH 10	2.07

Absorbance values varied with photoperiod and pH, peaking at pH 8 under an 18-hours photoperiod on Day 14 (3.58) as per show in and Table 4.30. The lowest absorbance was observed at pH 6.8 under a 6-hours photoperiod on Day 14 (1.85). Extended photoperiods (18H, 24H) supported higher growth rates, while shorter durations (6H, 12H) limited growth. Generally, pH 6.8–10 favoured higher absorbance values.

4.3.6 Effect of BG11 Medium Formulation, pH and Photoperiod on *Alkalinema* sp. Biomass and Carbon Sequestration Rate (CSR)

Optimal biomass production (0.55 g/L) and CO₂ sequestration (0.86 g/L CO₂e) were achieved at pH 8 with a 24-hours photoperiod. Conversely, the lowest values were recorded at pH 6.8 under a 6-hours photoperiod (biomass: 0.04 g/L, CO₂ sequestration: 0.06 g/L CO₂e). While continuous light (24H) supported growth, the 18-hours photoperiod proved slightly more effective, with biomass and CO₂ sequestration peaking at pH 8 (0.52 g/L and 0.81 g/L CO₂e). Moderate conditions, such as pH 6 with an 18-hours photoperiod, also yielded notable results (biomass: 0.41 g/L, CO₂ sequestration: 0.64 g/L CO₂e). In contrast, shorter photoperiods restricted growth performance as per showed in Figure 4.33 and Table 4.31.

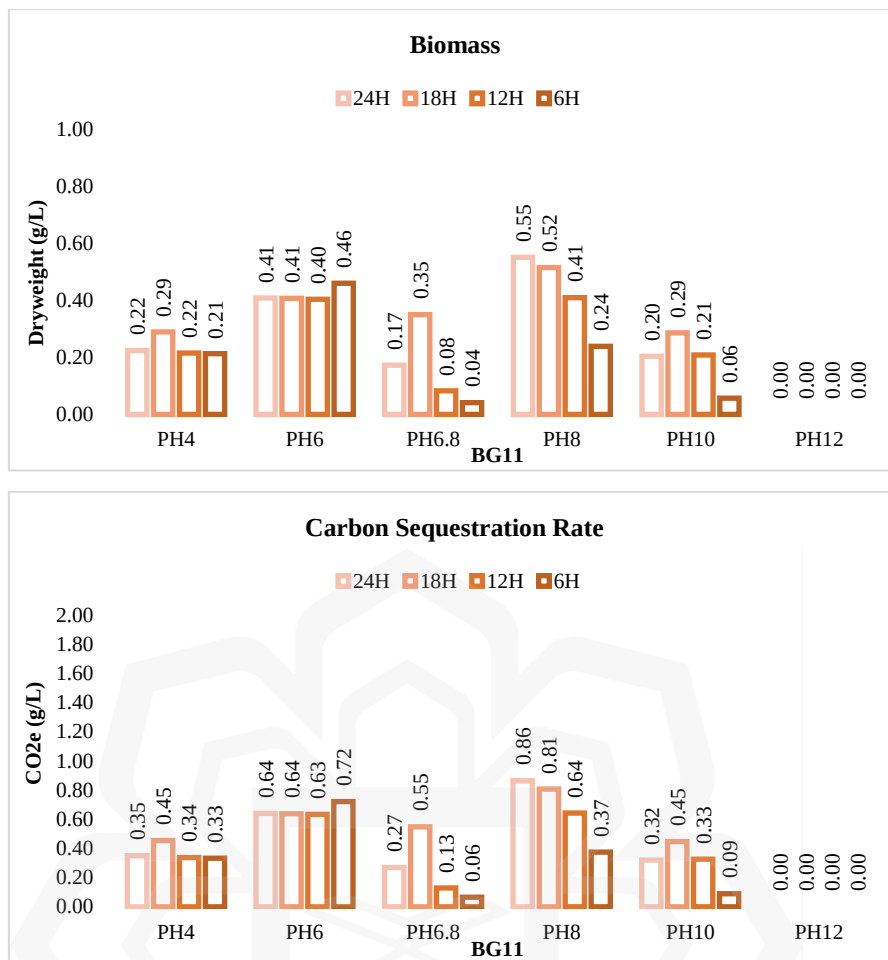


Figure 4.33 Biomass and CSR of of *Alkalinema* sp. cultured in BG11 medium at different pH and photoperiod after 2 weeks

Table 4.31 The optimum biomass and CSR distribution of *Alkalinema* sp. cultured in BG11 medium at different pH and photoperiod after 2 weeks

Cynobacteria	pH	Photoperiod	Biomass(g/L)	CSR (CO ₂ e)
<i>Alkalinema</i> sp.	pH 4	18:6	0.29	0.45
	pH 6	6:18	0.46	0.72
	pH 6.8	18:6	0.35	0.55
	pH 8	24:0	0.55	0.86
	pH 10	18:0	0.29	0.45

4.3.7 Effect of BG11 Medium Formulation, pH and Photoperiod on *Alkalinema* sp. Chlorophyll Content

Variations in the 600–700 nm wavelength range, as illustrated in Figure 4.34, reveal distinct patterns influenced by differences in chlorophyll content. These variations are significantly affected by light exposure and pH levels. Notably, the intensity of green colouration plays a crucial role in determining absorbance measurements. The graphs for light exposure ratios of 24:0 and 18:6 exhibit a prominent peak around 680 nm, particularly at pH levels 6, 8, and 10, indicating optimal chlorophyll activity in these conditions. In contrast, the graphs for 12:12 and 6:18 show consistently lower absorbance across all pH levels, suggesting reduced chlorophyll content or activity. These variations underline the combined effects of light and pH on chlorophyll absorbance properties.

Chlorophyll production peaked at pH 6 and 8 under 24-hours and 18-hours photoperiods, with absorbance values in the 660–666 nm range (4.01 ± 4.02) as shown in Figure 4.34. Under limited light (6H), chlorophyll production was minimal across all pH levels, ranging from (0.03 ± 0.27). Light-dark cycles of 24:0 and 18:6 significantly enhanced chlorophyll synthesis, while pH 6.8 and 10 resulted in the lowest levels.

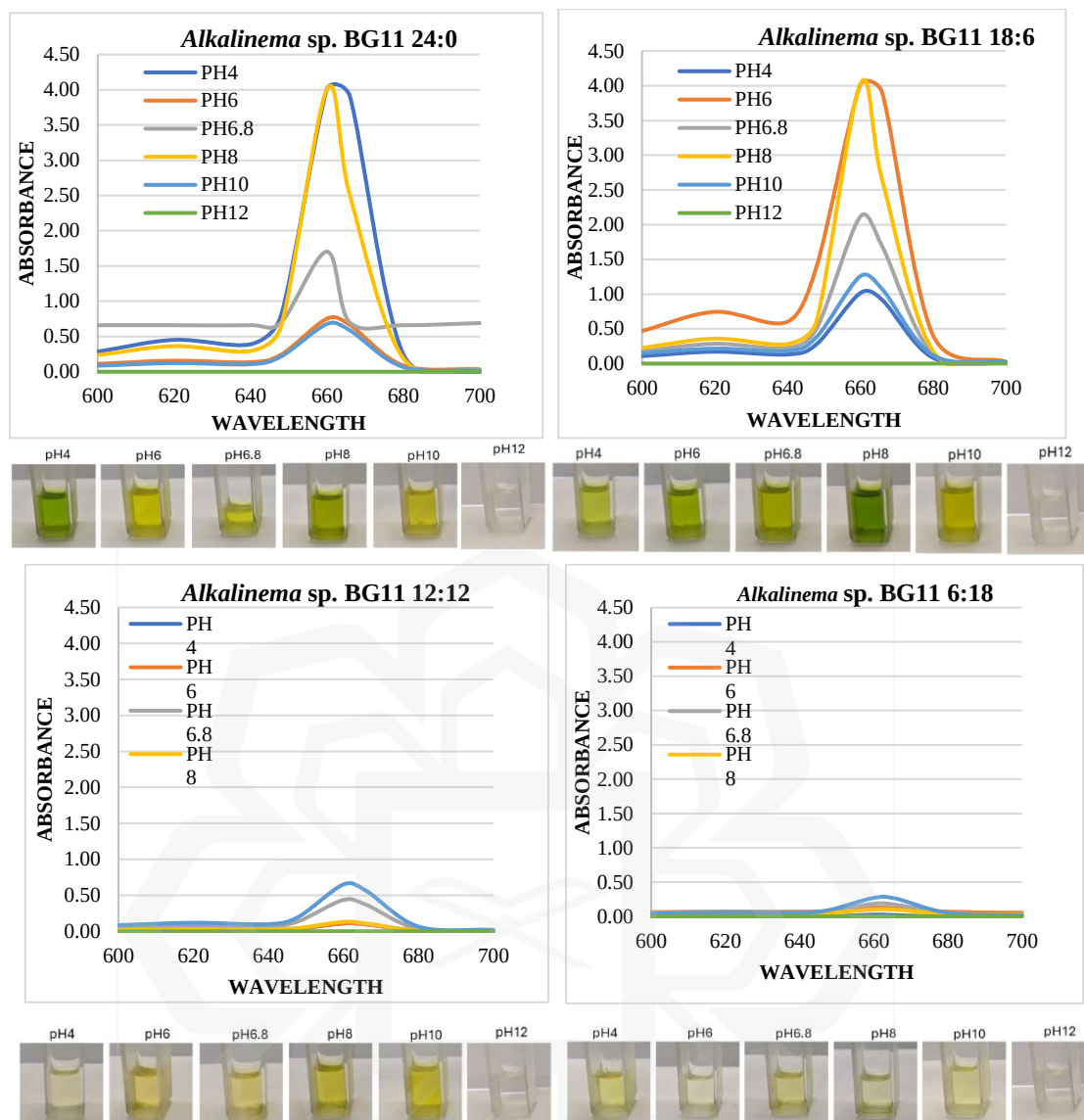


Figure 4.34 Effects of pH and photoperiod on chlorophyll content of *Alkalinema* sp. cell culture in BG11 medium after 2 weeks

4.3.8 Effect of BG11Medium Formulation, pH and Photoperiod on *Alkalinema* sp. Cell Culture Chromaticity

Green intensity reached its maximum at pH 4 under a 24-hours photoperiod (41.06) and its minimum at pH 6.8 under the same conditions (1.25) refer to Figure 4.35 and Table 4.32. The 18-hours photoperiod consistently produced moderate green intensity, whereas the 6-hours photoperiod resulted in the lowest values. Lightness was also at its

lowest at pH 6 under a 18-hours photoperiod (70.06) and highest at pH 10 under a 6- hours photoperiod (99.33). Longer photoperiods (24H, 18H) combined with pH 10 enhanced light absorption, whereas shorter photoperiods and acidic conditions decreased efficiency as shown in Figure 4.36 and Table 4.33.

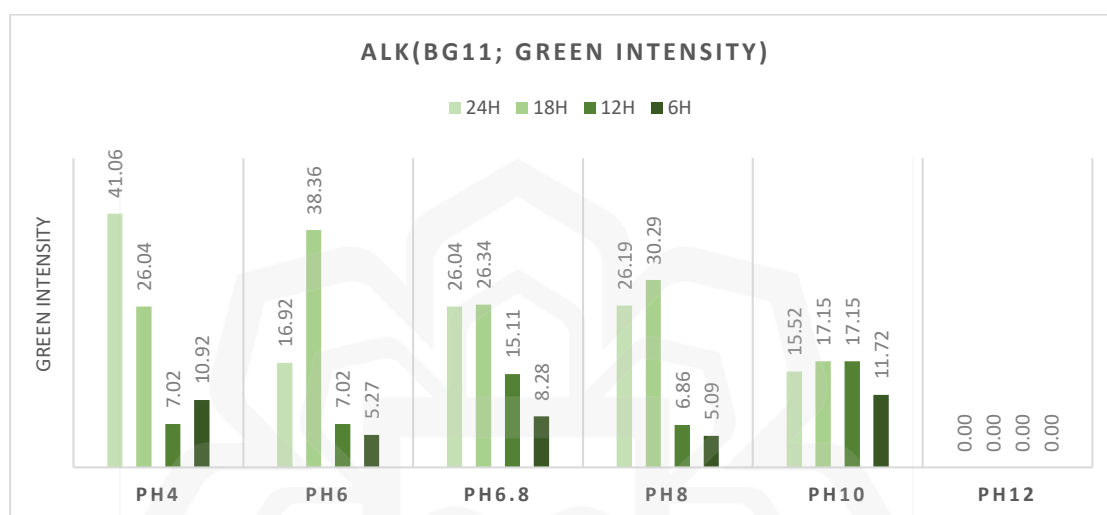


Figure 4.35 Effects of pH and photoperiod on green intensity values (a^*) of *Alkalinema* sp. cell culture in BG11 medium after 2 weeks

Table 4.32 Green intensity (a^*) distribution of *Alkalinema* sp. cell culture in BG11 medium at different pH and photoperiod after 2 weeks

Cynobacteria	Photoperiod	Peak pH	a^*
<i>Alkalinema</i> sp.	24:0	pH 4	41.06
	18:6	pH 6	38.36
	12:12	pH 10	17.15
	6:18	pH 10	11.72

a^* , ranges from white (0) to green (100)

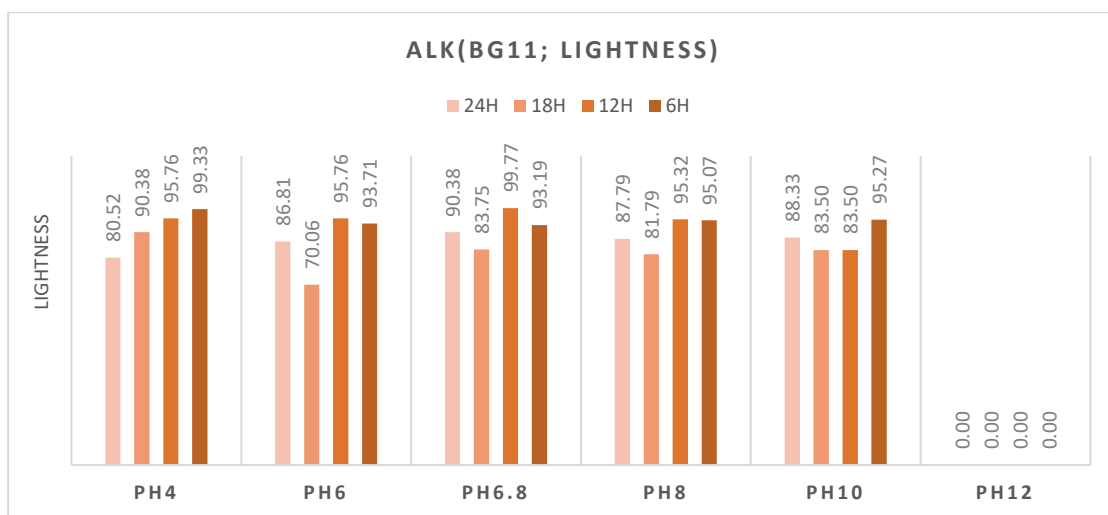


Figure 4.36 Effects of pH and photoperiod on lightness values (L^*) of *Alkalinema* sp. cell culture in BG11 medium after 2 weeks

Table 4.33 Lightness (L^*) values distribution of *Alkalinema* sp. cell culture in BG11 medium at different pH and photoperiod after 2 weeks

Cynobacteria	Photoperiod	Peak pH	L^*
<i>Alkalinema</i> sp.	24:0	pH 4	80.52
	18:6	pH 6	70.06
	12:12	pH 10	83.50
	6:18	pH 6.8	93.19

*L**, ranges from black (0) to white (100)

In summary, optimal growth conditions were observed at pH 8–10 with longer photoperiods (18H, 24H), resulting in higher cell counts, biomass (0.55 g/L), CO₂ sequestration (0.86 g/L CO₂e), and chlorophyll production (4.02) with lightness intensity (81.79). Absorbance peaked (3.58) at pH 8 under an 18-hours photoperiod.

Short photoperiods (6H) and acidic pH levels (4–6) significantly limited growth performance. Light-dark cycles of 24:0 and 18:6 further enhanced outcomes, while pH 6.8 consistently produced the lowest results across biomass, chlorophyll production, and light absorption.

4.3.9 Effect of BRISTOL Medium Formulation, pH and Photoperiod on *Alkalinema* sp. Cell Culture Growth

In Figure 4.37, the cell counts of *Alkalinema* sp. exhibit a significant increase after Day 6, reaching their peak by Day 14 in Bristol medium. The overall results indicate that growth is lower under a 24:0 light cycle, followed by the 18:6 light cycle. Although the 12:12 light cycle provides less light, it still supports substantial growth, albeit at a slightly slower rate. Conversely, the 6:18 light cycle results in visibly slower growth.

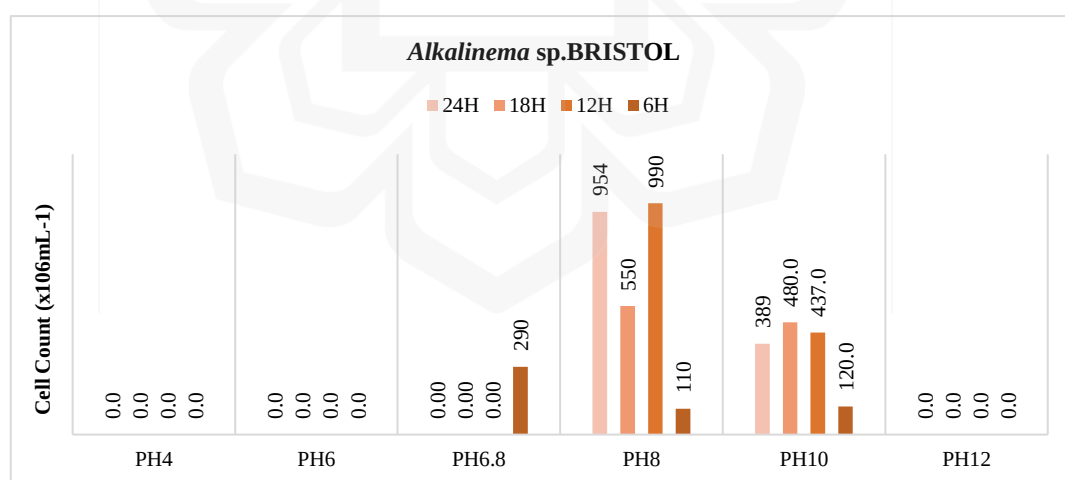


Figure 4.37 Cell counts of *Alkalinema* sp. cultured in BRISTOL medium at different pH and photoperiod after 2 weeks

Table 4.34 The optimum cell counts distribution of *Alkalinema sp.* cultured in BRISTOL medium at different pH and photoperiod after 2 weeks

Cynobacteria	Photoperiod	Peak pH	Cell Counts ($\times 10^6 \text{mL}^{-1}$)
<i>Alkalinema sp.</i>	24:0	pH 8	954
	18:6	pH 8	650
	12:12	pH. 8	990
	6:18	pH 6.8	290

The data collected using Bristol medium indicate that the highest cell counts was recorded under a 12-hours photoperiod at pH 8 (990×10^6 cells/mL), followed by the 24-hours photoperiod (954×10^6 cells/mL). The least cell growth was observed under a 6-hours photoperiod at the same pH 8 (110×10^6 cells/mL) as indicated in Table 4.34.

Continuous light exposure 24:0 produces the steady and slow growth conditions, followed by the 18:6 photoperiod with slightly reduced growth as per showed in Figure 4.38. The 12:12 photoperiod results in highest growth at peak of Ph 8, while the 6:18 photoperiod show the lowest absorbance, reflecting minimal growth due to limited light exposure.

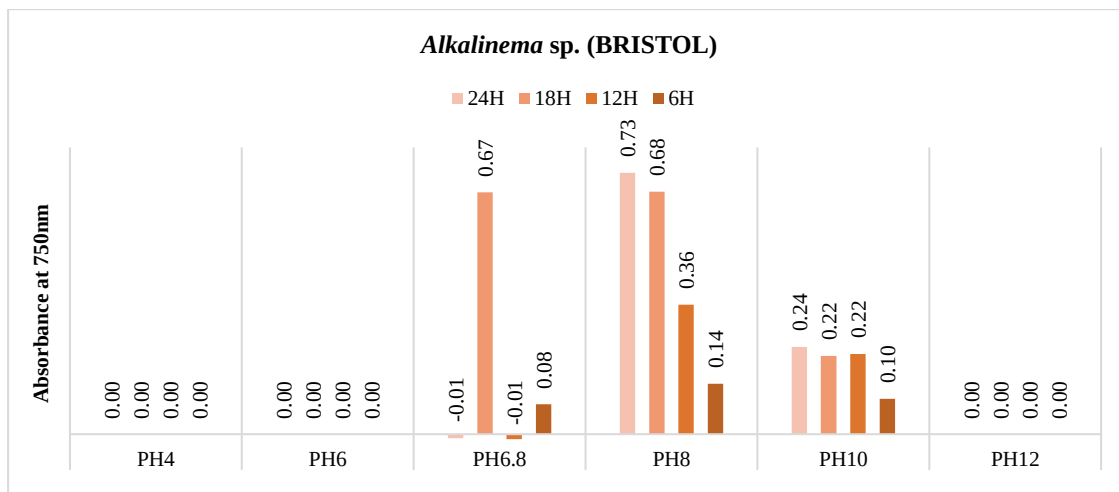


Figure 4.38 The effect of different photoperiod and pH on cell density measured at 750 nm (OD_{750}) of *Alkalinema sp.* cultured in BRISTOL medium after 2 weeks

Table 4.35 The optimum cell density distribution measured at (OD_{750}) of *Alkalinema sp.* in BRISTOL medium at different pH and photoperiod after 2 weeks

Cynobacteria	Photoperiod	Peak pH	Abs
<i>Alkalinema sp.</i>	24:0	pH 8	0.73
	18:6	pH 8	0.68
	12:12	pH 8	0.36
	6:18	pH 8	0.14

Absorbance results revealed that the highest value occurred at pH 8 with a 24-hours photoperiod on Day 14 (0.73), while the lowest absorbance was recorded at pH 6.8 with a 6-hours photoperiod (0.08). Overall, longer photoperiods (24 and 18 hours) and pH levels near neutral to slightly alkaline (8–10) supported better growths refer to Table 4.35.

4.3.10 Effect of BRISTOL Medium Formulation, pH and Photoperiod on *Alkalinema* sp. Biomass and Carbon Sequestration Rate (CSR)

Biomass and CO₂ sequestration reached their highest levels under a 6-hours photoperiod at pH 6.8, achieving values of (0.57 g/L) and (0.89 g/L CO₂e), respectively. Conversely, the lowest biomass (0.05 g/L) and CO₂ sequestration (0.07 g/L CO₂e) were observed at pH levels of 8 and 10 during the same 6-hours photoperiod as illustrated in Figure 4.39 and Table 4.36.

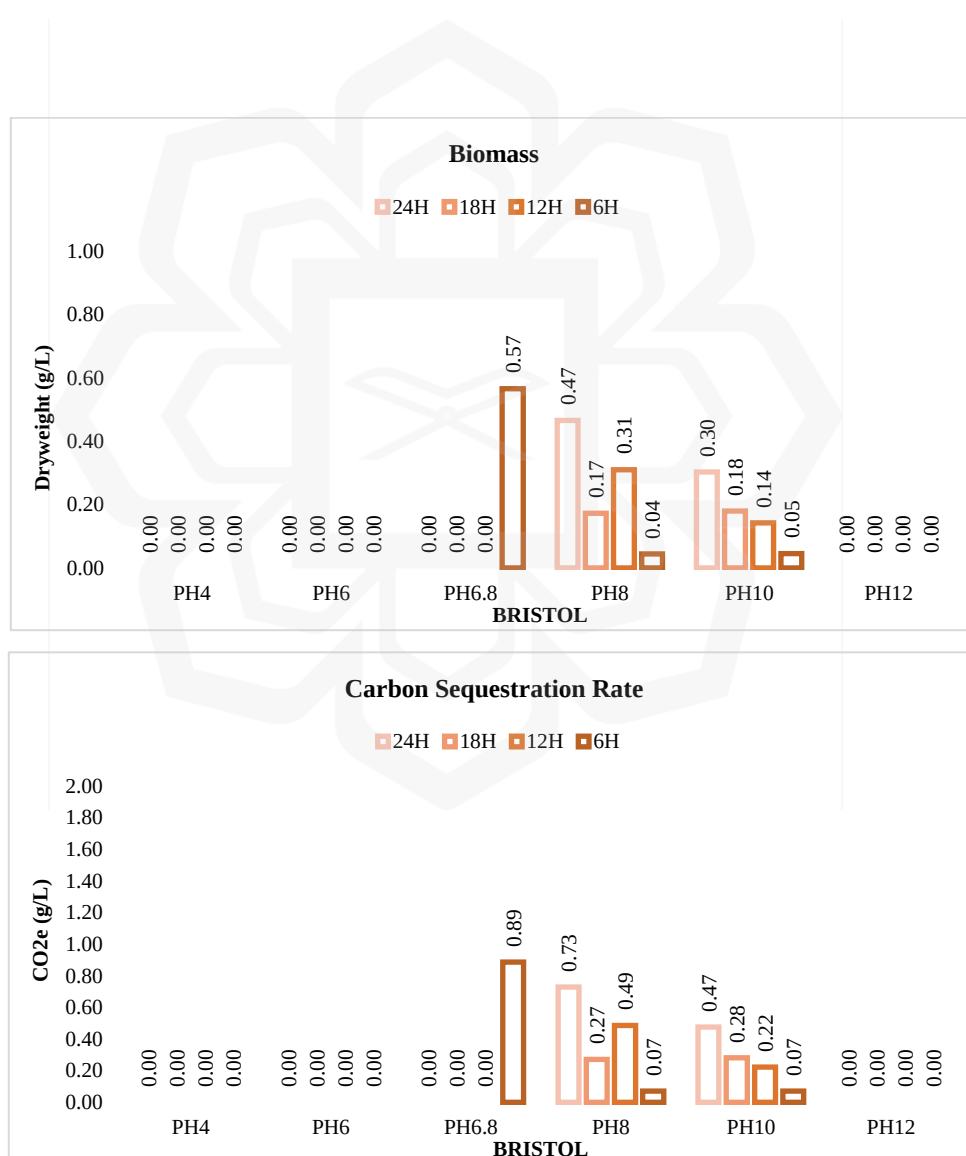


Figure 4.39 Biomass and CSR of *Alkalinema* sp. cultured in BRISTOL medium at different pH and photoperiod after 2 weeks

Table 4.36 The optimum biomass and CSR distribution of *Alkalinema* sp. cultured in BRISTOL medium at different pH and photoperiod after 2 weeks

Green Algae	pH	Photoperiod	Biomass (g/L)	CSR (CO ₂ e)
<i>Alkalinema</i> sp.	pH 6.8	6:18	0.57	0.89
	pH 8	24:0	0.47	0.73
	pH 10	24:0	0.30	0.47

4.3.11 Effect of BRISTOL Medium Formulation, pH and Photoperiod on *Alkalinema* sp. Chlorophyll Content

Figure 4.40 display distinct patterns in the 600–700 nm wavelength range, indicating variations in chlorophyll content influenced by light exposure and pH. The 24:0 and 18:6 and 6:18 graph show with lower absorbance at all pH levels. In contrast, 12:12, there were raising peak for pH 8 and 10. Optimal chlorophyll production was observed at pH 8 with a 12-hours photoperiod, achieving (1.51), while the lowest chlorophyll synthesis occurred at pH 6.8 with a 6-hours photoperiod (0.18). A balance photoperiod, such as 24 hours and 18 hours of light exposure, consistently enhance chlorophyll synthesis compared to shorter photoperiods and supported by high level of pH refer to Figure 4.40.

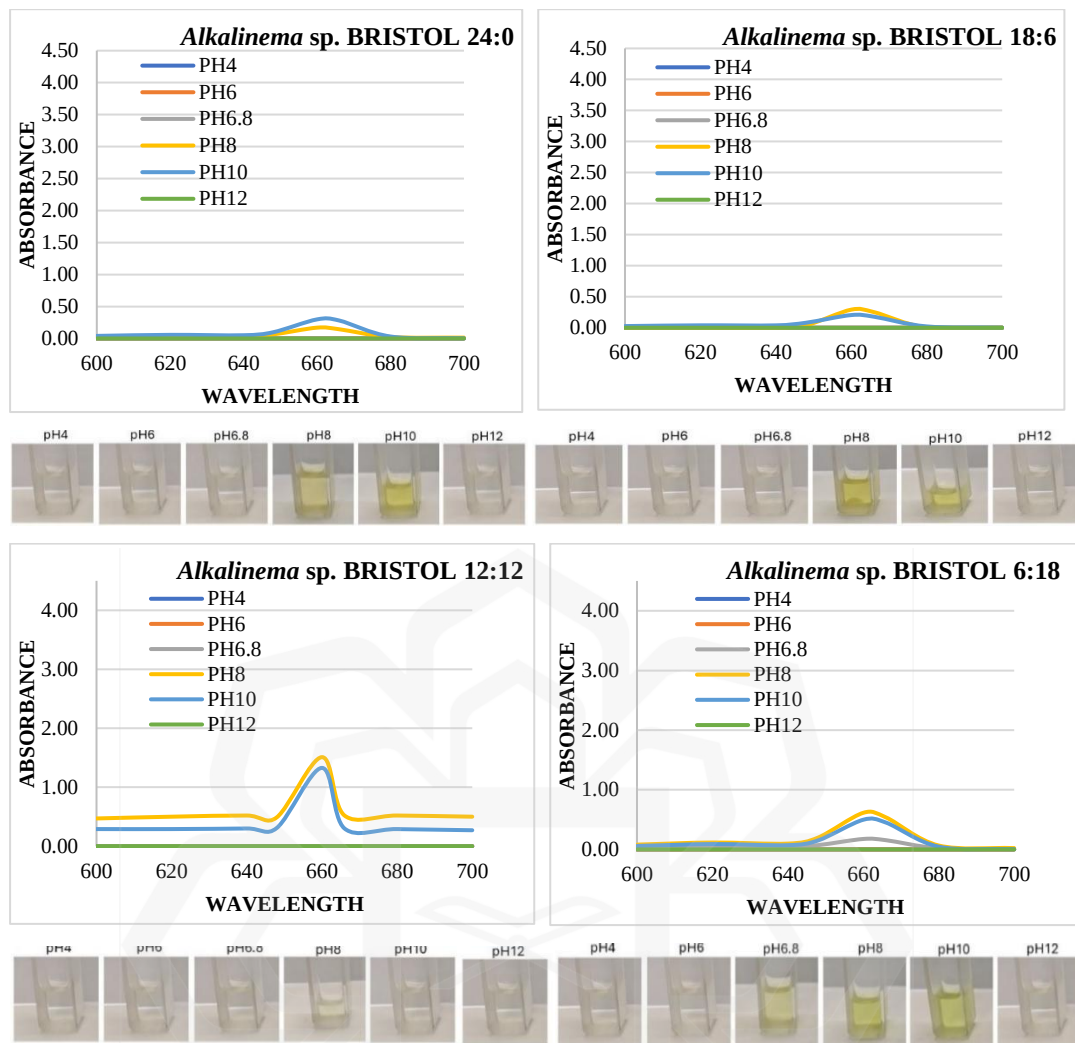


Figure 4.40 Effects of pH and photoperiod on chlorophyll content of *Alkalinema* sp. cell culture in BBM medium after 2 weeks

4.3.12 Effect of BRISTOL Medium Formulation, pH and Photoperiod on *Alkalinema* sp. Cell Culture Chromaticity

The highest green intensity (19.80) was recorded at pH 8 with a 6-hours photoperiod, whereas the lowest green intensity (0.06) occurred at pH 8 under a 12-hours photoperiod refer to Figure 4.41 and Table 4.37. Lightness values, which indicate light absorption efficiency, were lowest (26.16 and 29.54) at pH 8 and 10 under the 12-hours photoperiod. In contrast, the highest lightness value (100.19) as shown in Figure 4.42

and Table 4.38, suggesting reduced absorption, was observed at pH 8 with an 18-hours photoperiod.

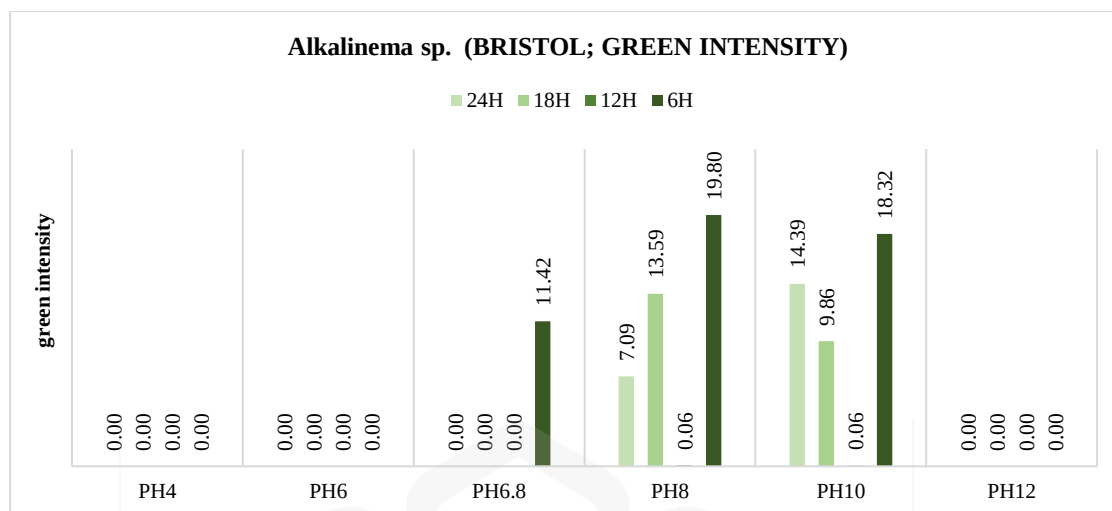


Figure 4.41 Effects of pH and photoperiod on green intensity values (a^*) of *Alkalinema* sp. cell culture in BRISTOL medium after 2 weeks

Table 4.37 Green intensity (a^*) distribution of *Alkalinema* sp. cell culture in BRISTOL medium at different pH and photoperiod after 2 weeks

Cynobacteria	Photoperiod	Peak pH	a^*
<i>Alkalinema</i> sp.	24:0	pH 10	14.39
	18:6	pH 8	13.59
	12:12	pH 8	0.06
	6:18	pH 8	19.80
<i>a*</i> , ranges from white (0) to green (100)			

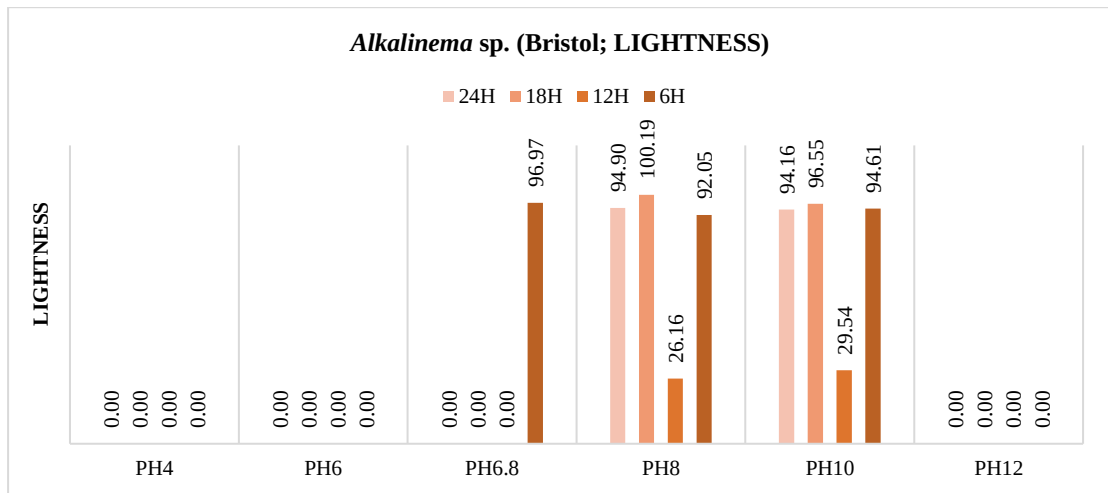


Figure 4.42 Effects of pH and photoperiod on lightness values (L^*) of *Alkalinema sp.* cell culture in BRISTOL medium after 2 weeks

Table 4.38 Lightness (L^*) values distribution of *Alkalinema sp.* cell culture in BRISTOL medium at different pH and photoperiod after 2 weeks

Cynobacteria	Photoperiod	Peak pH	L^*
<i>Alkalinema sp.</i>	24:0	pH 10	94.16
	18:6	pH 10	96.55
	12:12	pH 8	26.16
	6:18	pH 8	92.05
<i>L*</i> , ranges from black (0) to white (100)			

In summary, the study highlights optimal conditions for cell growth and chlorophyll absorbance at pH 8 with a 12-hours photoperiod, achieving $990 \times 10^6 \text{ mL}^{-1}$ and 1.51, respectively. Maximum absorbance (0.73) occurred under a 24-hours photoperiod at pH 8. Biomass (0.57 g/L) and CO_2 sequestration (0.89 g/L CO_2e) were highest at pH 6.8 with a 6-hours photoperiod. Overall, longer photoperiods (12–24

hours) and slightly alkaline pH levels (8–10) supported optimal growth and light absorption.

4.3.13 Effect of Chu Medium Formulation, pH and Photoperiod on *Alkalinema* sp. Cell Culture Growth

Alkalinema sp. cell counts lower increasing from Day 6 until by Day 14 in Chu medium. Overall result leads to the lower growth, under 24:0 light followed by the 18:6 light cycle as shown in Figure 4.43. Less light in the 12:12 and 6:18 which still supports moderate growth but at a slightly slower rate with slow growth visibly.

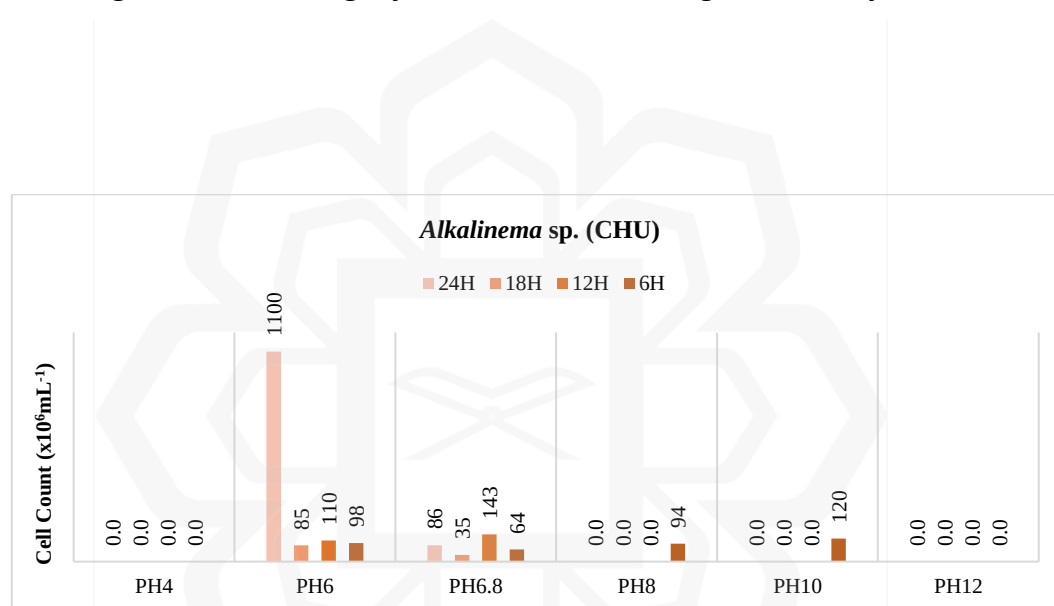


Figure 4.43 Cell counts of *Alkalinema* sp. cultured in Chu medium at different pH and photoperiod after 2 weeks

Cynobacteria	Photoperiod	Peak pH (day)	Cell Counts (x10 ⁶ mL ⁻¹)
<i>Alkalinema</i> sp	24:0	pH 6	1100
	18:6	pH 6	85

	12:12	pH 6.8	143
	6:18	pH 10	120

Table 4.39 The optimum cell counts distribution of *Alkalinema sp.* cultured in Chu medium at different pH and photoperiod after 2 weeks

The data collected using Chu medium reveals that the highest cell counts was recorded under a 24-hours photoperiod at pH 6, reaching 1100×10^6 cells/mL as per Table 4.39. On the other hand, the lowest cell growth occurred under an 18-hours photoperiod at pH 6.8, with only 35×10^6 cells/mL. Overall, most cell counts results did not show significant increases and the data remains limited except to pH 4 at 24-hours photoperiod refer to Figure 4.43.

The absorbance analysis of *Alkalinema sp.* cultured in CHU medium reveals that pH 6 consistently supports optimal growth across all photoperiods, followed by pH 6.8, while pH 10 and pH 12 exhibit same result at 6:18 photoperiod. Continuous light (24:0) and extended light exposure (18:6) result in higher absorbance values and faster growth compared to shorter light periods (12:12 and 6:18). Growth peaks are generally observed between days 6 to 10 under encouraging conditions.

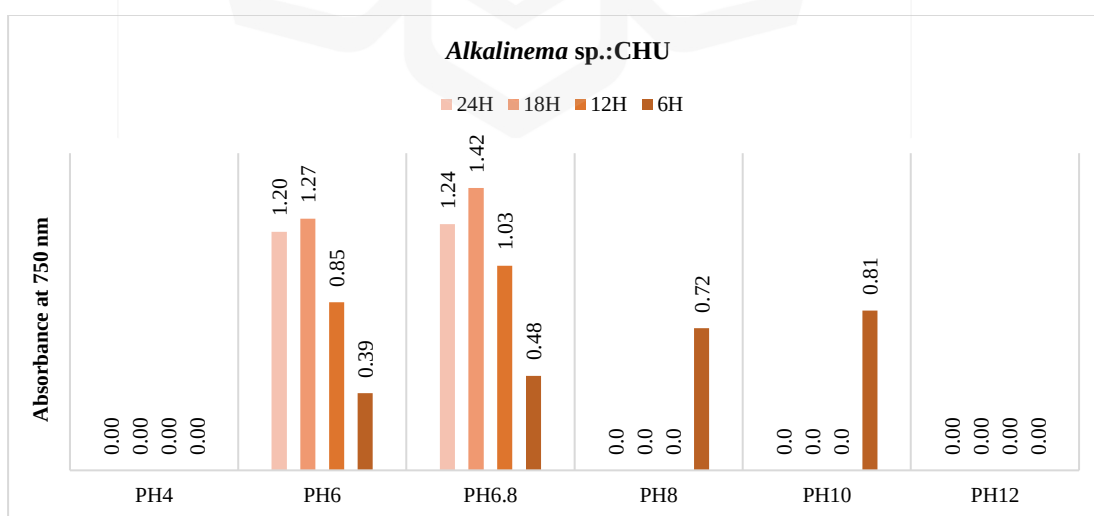


Figure 4.44 The effect of different photoperiod and pH on cell density measured at 750 nm (OD₇₅₀) of *Alkalinema sp.* cultured in Chu medium after 2 weeks

Table 4.40 The optimum cell density distribution measured at (OD₇₅₀) of *Alkalinema* sp. in Chu medium at different pH and photoperiod after 2 weeks

Cynobacteria	Photoperiod	Peak pH	Abs
<i>Alkalinema</i> sp	24:0	pH 10	1.41
	18:6	pH 10	2.06
	12:12	pH 10	1.71
	6:18	pH 10	0.81

The highest absorbance was observed at pH 10 with an 18-hours photoperiod on Day 14 (2.06), while the lowest absorbance occurred at pH 6 with a 6-hours photoperiod (0.39). Longer photoperiods (24 hours) and mid-range pH values (6-6.8) generally supported better growth refer to Figure 4.44 and Table 4.40.

4.3.14 Effect of Chu Medium Formulation, pH and Photoperiod on *Alkalinema* sp. Biomass and Carbon Sequestration Rate (CSR)

The highest biomass was achieved under a 24-hours photoperiod at pH 6, peaking at (0.38 g/L), with CO₂ sequestration reaching (0.59 g/L CO₂e) as per Figure 4.45. In contrast, the lowest biomass (0.01 g/L) and CO₂ sequestration (0.02 g/L CO₂e) were recorded under a 6-hours photoperiod across all pH levels (Table 4.41).

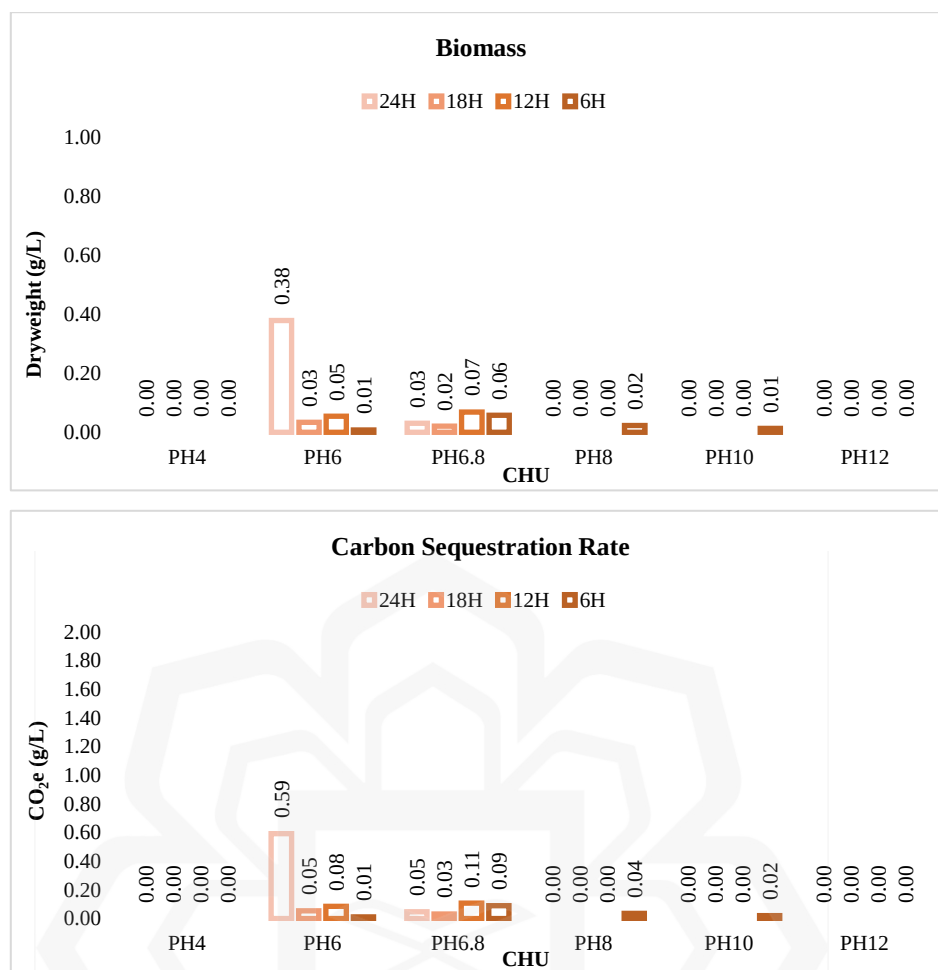


Figure 4.45 Biomass and CSR of of *Alkalinema* sp. cultured in Chu medium at different pH and photoperiod after 2 weeks

Table 4.41 The optimum biomass and CSR distribution of *Alkalinema* sp. cultured in Chu medium at different pH and photoperiod after 2 weeks

Green Algae	pH	Photoperiod	Biomass (g/L)	CSR (CO ₂ e)
<i>Alkalinema</i> sp .	pH 6	24:0	0.38	0.59
	pH 6.8	12:12	0.07	0.11
	pH 8	6:18	0.02	0.04
	pH 10	6:18	0.01	0.02

4.3.15 Effect of Chu Medium Formulation, pH and Photoperiod on *Alkalinema* sp. Chlorophyll Content

Distinct patterns in the 600–700 nm wavelength range, indicating variations in chlorophyll content influenced by light exposure and pH refer to Figure 4.46. The 24:0 and 12:12 and 18:6 graph show overall trend almost flat to the lowers accept pH 6.8. Followed by 6:18 graphs with lower absorbance result but still showing good peaking at pH 8. Chlorophyll production peaked at pH 8 under a 6-hours photoperiod, with a maximum value of (2.96), while the lowest value (0.02) was recorded at pH 6 with a 6-hours photoperiod.

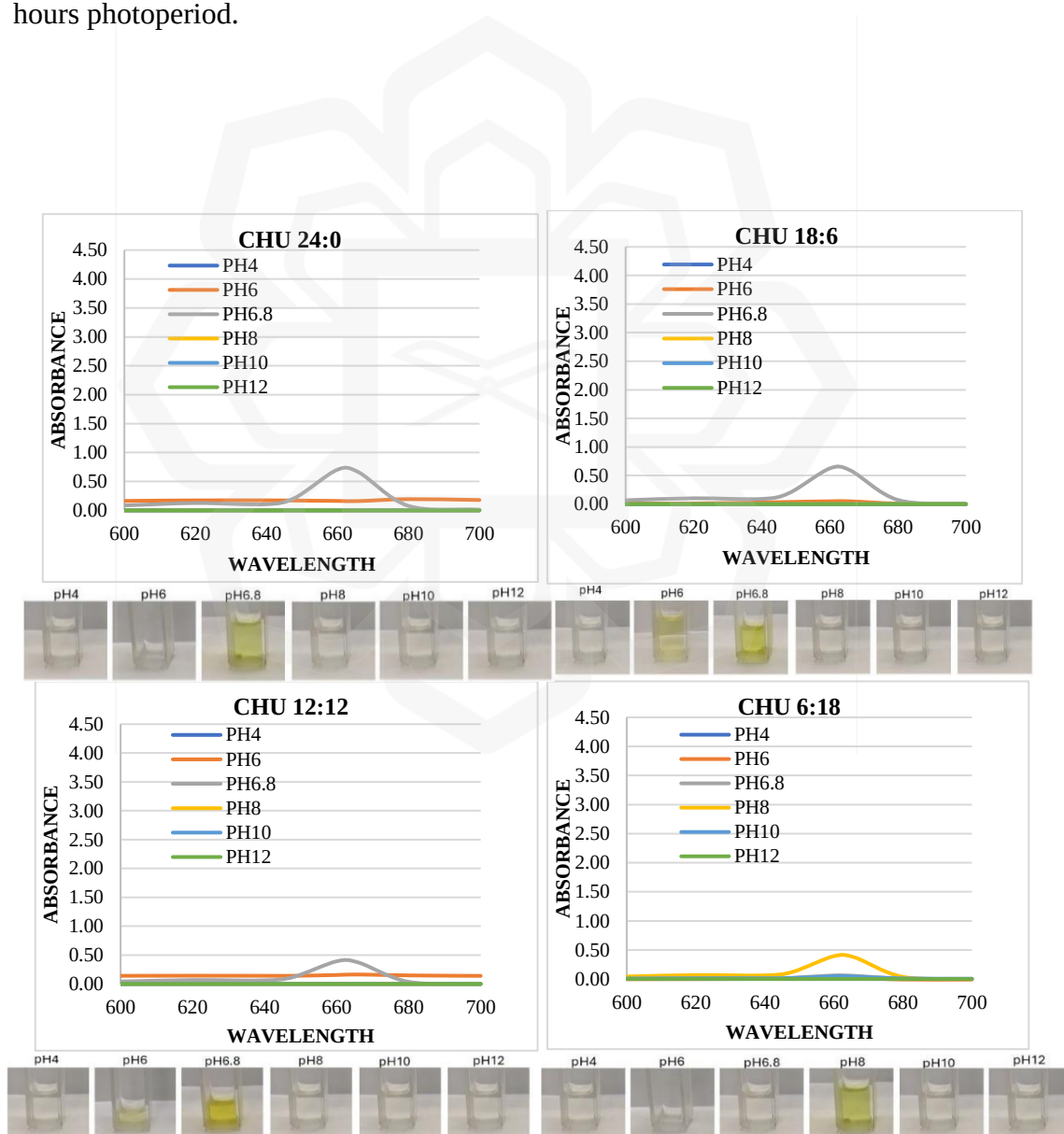


Figure 4.46 Effects of pH and photoperiod on chlorophyll content of *Alkalinema* sp. cell culture in Chu medium after 2 weeks

4.3.16 Effect of Chu Medium Formulation, pH and Photoperiod on *Alkalinema* sp. Cell Culture Chromaticity

Figure 4.47 and Table 4.42 show the highest green intensity (a^*) was observed at pH 6.8 with an 18-hours photoperiod (20.17), while the lowest green intensity occurred at pH 6.8 with a 6-hours photoperiod (1.85). Across all photoperiods, green intensity generally peaked at pH 6.8. Lightness (L^*) values, which reflect light absorption, were lowest at (91.33) under a 12-hours photoperiod at pH 6, indicating optimal light absorption. The highest lightness value (100.37), indicating reduced absorption, occurred at pH 6.8 with a 6-hours photoperiod refer to Figure 4.48 and Table 4.43.

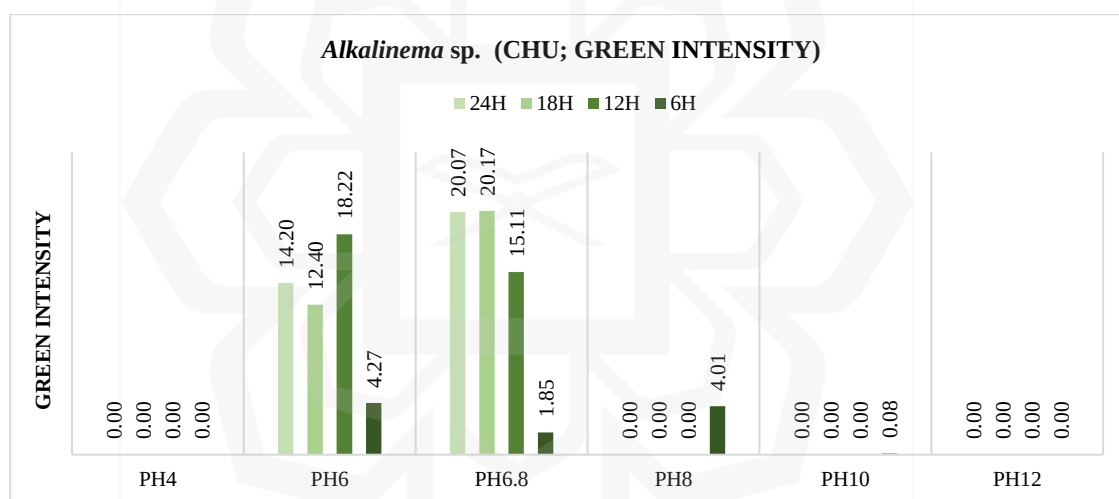


Figure 4.47 Effects of pH and photoperiod on green intensity values (a^*) of *Alkalinema* sp. cell culture in Chu medium after 2 weeks

Table 4.42 Green intensity (a^*) distribution of *Alkalinema sp.* cell culture in Chu medium at different pH and photoperiod after 2 weeks

Cynobacteria	Photoperiod	Peak pH	a^*
<i>Alkalinema sp.</i>	24:0	pH 6.8	20.07
	18:6	pH 6.8	20.17
	12:12	pH 6.8	16.27
	6:18	pH 6	4.27

a^* , ranges from white (0) to green (100)

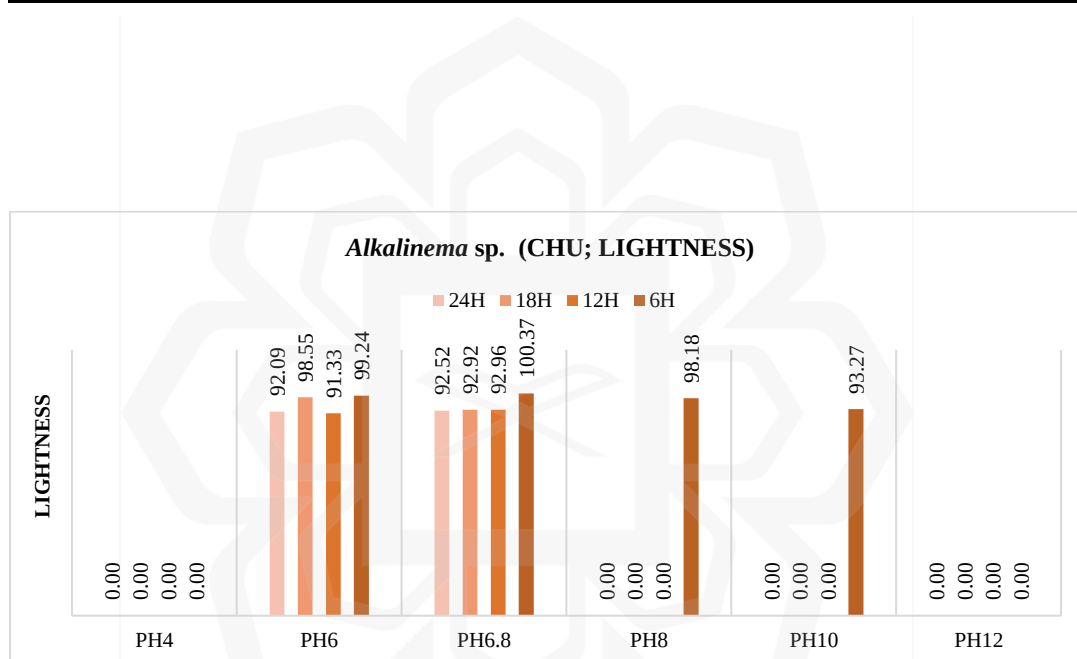


Figure 4.48 Effects of pH and photoperiod on lightness values (L^*) of *Alkalinema sp.* cell culture in Chu medium after 2 weeks

Table 4.43 Lightness (L*) values distribution of *Alkalinema sp.* cell culture in Chu medium at different pH and photoperiod after 2 weeks

Cynobacteria	Photoperiod	Peak pH	L*
<i>Alkalinema sp.</i>	24:0	pH 6	92.09
	18:6	pH 6.8	92.92
	12:12	pH 6	91.33
	6:18	pH 10	93.27
<i>L*, ranges from black (0) to white (100)</i>			

In conclusion, the study highlights that the highest cell growth, biomass (0.38 g/L), and CO₂ sequestration (0.59 g/L CO₂e) for *Alkalinema sp.* cell culture growth in CHU medium were achieved at pH 6 with a 24-hours photoperiod, while minimal growth occurred at pH 6.8 with a 6-hours photoperiod. The maximum absorbance (2.06) was recorded at pH 10 with an 18-hours photoperiod. Chlorophyll production peaked at pH 8 with a 6-hours photoperiod (2.96), and lightness intensity was highest at pH 6.8 (91.30). Optimal light absorption occurred at pH 6 under a 12-hours photoperiod. These findings emphasise the significant influence of pH and photoperiod on growth parameters.

4.3.17 Multivariate Data Analysis

4.3.17.1 Multivariate analysis

The KMO values for the 288 datasets yielded a score of 0.792 (Table 4.44), indicating that the dataset falls within the "good" category and is suitable for PCA analysis.

Bartlett's Test of Sphericity was conducted to verify that the R-matrix is not equivalent to the identity matrix. The *p*-value for the *Alkalinema* sp. datasets on cell growth, carbon sequestration, and chromaticity showed highly significant differences at 0.0001.

Table 4.44 Kaiser-Meyer-Olkin and Bartlett's test for *Alkalinema* sp. Cell Culture Growth, Carbon Sequestration, and Chromaticity

Kaiser-Meyer-Olkin Measure of Sampling Adequacy		0.792
Bartlett's Test of Sphericity	Chi-square (Observed value)	4817.74
	DF	45
	<i>p</i> -value (Two-tailed)	< 0.0001

Correlation coefficient matrix (r^2) in Table 4.45 established a very strong positive correlation among biomass and CSR ($r^2 = 1$). High positive correlations were observed in lightness, green intensity, Chlorophyll content, cell density, biomass and CSR ($r^2 = 0.731$ to 0.797).

Table 4.45 Correlation coefficient matrix for the *Alkalinema* sp. Cell Growth, Carbon Sequestration, and Chromaticity

Variables	L*	a*	Chl	CCt	CDt	BM	CSR	PH	PHPD
L*	1								
a*	0.797	1							
Chl	0.518	0.792	1						
CCt	0.475	0.431	0.510	1					
CDt	0.639	0.613	0.601	0.765	1				
BM	0.731	0.619	0.596	0.679	0.671	1			
CSR	0.731	0.618	0.596	0.679	0.671	1.000	1		
pH	-0.052	-0.049	-0.019	0.091	-0.029	-0.039	-0.039	1	
PHPD	-0.052	0.024	0.106	0.179	0.112	0.085	0.085	0.000	1
Day	0.635	0.528	0.374	0.386	0.494	0.487	0.487	0.000	0.000

Values in bold are different from 0 with a significance level $\alpha=0.01$

4.3.17.2 Principal Component Analysis (PCA)

The PCA analysis revealed two principal components (PCs) encompassing the 10 variables, which together accounted for a cumulative variability of 64.57 %. The eigenvalues for PC1 and PC2 were 5.3 and 1.1, respectively, as shown in Table 4.46. In principle, variables far away from the axes PC1 and PC2 had a strong factor loading (FL). Referring to the Table 5.24, L*, a*, Chl, CDt, CCt, BM, CSR and PHPD had strong FL ($FL > 0.75$) whereas Day had moderate FL ($0.500 < FL < 0.749$) and pH had a weak FL ($FL < 0.499$).

Table 4.46 The principal components factor loading and eigenvalues of the correlation matrix for *Alkalinema* sp. Cell Growth, Carbon Sequestration, and Chromaticity

Variables	PC1	PC2
L* (Lightness)	0.850	-0.278
a* (green intensity)	0.828	-0.211
Chl (Chlorophyll content)	0.765	0.023
CCt (Cell counts)	0.758	0.365
CDt (Cell Density)	0.839	0.130
BM (Biomass)	0.899	0.047
CSR	0.899	0.047
pH	-0.029	0.400
PHPD (Photoperiod)	0.101	0.799
Day	0.657	-0.224
Eigenvalue	5.332	1.125
Variability (%)	53.324	11.247
Cumulative (%)	53.324	64.571

The first principal component (PC1) explained 53.32% of the total variance, with strong factor loadings observed for L*, a*, Chl, CDt, CCt, BM and CSR. In contrast, the second principal component (F2) accounted for 11.25% of the total variance, with PHPD identified as the only variable showing a strong association.

4.3.18 Summary of Results

1. There is a strong relationship between the cell growth, biomass, carbon sequestration, lightness and green intensity of the *Alkalinema sp.* with time exposure in response to light and dark condition
2. BG11 medium is the optimal choice for cultivating *Alkalinema sp.*, achieving the highest overall growth, biomass production, CO₂ sequestration, and chlorophyll content.
3. *Alkalinema sp.* at pH 6 with an 18-hours photoperiod is recommended as the optimal condition for optimal cell growth and application.
4. BBM medium is a strong alternative for applications focused on carbon capture, with the highest CO₂ sequestration (1.19 g/L) and robust biomass production (0.76 g/L) under photoperiod 18:6 at pH 8.
5. Study highlights the sensitivity of *Alkalinema sp.* to environmental conditions, with shorter photoperiods and neutral to slightly alkaline pH levels supporting better chromatic responses.
6. The findings revealed strong correlations among variables with high positive relationships, including lightness, green intensity, Chlorophyll content, cell density, biomass and CSR, which are key parameters for the application algae model system.

4.4 CARTERIA RADIOSA

4.4.1 Effect of BBM Medium Formulation, pH and Photoperiod on *C. radiosa* Cell Culture Growth

Cell counts data for *C. radiosa* cultured in BBM medium over a 14-day period. Under the 24:0 photoperiod, cell counts consistently increased across all pH levels, with optimal growth observed at pH 6.8 and 8 as display in Figure 4.49. Similarly, the 18:6 photoperiod showed comparable trends, with higher cell counts and notable growth at

pH 10. For the 12:12 photoperiod, growth rates were moderate, with the most growth observed around pH 8 and 10. In contrast, the 6:18 photoperiod resulted in significantly lower cell counts, indicating limited growth across all pH levels with minimal variation between conditions.

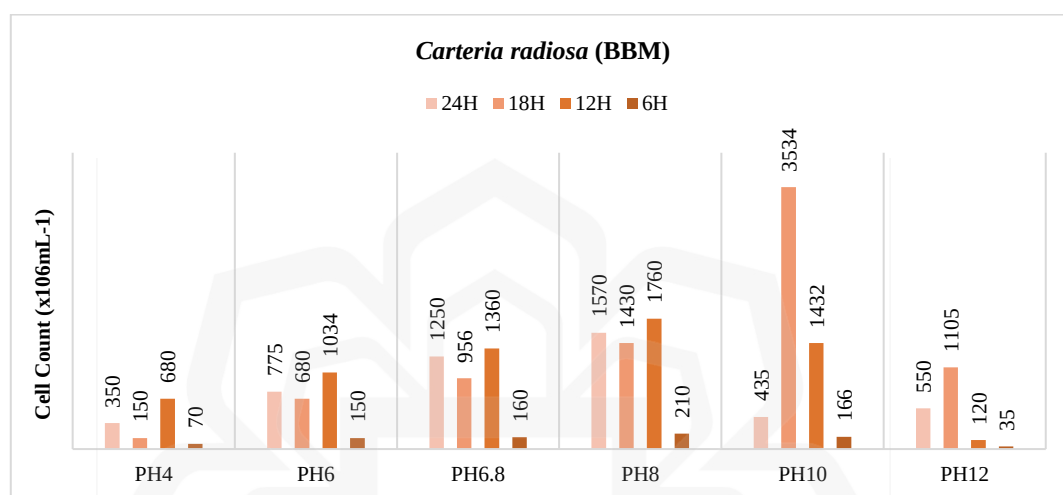


Figure 4.49 Cell counts of *C. radiosa* cultured in BBM medium at different pH and photoperiod after 2 weeks

Table 4.47 The optimum cell counts distribution of *C. radiosa* cultured in BBM medium at different pH and photoperiod after 2 weeks

Green Algae	Photoperiod	Peak pH	Cell Counts (x10 ⁶ mL ⁻¹)
<i>C. radiosa</i>	24:0	pH 8	1570
	18:6	pH 10	3534
	12:12	pH 8	1760
	6:18	pH 8	210

The maximum cell counts in BBM medium with an 18-hours photoperiod were shown in Figure 4.49 and Table 4.47, peaking at 5768×10^6 cells/mL at pH 10. During the same 12-hours photoperiod, significant growth was also seen at pH 8, reaching 1760×10^6 cells/mL. In contrast, the lowest growth was recorded under a 6-hours photoperiod at pH 12, with only 35 cells counted. Overall, the growth trends indicate that photoperiods of 18–24 hours, coupled with pH levels between 8 and 10, have a strong positive impact on growth, particularly within more light exposure.

Absorbance graphs at 750 nm in BBM media during a 14-day period are shown in Figure 4.50, which show how pH and light exposure impact growth trajectories. Absorbance continuously rises at all pH levels during photoperiods of 24:0, 18:6, and 12:12, with the greatest values seen at pH 8 and 10. In contrast, the 6:18 photoperiod show a moderate increase in absorbance, with pH 8 and 10 still promoting the most significant growth, although less pronounced than in the other photoperiods. These findings highlight the critical role of continuous light exposure and an optimal pH range of 8 to 10 in enhancing *C. radiosa* growth.

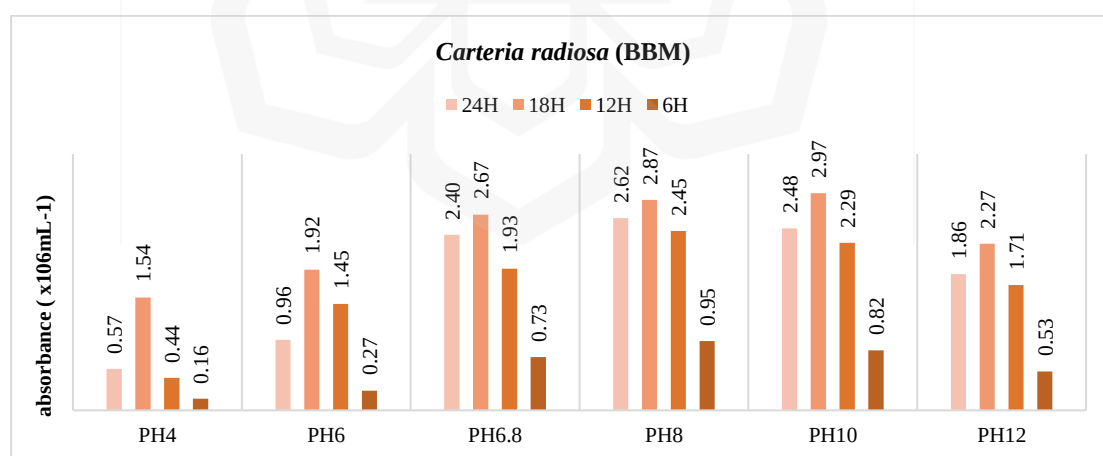


Figure 4.50 The effect of different photoperiod and pH on cell density measured at 750 nm (OD_{750}) of *C. radiosa* cultured in BBM medium after 2 weeks

Table 4.48 The optimum cell density distribution measured at (OD₇₅₀) of *C. radiosa* in BBM medium at different pH and photoperiod after 2 weeks

Green Algae	Photoperiod	Peak pH	Abs
<i>C. radiosa</i>	24:0	pH 8	2.62
	18:6	pH 10	2.97
	12:12	pH 8	2.45
	6:18	pH 8	0.95

The maximum absorbance for cell growth was recorded at pH 10 with an 18-hours photoperiod (2.97), as shown in Table 4.48. In comparison, the 6-hours photoperiod showed its peak growth at pH 4 (0.16) but also recorded the lowest absorbance at pH 6 (0.27). Overall, balanced photoperiods of 12 and 18 hours consistently supported higher absorbance values.

4.4.2 Effect of BBM Medium Formulation, pH and Photoperiod on *C. radiosa* Biomass and Carbon Sequestration Rate (CSR)

The optimal biomass production (0.75 g/L) and CO₂ sequestration (1.18 g/L CO₂e) occurred at pH 8 under a 24-hours photoperiod. Similarly, 12-hours photoperiod also supported significant growth, yielding biomass of (0.64 g/L) and CO₂ sequestration of (0.99 g/L CO₂e). In contrast, pH levels of 6 and 10, combined with shorter light cycles of 6, resulted in the lowest values, with biomass at (0.02 g/L) and CO₂ sequestration at (0.04 g/L CO₂e) refer to Figure 4.51 and Table 4.49. These findings highlight that moderate conditions particularly pH 8 and a balanced light cycle will maximise both growth and carbon sequestration.

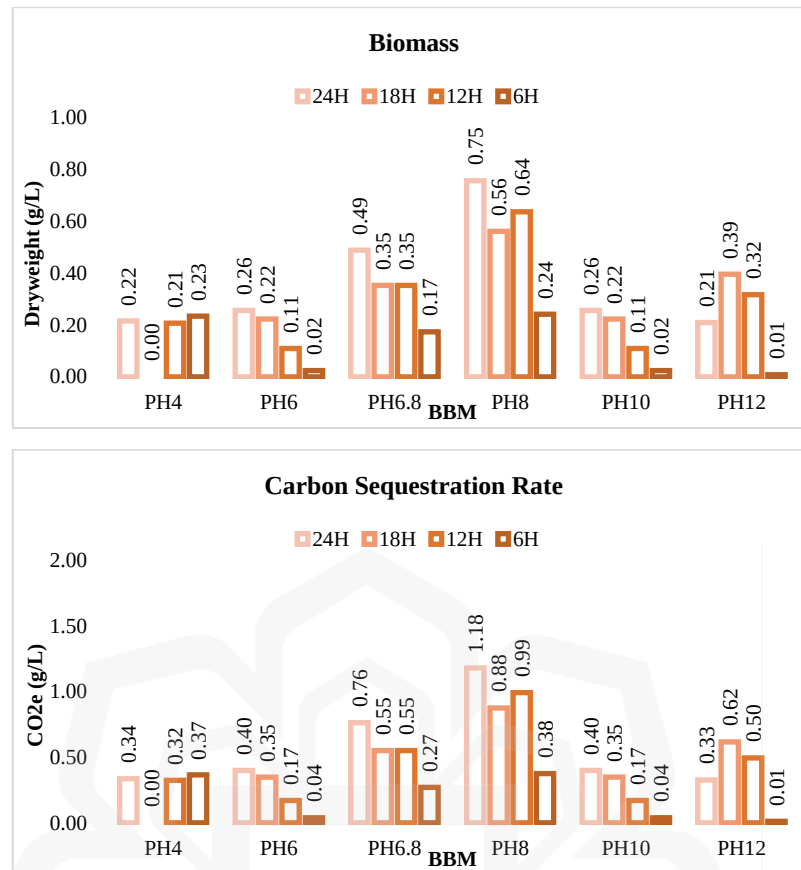


Figure 4.51 Biomass and CSR of of *C. radiososa* cultured in BBM medium at different pH and photoperiod after 2 weeks

Table 4.49 The optimum biomass and CSR distribution of *C. radiososa* cultured in BBM medium at different pH and photoperiod after 2 weeks

Green Algae	pH	Photoperiod	Biomass (g/L)	CSR (CO ₂ e)
<i>C. radiososa</i> .	pH 4 (6H)	6:18	0.23	0.37
	pH 6 (24H)	24:0	0.26	0.40
	pH 6.8 (24H)	24:0	0.49	0.76
	pH 8 (24H)	24:0	0.75	1.18
	pH 10 (24H)	24:0	0.26	0.40
	pH 12 (18H)	18:6	0.39	0.62

4.4.3 Effect of BBM Medium Formulation, pH and Photoperiod on *C. radiosa* Chlorophyll Content

Different patterns in the 600–700 nm wavelength range are shown in Figure 4.52, which show how light exposure and pH levels affect the amount of chlorophyll. Around 680 nm at pH 10, a noticeable peak can be seen in the 24:0 graph, with lower absorbance at more extreme pH values. Similarly, the 18:6, 12:12, and 6:18 graphs show high absorbance near 680 nm, particularly at pH levels of 6.8, 8, and 10, indicating adaptability to moderate light-dark cycles. Additionally, Figure 4.4.4 illustrates a direct correlation between the intensity of green colouration and absorbance values, suggesting that greener samples generally exhibit higher chlorophyll content and greater light absorption efficiency.

The absorbance data indicated that chlorophyll production was highest at pH 10, with an absorbance value of (3.95), slightly better value of (3.94) observed under pH 10 conditions with 24-hours and 6-hours photoperiods as showed in Figure 4.52. In contrast, acidic environments demonstrated a marked decline in chlorophyll production. At pH levels 4 and 6, the absorbance values dropped significantly to (0.14 and 0.13), respectively, across all photoperiod durations. These findings highlight the critical role of maintaining optimal pH conditions for maximising chlorophyll synthesis. Alkaline conditions appear to provide a good environment for chlorophyll activity, while acidic settings inhibit its production. Furthermore, the study emphasises the synergistic effect of moderate light-dark cycles in promoting chlorophyll efficiency, suggesting that both pH balance and controlled photoperiods are essential for enhancing photosynthetic performance.

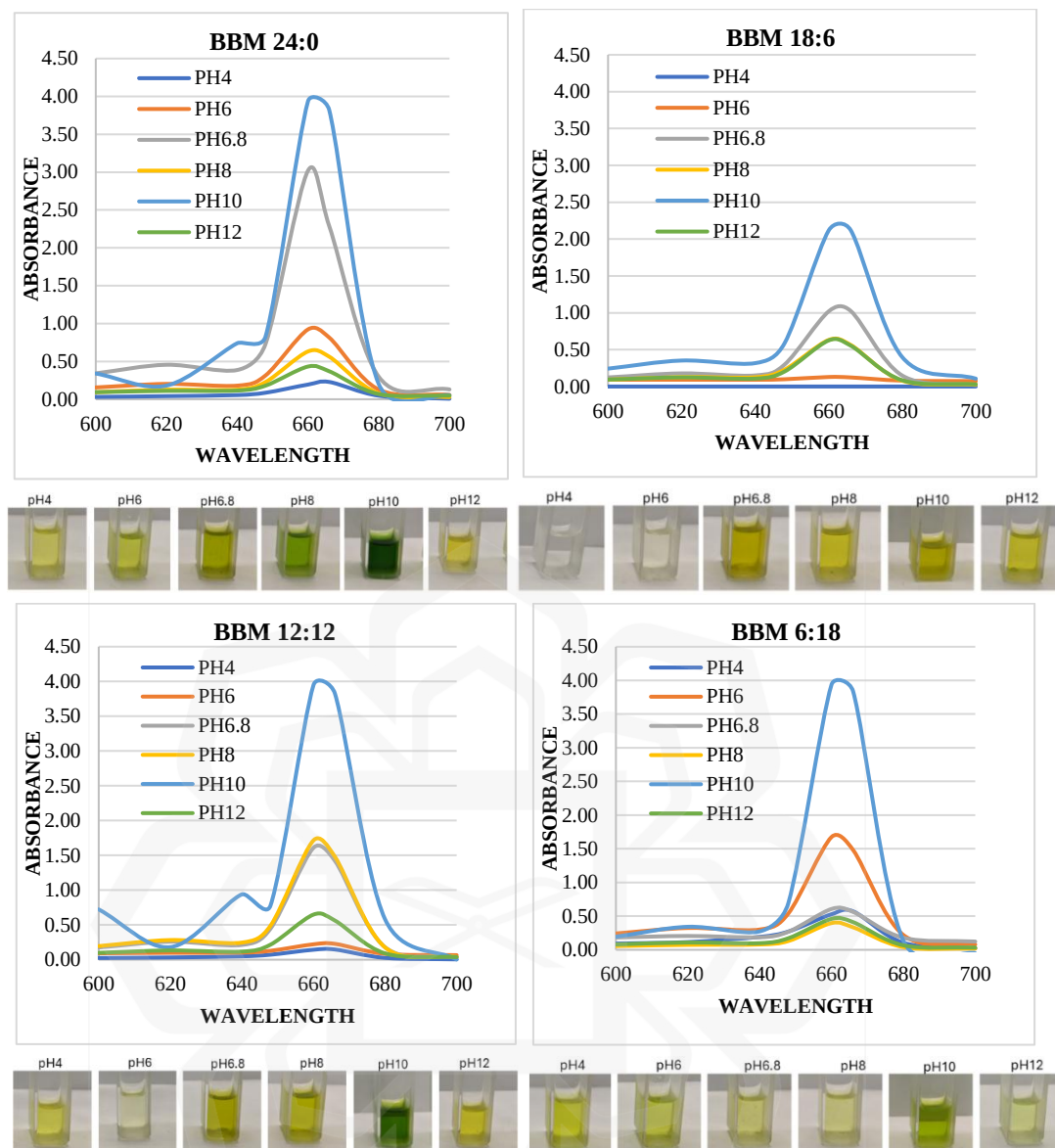


Figure 4.52 Effects of pH and photoperiod on chlorophyll content of *C. radiosa* cell culture in BBM medium after 2 weeks

4.4.4 Effect of BBM Medium Formulation, pH and Photoperiod on *C. radiosa* Cell Culture Chromaticity

The highest green intensity (a^*) value was recorded at pH 10 under 24-hours photoperiod, reaching (50.89). In contrast, the lowest green intensity occurred at pH 6 under an 18-hours photoperiod, with a value of (3.77) as indicated in Figure 4.53 and Table 4.50. Among photoperiods, the 6-hours cycle consistently exhibited mid-range

green intensity values, indicating it as the most favourable condition, while the 18-hours photoperiod generally resulted in the lowest values, particularly at pH 6.

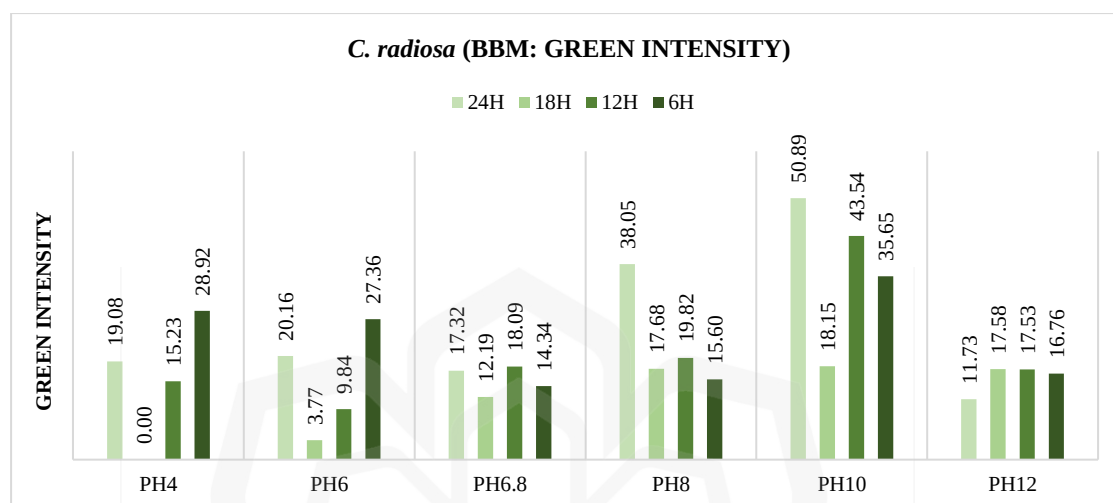


Figure 4.53 Effects of pH and photoperiod on green intensity values (a^*) of *C. radiosa* cell culture in BBM medium after 2 weeks

Table 4.50 Green intensity (a^*) distribution of *C. radiosa* cell culture in BBM medium at different pH and photoperiod after 2 weeks

Green Algae	Photoperiod	Peak pH	a^*
<i>C. radiosa</i> .	24:0	pH 10	50.89
	18:6	pH 10	18.15
	12:12	pH 10	45.54
	6:18	pH 10	35.65
<i>a*</i> , ranges from white (0) to green (100)			

For lightness (L^*), the highest value of (45.53) was observed at pH 10 under a 24-hours photoperiod, indicating reduced light absorption. In opposition, the lowest lightness value (97.23) was recorded at pH 4 under 12-hours photoperiod. Overall, longer photoperiods, especially 24 hours, combined with moderately acidic to neutral pH levels (pH 6.8–10), appear to enhance light absorption efficiency in algae refer to Figure 4.54 and Table 4.51.

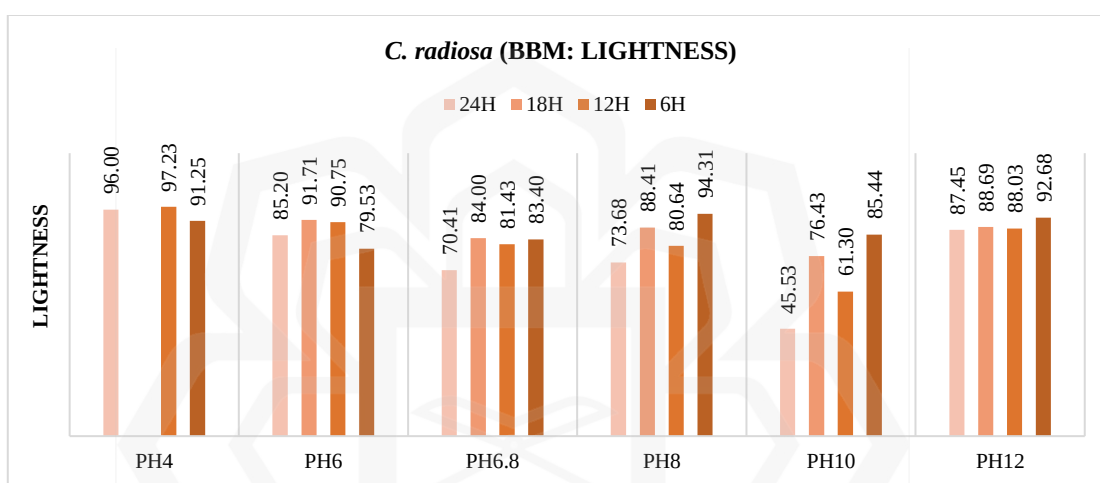


Figure 4.54 Effects of pH and photoperiod on lightness values (L^*) of *C. radiosa* cell culture in BBM medium after 2 weeks

Table 4.51 Lightness (L^*) values distribution of *C. radiosa* cell culture in BBM medium at different pH and photoperiod after 2 weeks

Green Algae	Photoperiod	Peak pH	L^*
<i>C. radiosa</i>	24:0	pH 10	45.53
	18:6	pH 10	76.43
	12:12	pH 10	61.30
	6:18	pH 6	79.53
<i>L*</i> , ranges from black (0) to white (100)			

In conclusion, *C. radiosa* demonstrated optimal growth, biomass production, and CO₂ sequestration under pH 8–10 with photoperiods of 18–24 hours, peaking at 5768×10^6 cells/mL, (0.75 g/L) biomass, and (1.18 g/L CO₂e) CO₂ sequestration. Chlorophyll activity and green intensity were highest at pH 10 under a 24-hours photoperiod. In contrast, acidic conditions and shorter light cycles resulted in minimal growth. Balanced pH (8–10) and extended light exposure are critical for maximising algae productivity and efficiency.

4.4.5 Effect of BG11 Medium Formulation, pH and Photoperiod on *C. radiosa* Cell Culture Growth

C. radiosa cell counts grown on BG11 medium show a significant rise starting after Day 6 and reaching their maximum growth by Day 14, as shown in Figure 4.55. According to the research, continuous light photoperiods (24:0) and prolonged light exposure (18:6) greatly increase cell proliferation, leading to the largest cell densities and the quickest growth rates (Chen et al. 2021b). These conditions provide optimal light availability, supporting sustained photosynthetic activity. On the other hand, shorter photoperiods such as 12:12 and 6:18, characterized by reduced light exposure, lead to significantly slower growth and lower peak cell counts. These findings underscore the critical role of light duration in promoting algal growth.

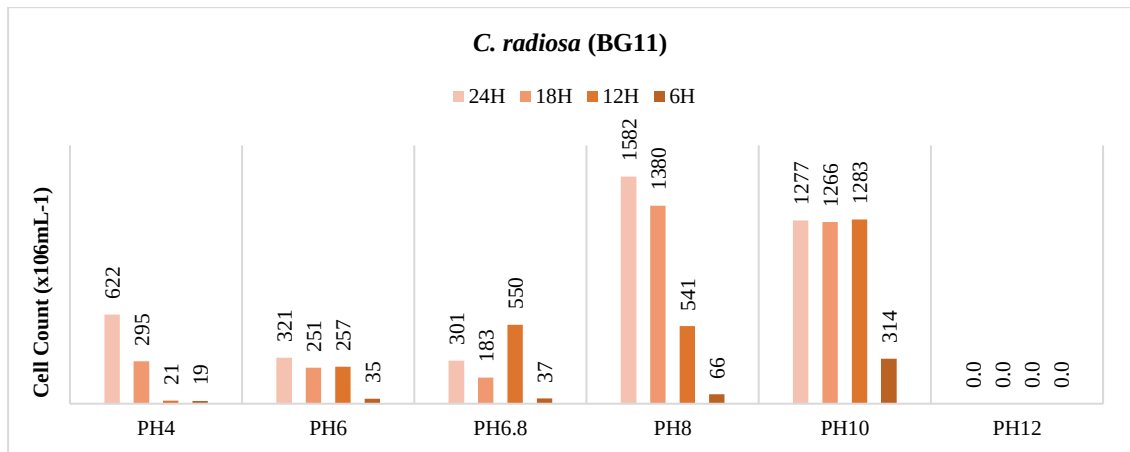


Figure 4.55 Cell counts of *C. radiosa* cultured in BG11 medium at different pH and photoperiod after 2 weeks

Table 4.52 The optimum cell counts distribution of *C. radiosa* cultured in BG11 medium at different pH and photoperiod after 2 weeks

Green Algae	Photoperiod	Peak pH	Cell Counts (x10 ⁶ mL ⁻¹)
<i>C. radiosa</i>	24:0	pH 8	1582
	18:6	pH 8	1380
	12:12	pH 10	1283
	6:18	pH 10	314

The highest cell counts, which peaked at 1582×10^6 cells/mL at pH 8, was seen in BG11 media over a 24-hours photoperiod, as shown in Table 4.52. During the 18-hours photoperiod, there was also notable growth, with 1380×10^6 cells/mL at pH 8. In contrast, minimal growth was recorded at pH levels 4 and 6, where cell counts ranged between 19 to 21×10^6 cells/mL under the 6-hours photoperiod. Overall, the results indicate that longer photoperiods (18–24 hours) combined with pH levels 8 and 10 significantly promote growth.

The absorbance trends at 750 nm in BG11 media over a 14-day period are shown in Figure 4.56, which show how pH and photoperiods affect growth. Absorbance continuously rises at all pH levels during the 24:0, 8:6, and 12:12 photoperiods, indicating ideal growth conditions; the maximum absorbance values are observed throughout these cycles. In contrast, the 6:18 photoperiod show minimal absorbance increases, indicating significantly reduced growth. This suggests that extended light exposure plays a critical role in promoting growth, regardless of pH conditions.

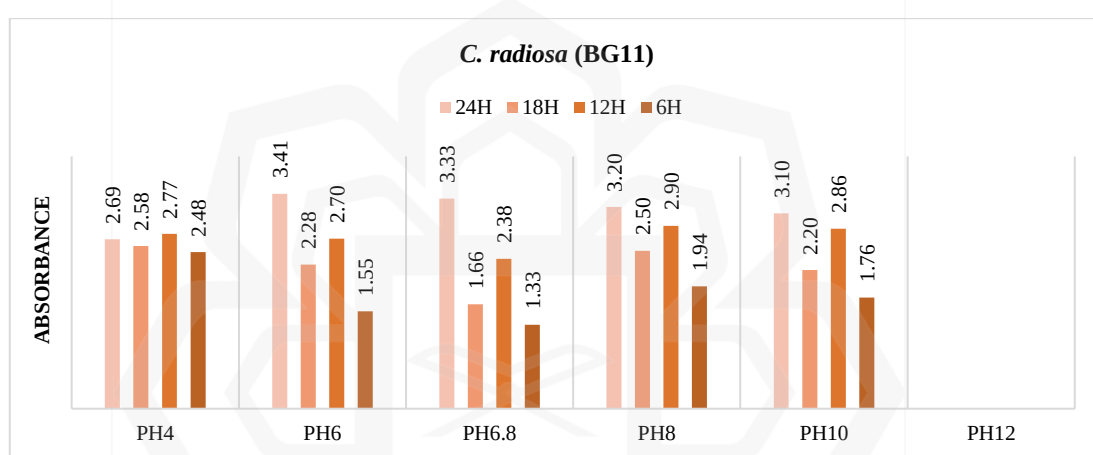


Figure 4.56 The effect of different photoperiod and pH on cell density measured at 750 nm (OD_{750}) of *C. radiosa* cultured in BG11 medium after 2 weeks

Table 4.53 The optimum cell density distribution measured at (OD_{750}) of *C. radiosa* in BG11 medium at different pH and photoperiod after 2 weeks

Green Algae	Photoperiod	Peak pH	Abs
<i>C. radiosa</i>	24:0	pH 6	3.41
	18:6	pH 4	2.58
	12:12	pH 8	2.90
	6:18	pH 4	2.48

Table 4.53 display the absorbance values varied with photoperiod and pH, peaking the highest at pH 6 under 24-hours photoperiod on Day 14 (3.41). The lowest absorbance was observed at pH 6.8 under a 6-hours photoperiod on Day 14 (1.33). Extended photoperiods (18H, 24H) supported higher growth rates, while shorter durations (6H, 12H) limited growth. Generally, pH 6-10 favoured higher absorbance values.

4.4.6 Effect of BG11 Medium Formulation, pH and Photoperiod on *C. radiosa* Biomass and Carbon Sequestration Rate (CSR)

Optimal biomass production (0.59 g/L) and CO₂ sequestration (0.93 g/L CO₂e) were achieved at pH 6 with a 6-hours photoperiod. In contrast, the lowest values were recorded at pH 6.8 under a 6-hours photoperiod (biomass: 0.06 g/L, CO₂ sequestration: 0.10 g/L CO₂e). While continuous light (24H) supported growth, the 18-hours photoperiod proved slightly more effective, with biomass and CO₂ sequestration peaking at pH 8 (0.53 g/L and 0.83 g/L CO₂e) refer to Table 4.54 and Figure 4.57.

Table 4.54 The optimum biomass and CSR distribution of *C. radiosa* cultured in BG11 medium at different pH and photoperiod after 2 weeks

Green Algae	pH	Photoperiod	Biomass (g/L)	CSR (CO ₂ e)
<i>C. radiosa</i>	pH 4	18:6	0.38	0.59
	ph 6	6:18	0.59	0.93
	pH 6.8	18:6	0.31	0.49
	pH 8	18:6	0.47	0.75
	pH 10	12:12	0.25	0.40

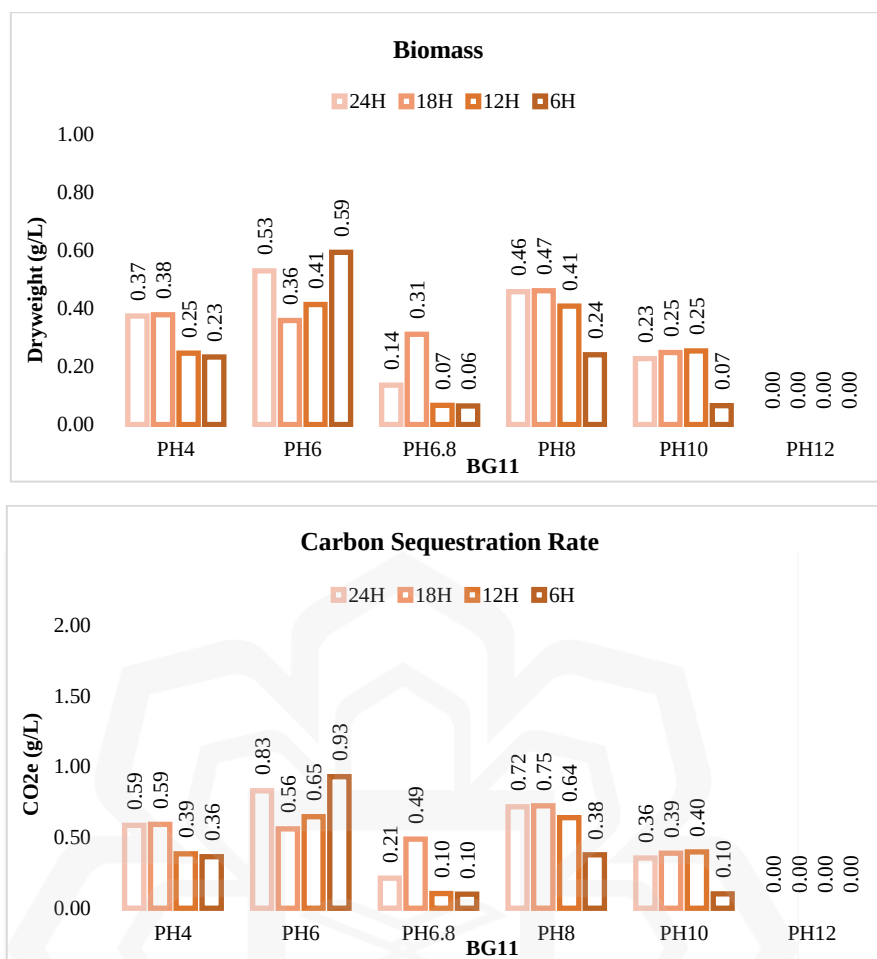


Figure 4.57 Biomass and CSR of *C. radiosa* cultured in BG11 medium at different pH and photoperiod after 2 weeks

4.4.7 Effect of BG11 Medium Formulation, pH and Photoperiod on *C. radiosa* Chlorophyll Content

Distinct patterns in the 600–700 nm wavelength range, reflecting variations in chlorophyll content influenced by light exposure and pH levels as highlighted in Figure 4.58. The data indicates that the green pigmentation of samples significantly impacts absorbance outcomes. Notably, the 18:6 graph show a pronounced peak around 680 nm for pH 6 and pH 8, suggesting optimal chlorophyll activity at these pH levels. In contrast, the 24:0, 12:12, and 6:18 graphs exhibit lower absorbance across the same range, indicating reduced chlorophyll performance under different photoperiod.

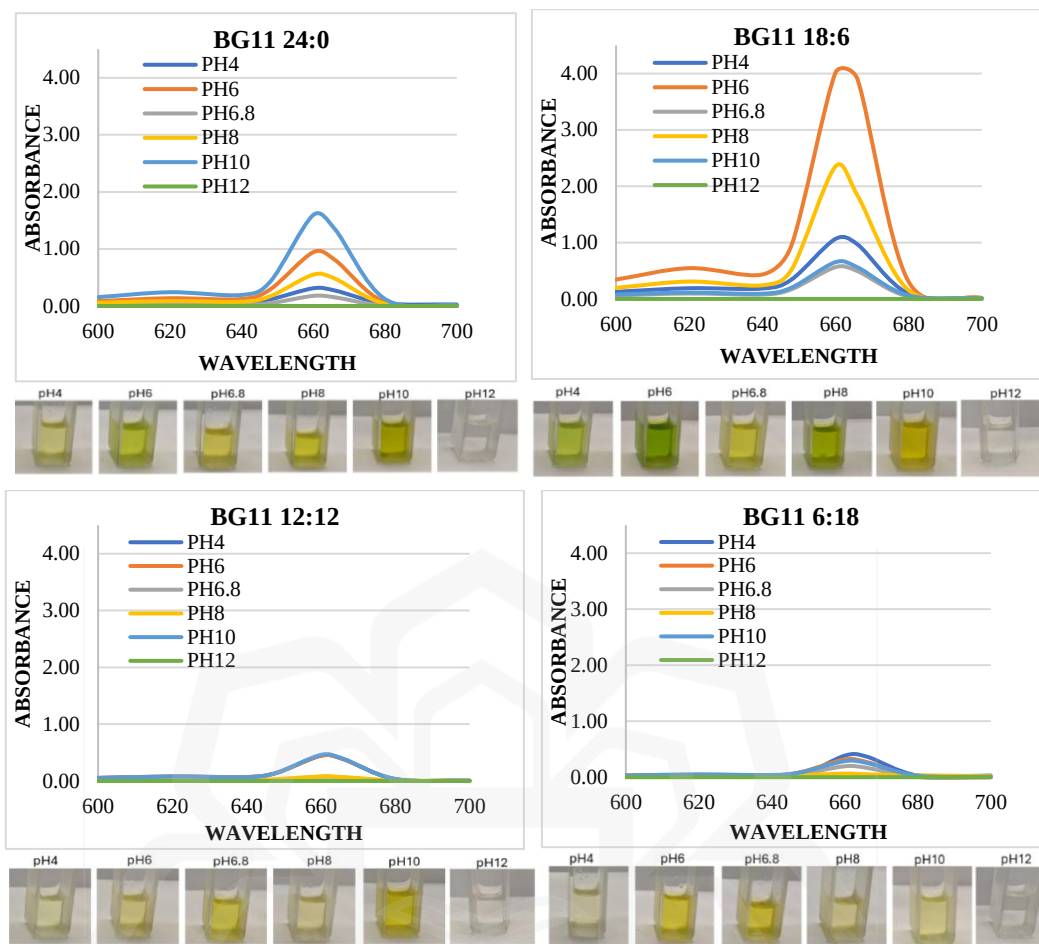


Figure 4.58 Effects of pH and photoperiod on chlorophyll content of *C. radiosa* cell culture in BG11 medium after 2 weeks

Chlorophyll production peaked at pH 6 under an 18-hours photoperiod, achieving the highest absorbance values of (4.02) at wavelengths between 660–666 nm. In contrast, limited light exposure (6-hours photoperiod) significantly reduced chlorophyll synthesis, with production ranging from only (0.07 to 0.20) across all pH levels as showed in Figure 4.59. Extended light-dark cycles of 18 hours were found to greatly enhance chlorophyll accumulation. However, pH 6.8 yielded the lowest chlorophyll levels under these conditions, highlighting the critical influence of both photoperiod and pH on photosynthetic pigment production efficiency.

4.4.8 Effect of BG11 Medium Formulation, pH and Photoperiod on *C. radiosa* Cell Culture Chromaticity

Green intensity, as illustrated in Figure 4.59 and detailed in Table 4.55, reached its peak at pH 6 under an 18-hours photoperiod (39.70) and its lowest point at pH 4 with a 6-hours photoperiod (3.14). The 18-hours photoperiod consistently produced moderate green intensity values, while the 6-hours photoperiod resulted in the lowest values. Lightness was also at its lowest at pH 4 under a 6-hours photoperiod (71.56) and highest at pH 6.8 under 12-hours photoperiod (98.01), suggesting reduced light absorption under acidic conditions. Longer photoperiods (24H, 18H) combined with pH 10 enhanced light absorption, whereas shorter photoperiods and acidic conditions decreased efficiency refer to Figure 4.60 and Table 4.56.

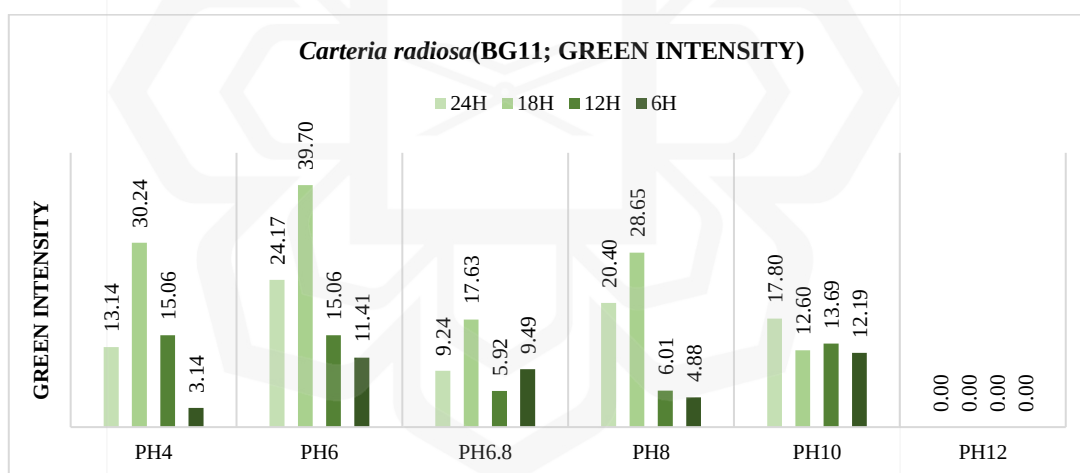


Figure 4.59 Effects of pH and photoperiod on green intensity values (a^*) of *C. radiosa* cell culture in BG11 medium after 2 weeks

Table 4.55 Green intensity (a^*) distribution of *C. radiosa* cell culture in BG11 medium at different pH and photoperiod after 2 weeks

Green Algae	Photoperiod	Peak pH	a^*
<i>C. radiosa</i>	24:0	pH 6	24.17
	18:6	pH 6	39.70
	12:12	pH 4 and 6	15.06
	6:18	pH 10	12.19

a^* , ranges from white (0) to green (100)

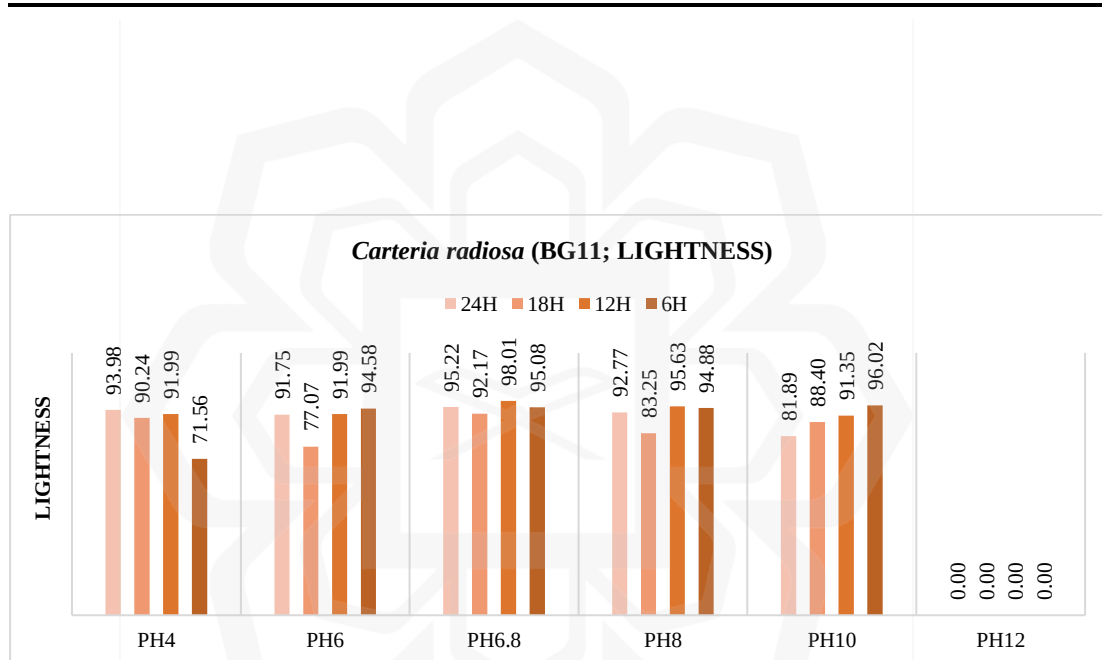


Figure 4.60 Effects of pH and photoperiod on lightness values (L^*) of *C. radiosa* cell culture in BG11 medium after 2 weeks

Table 4.56 Lightness (L*) values distribution of *C. radiosa* cell culture in BG11 medium at different pH and photoperiod after 2 weeks

Green Algae	Photoperiod	Peak pH	L*
<i>C. radiosa</i> .	24:0	pH 10	81.89
	18:6	pH 6	77.07
	12:12	pH 10	91.35
	6:18	pH 4	71.56
<i>L*</i> , ranges from black (0) to white (100)			

In summary, the study reveals those longer photoperiods (18–24 hours) and optimal pH levels (6–10) promote microalgae growth, with peak cell counts and absorbance at pH 8 (1582×10^6 cells/mL) and biomass (0.59 g/L) /CO₂ sequestration (0.93 g/L CO₂e) at pH 6. Chlorophyll production (4.02), green intensity (39.70) and Lightness (71.56) thrived under an 18-hours photoperiod, while acidic pH and shorter light exposure limited growth and light absorption. Extended light-dark cycles effectively enhance growth, demonstrating their potential for sustainable energy and climate control applications.

4.4.9 Effect of BRISTOL Medium Formulation, pH and Photoperiod on *C. radiosa* Cell Culture Growth

Figure 4.61 illustrates a significant increase in *C. radiosa* cell counts after Day 6, reaching a peak by Day 14 when cultured in Bristol medium. The overall findings indicate that the 24:0 light cycle resulted in the lowest growth rate, suggesting that continuous exposure to light may not be optimal for this species. Under an 18:6 light cycle, growth was better but still limited. While the 12:12, 6:18 cycle showed visibly slower growth, reflecting the impact of reduced light availability.

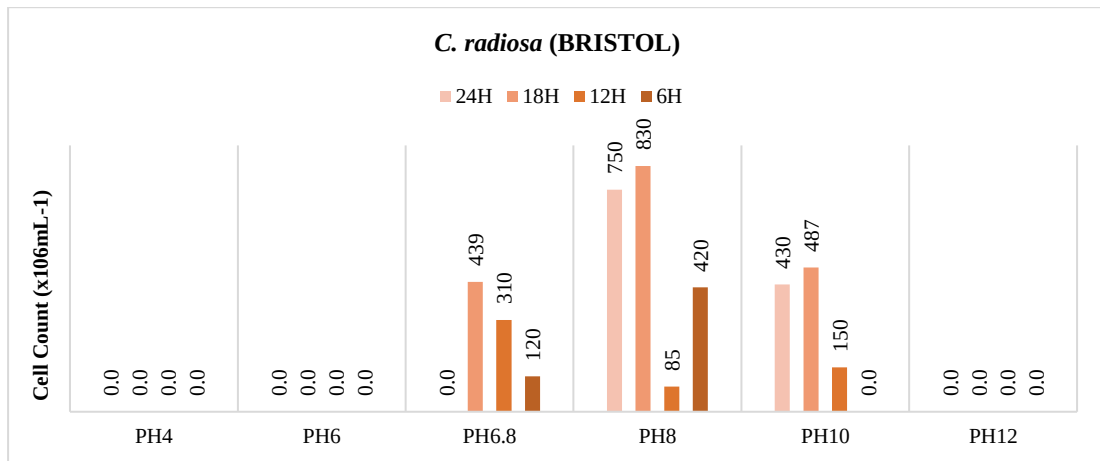


Figure 4.61 Cell counts of *C. radiosa* cultured in BRISTOL medium at different pH and photoperiod after 2 weeks

Table 4.57 The optimum cell counts distribution of *C. radiosa* cultured in BRISTOL medium at different pH and photoperiod after 2 weeks

Green Algae	Photoperiod	Peak pH	Cell Counts (x10 ⁶ mL ⁻¹)
<i>C. radiosa</i>	24:0	pH 8	750
	18:6	pH 8	830
	12:12	pH 10	478
	6:18	pH 8	420

The data collected using Bristol medium indicate that the highest cell counts was recorded under an 18-hours photoperiod at pH 8 (830 cells×10⁶ cells/mL), followed by the 24-hours photoperiod (750 × 10⁶ cells/mL). The least cell growth was observed under a 12-hours photoperiod at the same pH 8 (85 × 10⁶ cells/mL). refer to Figure 4.61 and Table 4.57 for detail.

Continuous light exposure 24:0 produces the steady and slow growth conditions, followed by the 18:6 photoperiod with slightly reduced growth as per showed in Figure 4.62. The 12:12 and 6:18 photoperiod show the lowest absorbance, reflecting minimal growth due to limited light exposure.

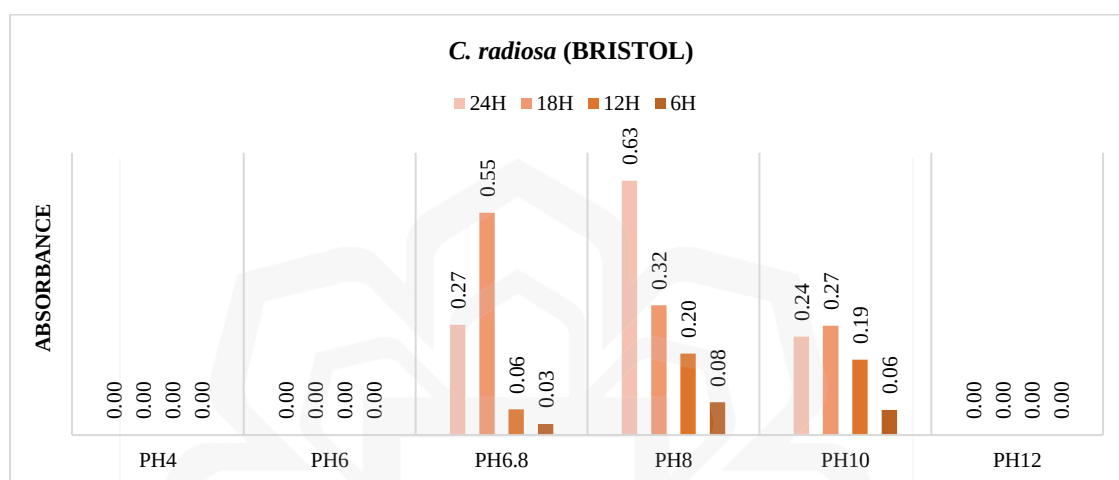


Figure 4.62 The effect of different photoperiod and pH on cell density measured at 750 nm (OD₇₅₀) of *C. radiosa* cultured in BRISTOL medium after 2 weeks

Table 4.58 The optimum cell density distribution measured at (OD₇₅₀) of *C. radiosa* in BRISTOL medium at different pH and photoperiod after 2 weeks

Green Algae	Photoperiod	Peak pH	Abs
<i>C. radiosa</i>	24:0	pH 8	0.63
	18:6	pH 6.8	0.55
	12:12	pH 10	0.19
	6:18	pH 8	0.08

Absorbance results revealed that the highest value occurred at pH 8 with a 24-hours photoperiod on Day 14 (0.63), while the lowest absorbance was recorded at pH 6.8 with a 6-hours photoperiod (0.03). Overall, longer photoperiods (24 and 18 hours) and pH levels near neutral to slightly alkaline (8–10) supported better growth as display in Figure 4.62 and Table 4.58.

4.4.10 Effect of BRISTOL Medium Formulation, pH and Photoperiod on *C. radiosa* Biomass and Carbon Sequestration Rate (CSR)

Biomass and CO₂ sequestration highest peaked under a 24-hours photoperiod at pH 8, reaching (0.35 g/L) and (0.55 g/L CO₂e). In contrast, the lowest biomass (0.05 g/L) and CO₂ sequestration (0.08 g/L CO₂e) were recorded at pH 8 under the same 6-hours photoperiod refer to Figure 4.63 and Table 4.59.

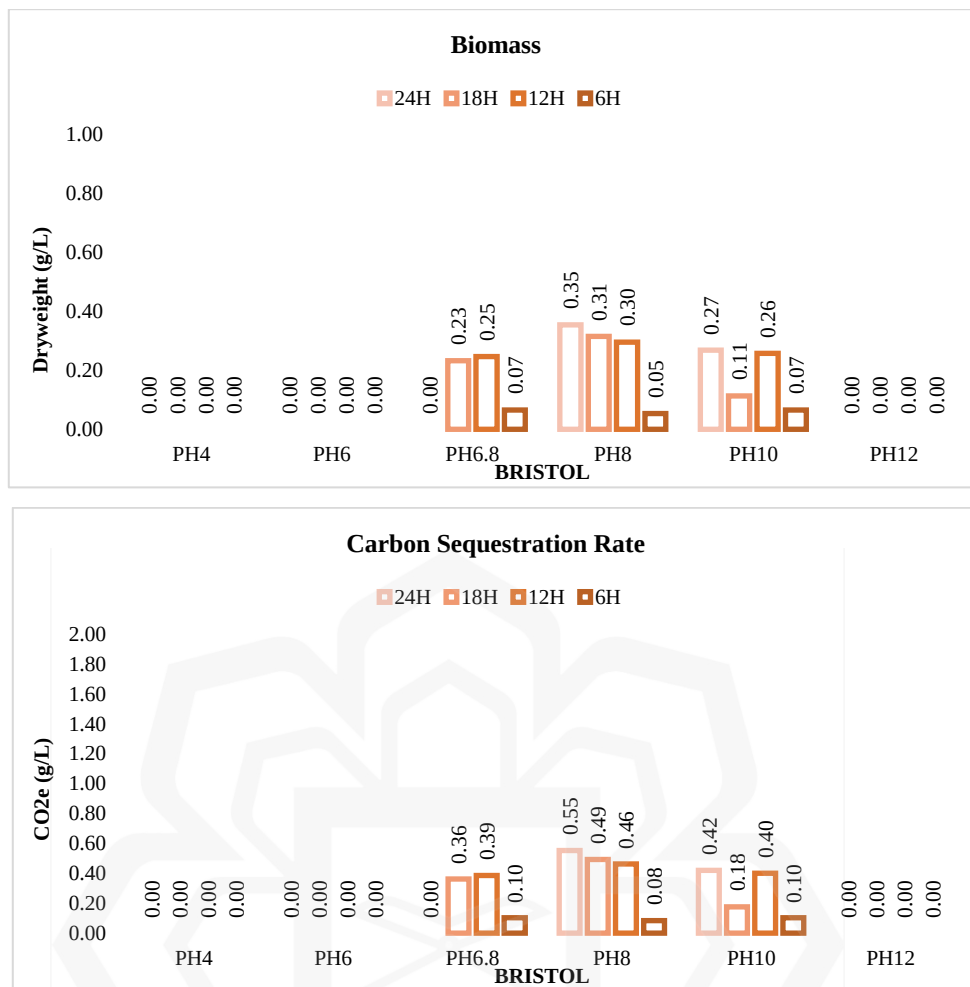


Figure 4.63 Biomass and CSR of of *C. radiosa* cultured in BRISTOL medium at different pH and photoperiod after 2 weeks

Table 4.59 The optimum biomass and CSR distribution of *C. radiosa* cultured in BRISTOL medium at different pH and photoperiod after 2 weeks

Green Algae	pH	Photoperiod	Biomass (g/L)	CSR (CO ₂ e)
<i>C. radiosa</i> .	pH 6.8	12:12	0.25	0.39
	Ph 8	24:0	0.35	0.55
	pH 10	24:0	0.27	0.42

4.4.11 Effect of BRISTOL Medium Formulation, pH and Photoperiod on *C. radiosa* Chlorophyll Content

Distinct patterns in the 600–700 nm wavelength range, indicating variations in chlorophyll content influenced by light exposure and pH. The 24:0 and 18:6 and 12:12 graph show with lower absorbance at all pH levels. In contrast, 6:18 there were raising peak for pH 8 and 10. It showed that greenery coloured will affect the absorbance result refer to Figure 4.64.

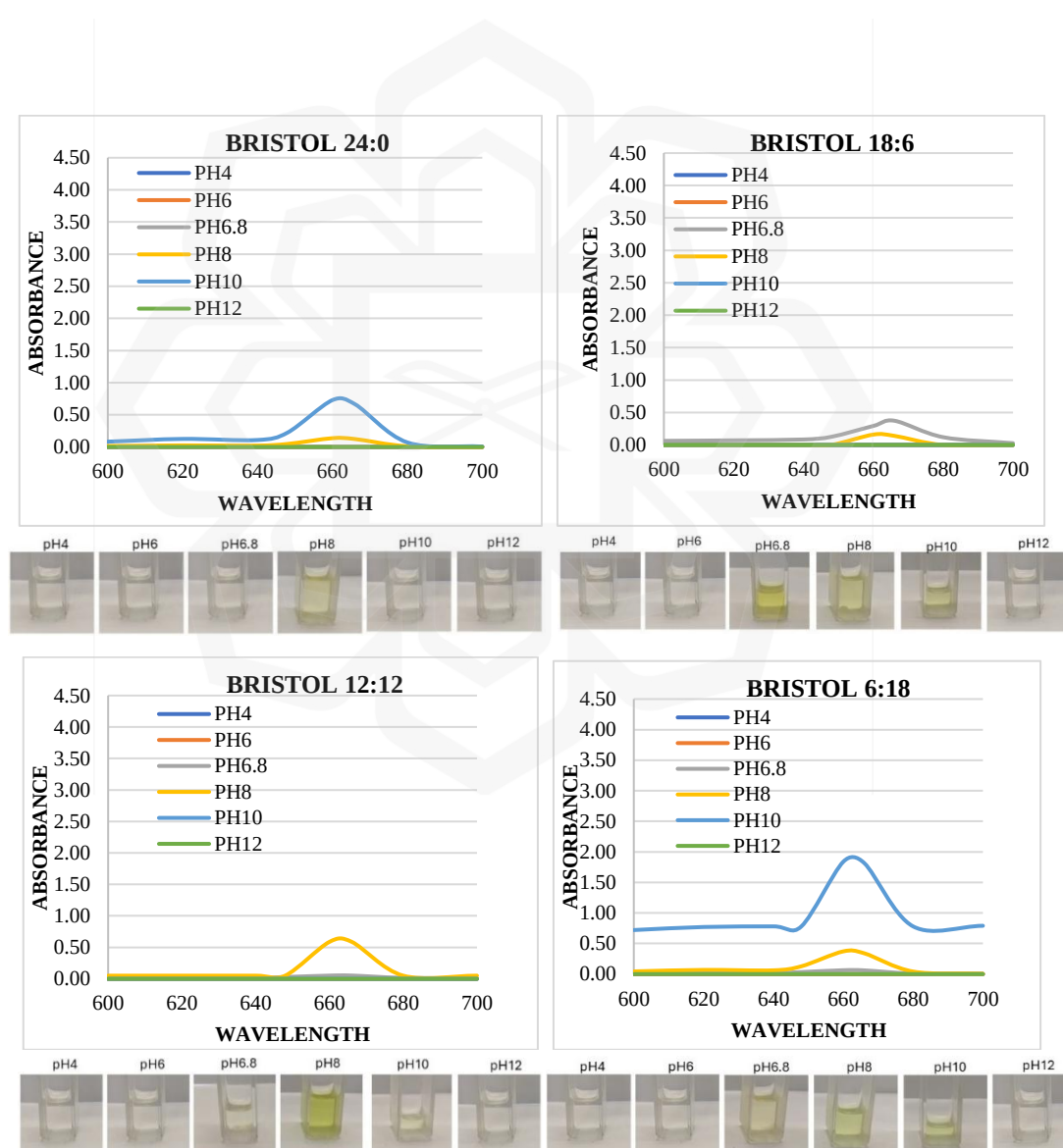


Figure 4.64 Effects of pH and photoperiod on chlorophyll content of *C. radiosa* cell culture in BRISTOL medium after 2 weeks

Optimal chlorophyll production was observed at pH 10 with a 6-hours photoperiod, achieving (1.84), while the lowest chlorophyll synthesis occurred at pH 6.8 with a 12-hours photoperiod (0.05). Others are in moderate result with pH8 show consistent growth from all photoperiods.

4.4.12 Effect of BRISTOL Medium Formulation, pH and Photoperiod on *C. radiosa* Cell Culture Chromaticity

The highest green intensity (22.90) was recorded at pH 10 with 24-hours photoperiod, whereas the lowest green intensity (0.13) occurred at pH 8 under a 12-hours photoperiod as showed in Figure 4.65 and Table 4.60. Lightness values, which indicate light absorption efficiency, were lowest (75.99) at pH 8 under the 12-hours photoperiod. In contrast, the highest lightness value (103.73), suggesting reduced absorption, was observed at pH 8 with an 18-hours photoperiod refer to Figure 4.66 and Table 4.61.

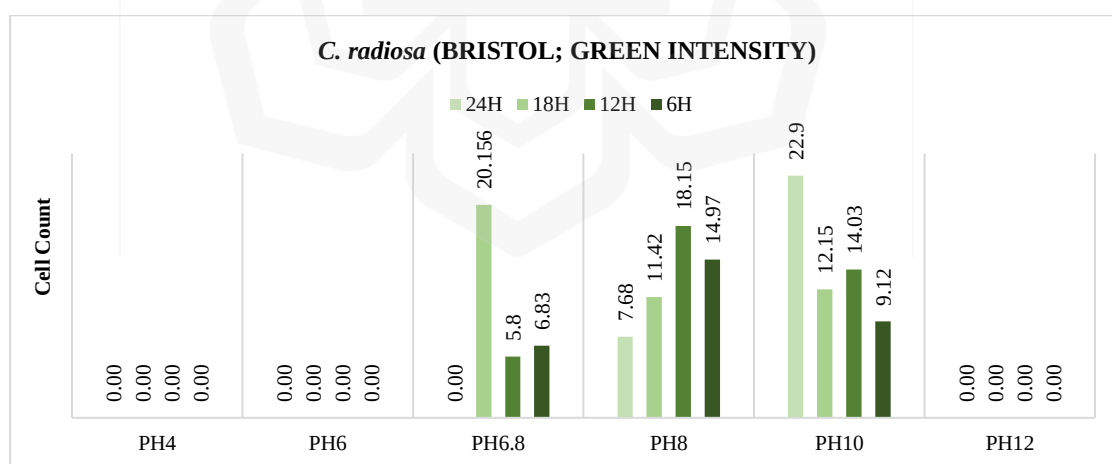


Figure 4.65 Effects of pH and photoperiod on green intensity values (a^*) of *C. radiosa* cell culture in BRISTOL medium after 2 weeks

Table 4.60 Green intensity (a*) distribution of *C. radiosa* cell culture in BRISTOL medium at different pH and photoperiod after 2 weeks

Green Algae	Photoperiod	Peak pH	a*
<i>C. radiosa</i> .	24:0	pH 10	22.90
	18:6	pH 6.8	20.16
	12:12	pH 8	18.15
	6:18	pH 8	14.97
<i>a*</i> , ranges from white (0) to green (100)			

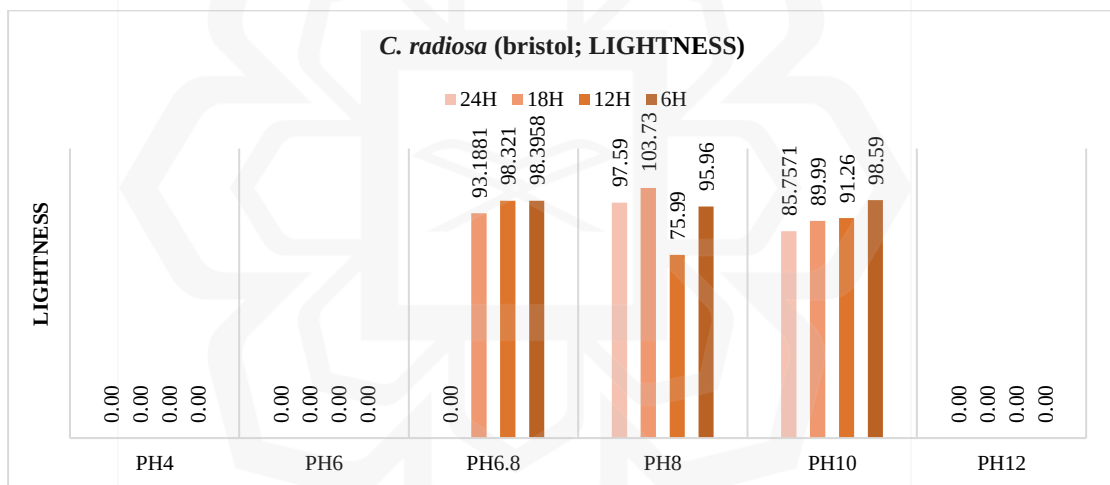


Figure 4.66 Effects of pH and photoperiod on lightness values (L*) of *C. radiosa* cell culture in BRISTOL medium after 2 weeks

Table 4.61 Lightness (L*) values distribution of *C. radiosa* cell culture in BRISTOL medium at different pH and photoperiod after 2 weeks

Green Algae	Photoperiod	Peak pH	L*
<i>C. radiosa</i> .	24:0	pH 10	85.76
	18:6	pH 10	89.99
	12:12	pH 8	75.99
	6:18	pH 8	79.96
<i>L*</i> , ranges from black (0) to white (100)			

In conclusion, the growth of *C. radiosa* in Bristol medium were optimal at pH 8, with a 24-hours and 18-hours photoperiod, resulting in peak biomass production of (0.55 g/L) and a cell counts of (830×10^6 cells/mL). Chlorophyll synthesis reached its highest level (1.84) at pH 10 under a 6-hours photoperiod. Longer photoperiods combined with an alkaline pH provided the most promising conditions for microalgal growth, while shorter photoperiods significantly reduced efficiency. Additionally, the patterns of green intensity and light absorption efficiency varied. The highest green intensity (22.90) and lightness (75.99) highlighting the complex interplay between photoperiod and pH in enhancing microalgae productivity and CO₂ sequestration potential.

4.4.13 Effect of Chu Medium Formulation, pH and Photoperiod on *C. radiosa* Cell Culture Growth

The results from Figure 4.67 indicate that the cell counts of *C. radiosa* decreases progressively from Day 6 to Day 14 in Chu medium. Overall, the growth is lower under continuous 24-hours light, followed by the 18:6 light cycle. The 12:12 and 6:18 light cycles, which provide less light, still support moderate growth, but at a slower rate, with visibly slower growth observed.

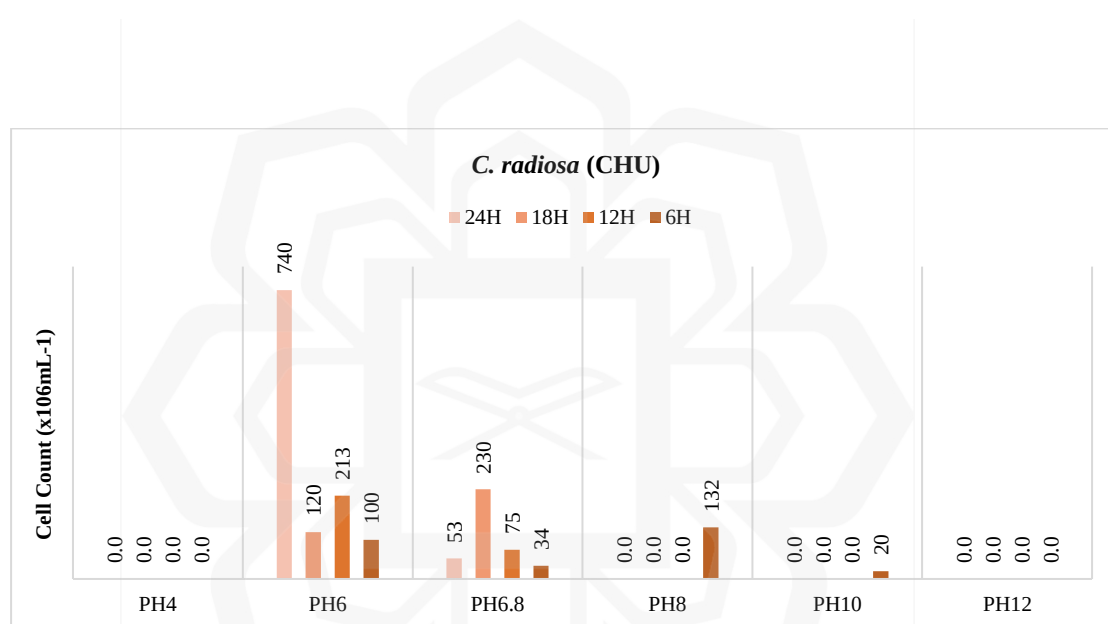


Figure 4.67 Cell counts of *C. radiosa* cultured in Chu medium at different pH and photoperiod after 2 weeks

Table 4.62 The optimum cell counts distribution of *C. radiosa* cultured in Chu medium at different pH and photoperiod after 2 weeks

Green Algae	Photoperiod	Peak pH	Cell Counts (x10 ⁶ mL ⁻¹)
<i>C. radiosa</i>	24:0	pH 8	740
	18:6	pH 6.8	230
	12:12	pH 6	213
	6:18	pH 8	132

The data collected using Chu medium reveals that the highest cell counts was recorded under a 24-hours photoperiod at pH 8, reaching 740×10^6 cells/mL. On the other hand, the lowest cell growth occurred under a 6-hours photoperiod at pH 10, with only 20×10^6 cells/mL. Overall, most cell counts results did not show significant increases, and the data remains limited refer to Table 4.62.

The absorbance analysis of *C. radiosa* cultured in CHU medium reveals that pH 10 consistently supports optimal growth across all photoperiods, followed by pH 8. Continuous light (24:0) and extended light exposure (18:6) result in higher absorbance values and faster growth compared to shorter light periods (12:12 and 6:18). Growth peaks are generally observed between days 6 to 10 under encouraging conditions and decrease until day 14 especially at photoperiod 18:6 and 6:18.

Figure 4.68 and Table 4.63 show the highest absorbance was observed at pH 10 with an 12-hours photoperiod on Day 14 (1.50), while the lowest absorbance occurred at pH 8 with 24-hours photoperiod (1.09). Longer photoperiods (24 hours) generally supported better growth.

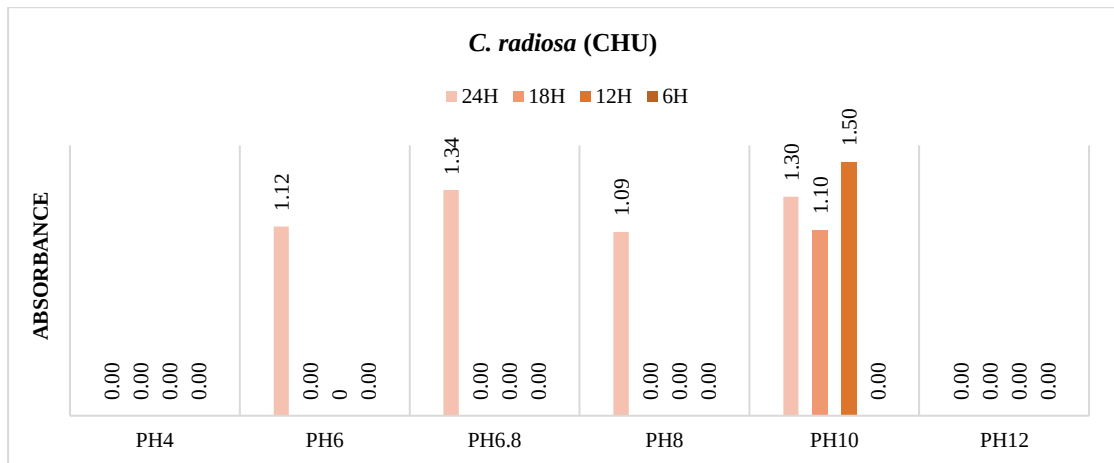


Figure 4.68 The effect of different photoperiod and pH on cell density measured at 750 nm (OD₇₅₀) of *C. radiosa* cultured in Chu medium after 2 weeks

Table 4.63 The optimum cell density distribution measured at (OD₇₅₀) of *C. radiosa* in Chu medium at different pH and photoperiod after 2 weeks

Green Algae	Photoperiod	Peak pH	Abs
<i>C. radiosa</i>	24:0	pH 6.8	1.34
	18:6	pH 10	1.10
	12:12	pH 10	1.50

4.4.14 Effect of Chu Medium Formulation, pH and Photoperiod on *C. radiosa* Biomass and Carbon Sequestration Rate (CSR)

The highest biomass was achieved under a 24-hours photoperiod at pH 6, peaking at 0.33 g/L, with CO₂ sequestration reaching 0.52 g/L. In contrast, the lowest biomass (0.01 g/L) and CO₂ sequestration (0.02 g/L) were recorded under a 6-hours photoperiod across pH 6.8 and 10 refer to Figure 4.69 and Table 4.64.

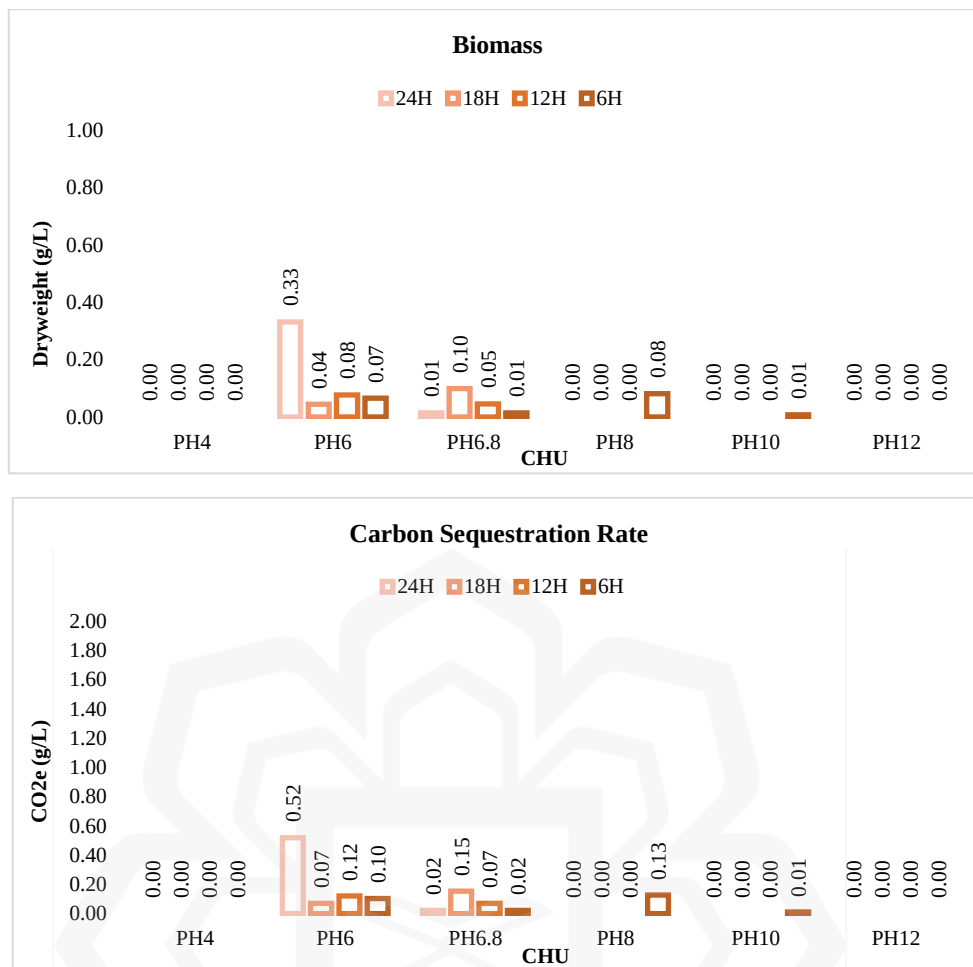


Figure 4.69 Biomass and CSR of of *C. radiosa* cultured in Chu medium at different pH and photoperiod after 2 weeks

Table 4.64 The optimum biomass and CSR distribution of *C. radiosa* cultured in Chu medium at different pH and photoperiod after 2 weeks

Green Algae	pH	Photoperiod	Biomass (g/L)	CSR (CO ₂ e)
<i>C. radiosa</i>	pH 6	24:0	0.33	0.52
	Ph 6.8	18:0	0.10	0.15
	pH 8	6:18	0.08	0.13
	pH 10	6:18	0.01	0.01

4.4.15 Effect of Chu Medium Formulation, pH and Photoperiod on *C. radiosa* Chlorophyll Content

Figure 4.70 display distinct patterns in the 600–700 nm wavelength range, indicating variations in chlorophyll content influenced by light exposure and pH. The 24:0 and 18:6 and 6:18 graph show a pronounced peak at ~680 nm for pH 6 and 6.8 and overall trend almost flat to the lowers for other pH. Followed by 12:12 graphs with lower absorbance result but still showing good peaking at pH 8. Chlorophyll production peaked at pH 6 under a 6-hours photoperiod, with a maximum value of $0.76 \times 10^6 \text{ mL}^{-1}$, while the lowest value ($0.01 \times 10^6 \text{ mL}^{-1}$) was recorded at pH 6.8 with a 6-hours photoperiod as demonstrated in Figure 4.70.

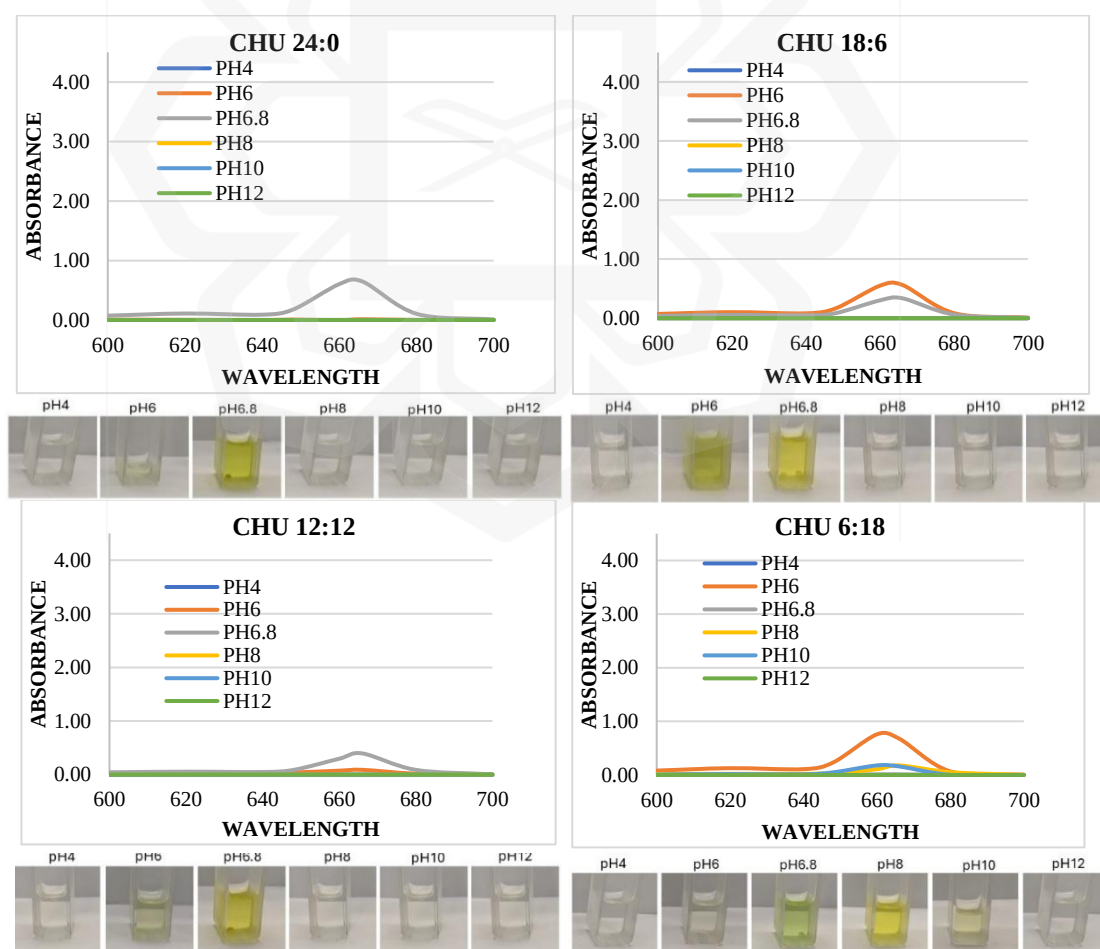


Figure 4.70 Effects of pH and photoperiod on chlorophyll content of *C. radiosa* cell culture in Chu medium after 2 weeks

4.4.16 Effect of Chu Medium Formulation, pH and Photoperiod on *C. radiosia* Cell Culture Chromaticity

The highest green intensity (a^*) was observed at pH 6.8 with a 6-hours photoperiod (23.79), while the lowest green intensity occurred at pH 6 with a 6-hours photoperiod (3.59). Across all photoperiods, green intensity generally peaked at pH 6.8 as display in Figure 4.71 and Table 4.65. The lowest Lightness (L^*) value, indicating optimal light absorption, was (92.44) under a 24-hours photoperiod at pH 6.8. In contrast, the highest Lightness value of (99.75), reflecting reduced absorption, was observed at pH 6 with a 6-hours photoperiod, as shown in Figure 4.72 and Table 4.66.

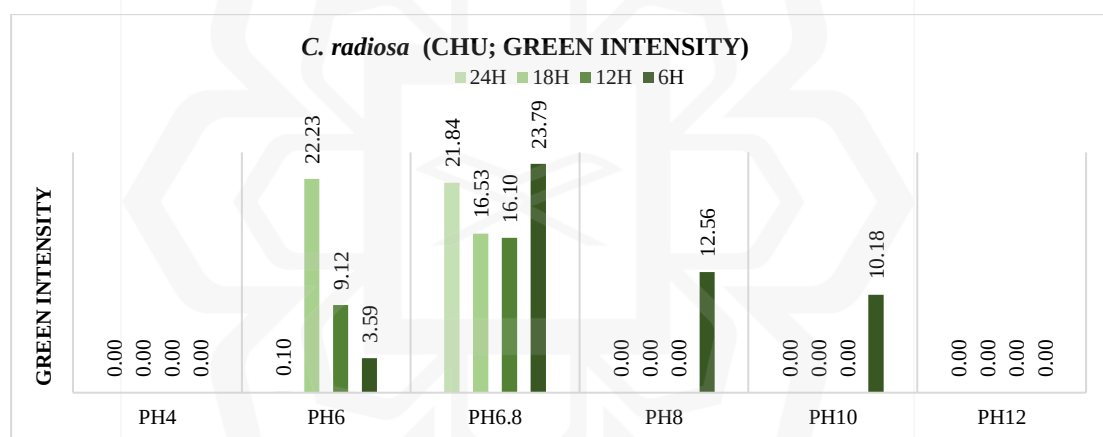


Figure 4.71 Effects of pH and photoperiod on green intensity values (a^*) of *C. radiosia* cell culture in Chu medium after 2 weeks

Table 4.65 Green intensity (a*) distribution of *C. radiosa* cell culture in Chu medium at different pH and photoperiod after 2 weeks

Green Algae	Photoperiod	Peak pH	a*
<i>C. radiosa</i>	24:0	pH 6.8	21.84
	18:6	pH 4	22.23
	12:12	pH 6.8	16.10
	6:18	pH 6.8	23.79
<i>a*</i> , ranges from white (0) to green (100)			

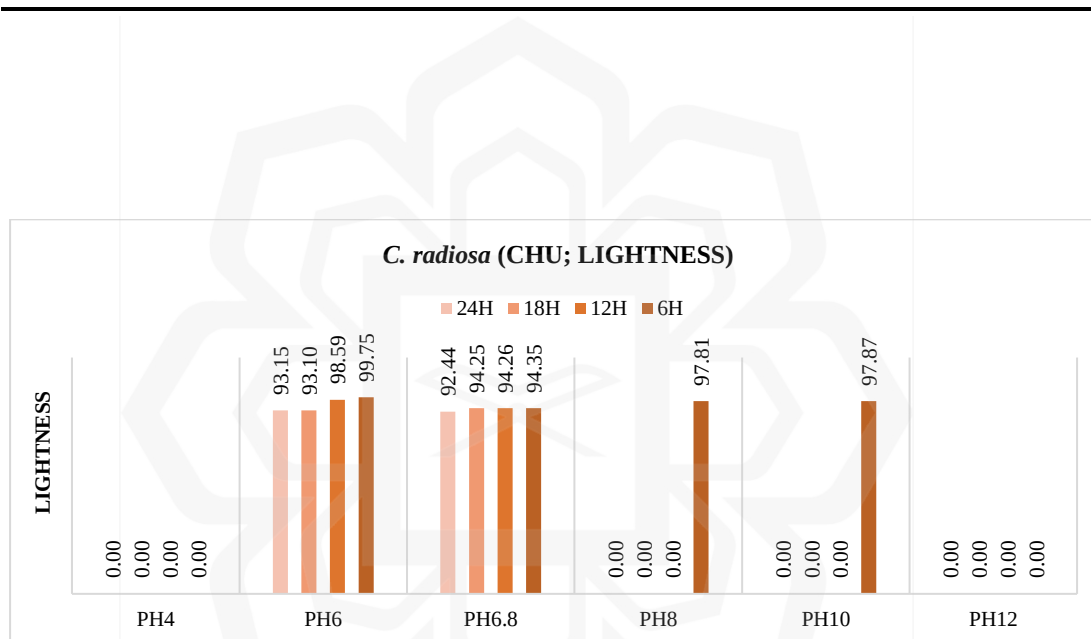


Figure 4.72 Effects of pH and photoperiod on lightness values (L*) of *C. radiosa* cell culture in CHU medium after 2 weeks

Table 4.66 Lightness (L*) values distribution of *C. radiosa* cell culture in Chu medium at different pH and photoperiod after 2 weeks

Green Algae	Photoperiod	Peak pH	L*
<i>C. radiosa</i>	24:0	pH 6.8	92.44
	18:6	pH 6	93.10
	12:12	Ph6.8	94.26
	6:18	pH 6.8	94.35
<i>L*</i> , ranges from black (0) to white (100)			

In conclusion, the result show that longer photoperiods (24 hours) and specific pH levels, notably pH 6 and 8, optimised microalgae growth and CO₂ sequestration (0.52 g/L CO₂e). The highest cell counts (740×10^6 cells/mL⁻¹) and biomass (0.33 g/L) occurred under 24-hours photoperiods, while peak chlorophyll (0.76×10^6 mL⁻¹) and green intensity (23.79) were recorded under shorter photoperiods at distinct pH levels. Lightness data suggests pH 6.8 and 24-hours photoperiods as optimal for light absorption efficiency.

4.4.17 Multivariate Data Analysis

4.4.17.1 Multivariate analysis

The KMO values for the 288 datasets yielded a score of **0.8255** (Table 4.67), indicating that the dataset falls within the "very good" category and is suitable for PCA analysis. Bartlett's Test of Sphericity was conducted to verify that the R-matrix is not equivalent

to the identity matrix. The p -value for the *C. radiosa* data on cell growth, carbon sequestration, and chromaticity stability showed highly significant differences at 0.0001.

Table 4.67 Kaiser-Meyer-Olkin and Bartlett's test for *C. radiosa* Cell Growth, Carbon Sequestration, and Chromaticity stability

Kaiser-Meyer-Olkin Measure of Sampling Adequacy		0.8255
Bartlett's Test of Sphericity	Chi-square (Observed value)	5369.17
	DF	45
	p -value (Two-tailed)	< 0.0001

Correlation coefficient matrix (r^2) in Table 4.68 revealed a very strong positive correlation among biomass and CSR ($r^2 = 1$), High positive correlations were observed in lightness, green intensity, Chlorophyll content, biomass and CSR ($r^2 = 0.728$ to 0.793)

Table 4.68 Correlation coefficient matrix for the *C. radiosa* Cell Growth, Carbon Sequestration, and Chromaticity

Variables	L*	a*	Chl	CCt	CDt	BM	CSR	PH	PHPD	Day
L*	1									
a*	0.785	1								
Chl	0.509	0.793	1							
CCt	0.558	0.540	0.512	1						
CDt	0.587	0.599	0.498	0.619	1					
BM	0.755	0.728	0.514	0.654	0.671	1				
CSR	0.755	0.728	0.514	0.654	0.671	1.000	1			
pH	-0.056	-0.043	0.036	0.059	-0.028	-0.063	-0.063	1		
PHPD	-0.051	0.018	0.030	0.153	0.157	0.100	0.100	0.000	1	
Day	0.650	0.551	0.385	0.423	0.524	0.516	0.516	0.000	0.000	1

4.4.17.2 Principal Component Analysis (PCA)

The PCA analysis revealed two principal components (PCs) encompassing the 10 variables, which together accounted for a cumulative variability of 64.41%. The eigenvalues for PC1 and PC2 were 5.3 and 1.0, respectively, as shown in Table 4.69. In principle, variables far away from the axes PC1 and PC2 had a strong factor loading (FL). Referring to the Table 4.69, L*, a*, CDt, CCt, BM, CSR and PHPD had strong FL (FL > 0.75) whereas Chl and Day had moderate FL (0.500 < FL < 0.749) and PH had a weak FL (FL < 0.499).

Table 4.69 The principal components factor loading and eigenvalues of the correlation matrix for *C. radios*a Cell Growth, Carbon Sequestration, and Chromaticity stability

Variables	PC1	PC2
L* (Lightness)	0.862	-0.212
a* (green intensity)	0.879	-0.141
Chl (Chlorophyll content)	0.715	-0.057
CCt (Cell counts)	0.758	0.230
CDt (Cell Density)	0.792	0.164
BM (Biomass)	0.908	0.040
CSR	0.908	0.040
pH	-0.035	0.241
PHPD (Photoperiod)	0.095	0.921
Day	0.687	-0.158
Eigenvalue	5.359	1.082
Variability (%)	53.594	10.820
Cumulative (%)	53.594	64.413

The first principal component (PC) explained 53.59 % of the total variance, with strong factor loadings observed for L*, a*, CDt, CCt, BM and CSR. In contrast, the second principal component (F2) accounted for 10.82% of the total variance, with PHPD identified as the only variable showing a strong association.

4.4.18 Summary of Results

1. There is a strong relationship between the cell growth, biomass, carbon sequestration, lightness and green intensity of the *C. radiosa* with time exposure in response to light and dark condition
2. BBM medium is the optimal choice for cultivating *C. radiosa*, achieving the highest overall growth, biomass production, CO₂ sequestration, and chlorophyll content.
3. The best performance was observed at pH 8 under a 24-hours photoperiod and pH 10 under a 12-hours photoperiod.
4. BBM medium is a strong alternative for applications focused on carbon capture, with the highest CO₂ sequestration (1.18 g/L CO₂e) and robust biomass production (0.75 g/L).
5. The high chlorophyll synthesis under these conditions suggests their effectiveness in enhancing light utilization, a critical factor for energy-efficient applications.
6. Maximising carbon sequestration requires leveraging the strong correlation between biomass (BMASS) and the carbon sequestration rate (CSR). By optimising growth media (nutrient composition, pH, water retention) or light conditions (intensity, spectrum, duration), photosynthetic efficiency and biomass production can be enhanced, resulting in increased CSR and contributing to sustainable carbon management.

4.5 DESMODESMUS BRASILIENSIS

4.5.1 Effect of BBM Medium Formulation, pH and Photoperiod on *D. brasiliensis* Cell Culture Growth

The cell counts data for *D. brasiliensis* cultured in BBM medium over a 14-day period. Under the 18:6 photoperiod, cell counts consistently increased across all pH levels, with optimal growth observed at pH 6.8 and 8 as illustrated in Figure 4.73. A similar trend was noted for the 24:0 photoperiod, although cell counts were slightly lower compared to continuous light exposure. The 12:12 and 6:18 photoperiod resulted in moderate growth rates, with pH 10 again showing the most promising conditions.

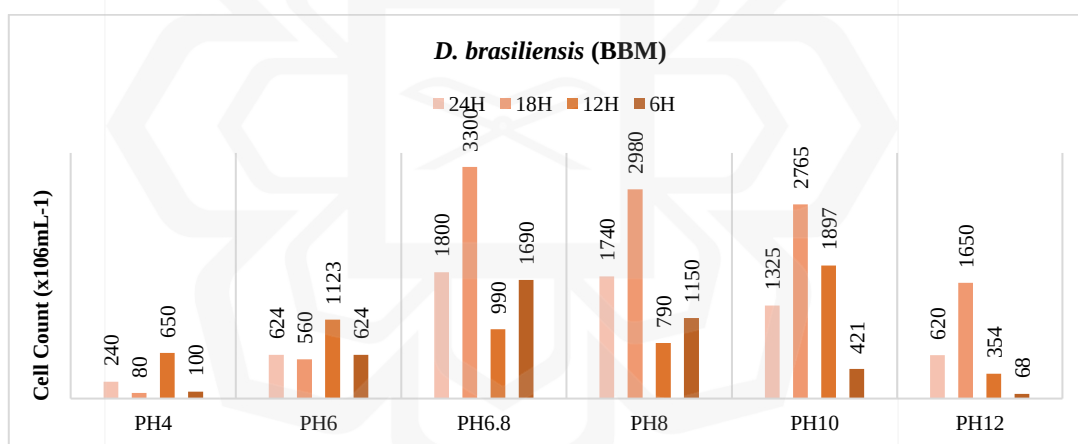


Figure 4.73 Cell counts of *D. brasiliensis* cultured in BBM medium at different pH and photoperiod after 2 weeks

Table 4.70 The optimum cell counts distribution of *D. brasiliensis* cultured in BBM medium at different pH and photoperiod after 2 weeks

Green Algae	Photoperiod	Peak pH	Cell Counts
<i>D. brasiliensis</i>	24:0	pH 6.8	1800
	18:6	pH 6.8	3300
	12:12	pH 10	1897
	6:18	pH 6.8	1800

D. brasiliensis with highest cell counts under BBM medium at 18-hours photoperiod, with a peak of (3300×10^6 cells/mL) at pH 6.8, followed by significant growth during a 18-hours photoperiod, reaching (2980×10^6 cells/mL) at pH 8 and (2765×10^6 cells/mL) at pH 10 as showed in Figure 4.73 and Table 4.70. In contrast, the lowest growth was observed under a 18-hours photoperiod, only 80 cells were countsed at pH 4. Overall, growth trends indicate that the optimal conditions at photoperiods of 18 hours and pH levels between 6.8, 8 and 10 that showed longer photoperiods strong positive impact, particularly within the mid-range pH levels.

Absorbance graphs at 750 nm in BBM medium over 14 days indicate that growth trends are influenced by light exposure and pH conditions. In the 24:0 photoperiod, absorbance steadily increases across all pH levels, with the highest readings observed at pH 8 and 10 starting from day 6 to 14. The 18:6 and 12:12 photoperiod show a similar trend, but the absorbance values are slightly lower, reflecting reduced light exposure as Figure 4.73 exhibited. The 6:18 photoperiod exhibits minimal absorbance increases, indicating limited growth under this light-dark cycle, regardless of pH. These results emphasise the importance of both continuous light and an optimal pH range of 8 to 10 for maximising *D. brasiliensis* growth.

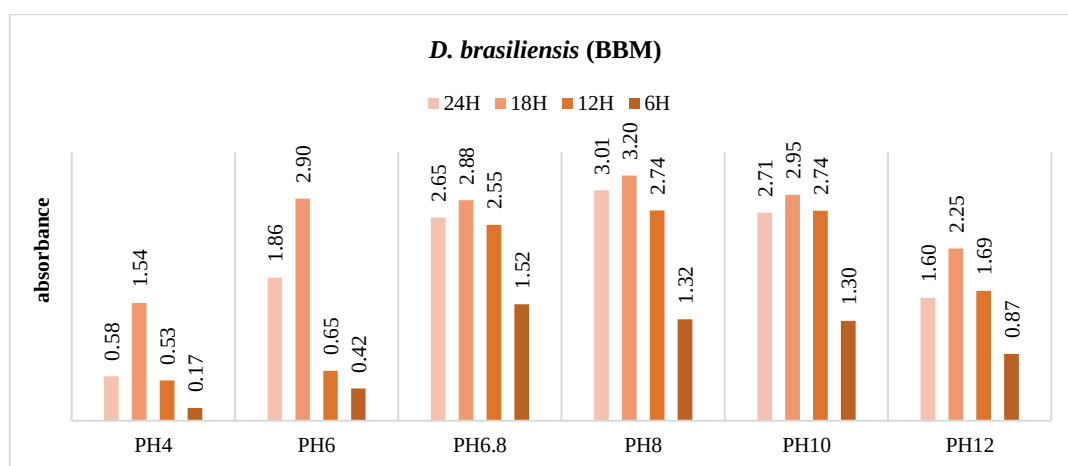


Figure 4.74 The effect of different photoperiod and pH on cell density measured at 750 nm (OD₇₅₀) of *D. brasiliensis* cultured in BBM medium after 2 weeks

Table 4.71 The optimum cell density distribution measured at (OD₇₅₀) of *D. brasiliensis* in BBM medium at different pH and photoperiod after 2 weeks

Green Algae	Photoperiod	Peak pH	Abs
<i>D. brasiliensis</i>	24:0	pH 8	3.01
	18:6	pH 8	3.20
	12:12	pH 10	2.74
	6:18	pH 6.8	1.52

The highest absorbance cell growth is observed at pH 8 for 18-hours photoperiods (3.20). In contrast, the lowest absorbance at pH 4 (0.11) at 6 hours. Overall, balance photoperiods 18 and 12 hours consistently support higher absorbance refer to Figure .4.74 and Table 4.71.

4.5.2 Effect of BBM Medium Formulation, pH and Photoperiod on *D. brasiliensis* Biomass and Carbon Sequestration Rate (CSR)

The highest biomass production (0.83 g/L) and CO₂ sequestration rate (1.30 g/L CO₂e) are achieved under optimal conditions of pH 8 and an 18-hours light cycle. Notably, a 24-hours continuous light cycle also supports substantial growth, yielding slightly lower values of (0.79 g/L) for biomass and (1.24 g/L CO₂e) for CO₂ sequestration. On the other hand, extreme pH levels, particularly pH 10 and 12, combined with shorter light cycles of 6 and 12 hours, result in significantly diminished performance, with the lowest recorded biomass at (0.02 g/L) and CO₂ sequestration at (0.03 g/L CO₂e) as highlighted Figure 4.75 and Figure 4.72. These findings underscore the critical role of moderate environmental conditions in fostering optimal microalgae growth and carbon capture. Specifically, maintaining a neutral-to-alkaline pH range and providing extended light exposure emerge as key factors in maximising these processes.

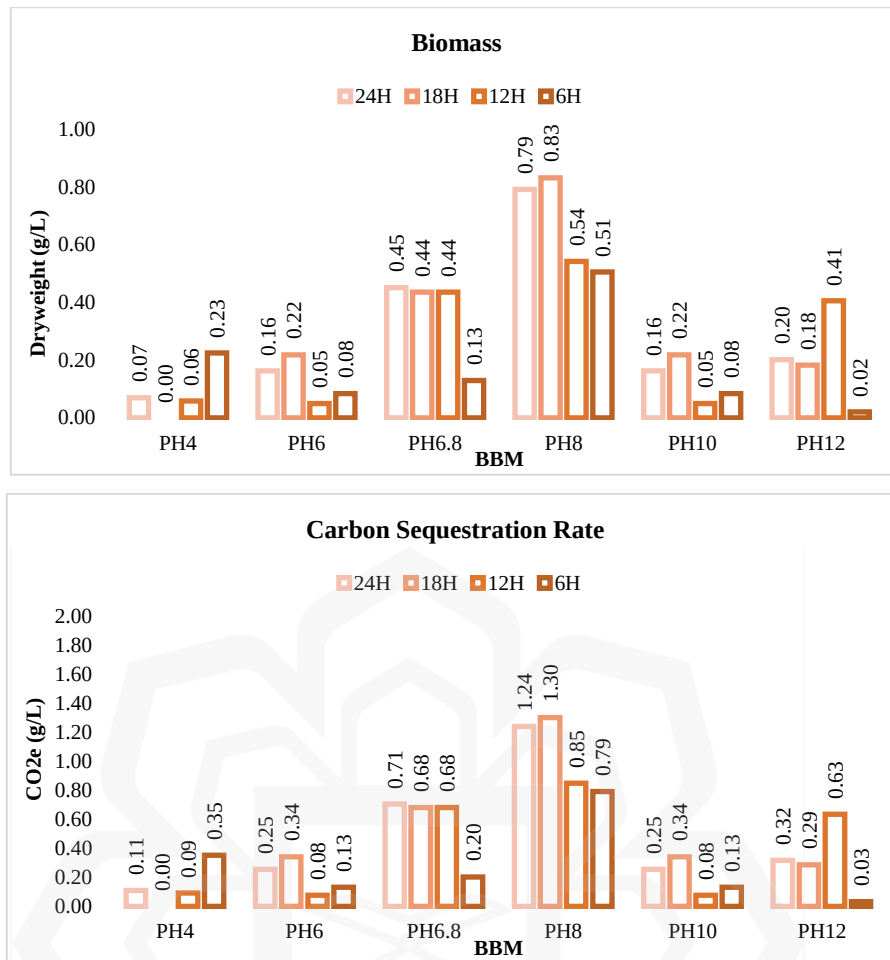


Figure 4.75 Biomass and CSR of of *D. brasiliensis* cultured in BBM medium at different pH and photoperiod after 2 weeks

Table 4.72 The optimum biomass and CSR distribution of *D. brasiliensis* cultured in BBM medium at different pH and photoperiod after 2 weeks

Green Algae	pH	Photoperiod	Biomass (g/L)	CSR (CO ₂ e)
<i>D. brasiliensis</i>	pH 4	6:18	0.23	0.35
	pH 6	18:6	0.22	0.34
	pH 6.8	24:0	0.45	0.71
	pH 8	18:6	0.83	1.30
	pH 10	18:6	0.22	0.34
	pH 12	12:12	0.41	0.63

4.5.3 Effect of BBM Medium Formulation, pH and Photoperiod on *D. brasiliensis* Chlorophyll Content

Distinct patterns in the 600–700 nm wavelength range, indicating variations in chlorophyll content influenced by light exposure and pH. The 24:0 graph show a pronounced peak at ~680 nm for pH 10, with lower absorbance at extreme pH levels. Similarly, the 18:6 and 6:18 photoperiod maintain moderate absorbance at ~680 nm, particularly at pH 6.8, 8 and 10, reflecting adaptability to light-dark cycles. The intensity of green colouration is directly linked to its absorbance values, suggesting that greener samples generally reflect higher chlorophyll content and enhanced light absorption efficiency demonstrated in Figure 4.76.

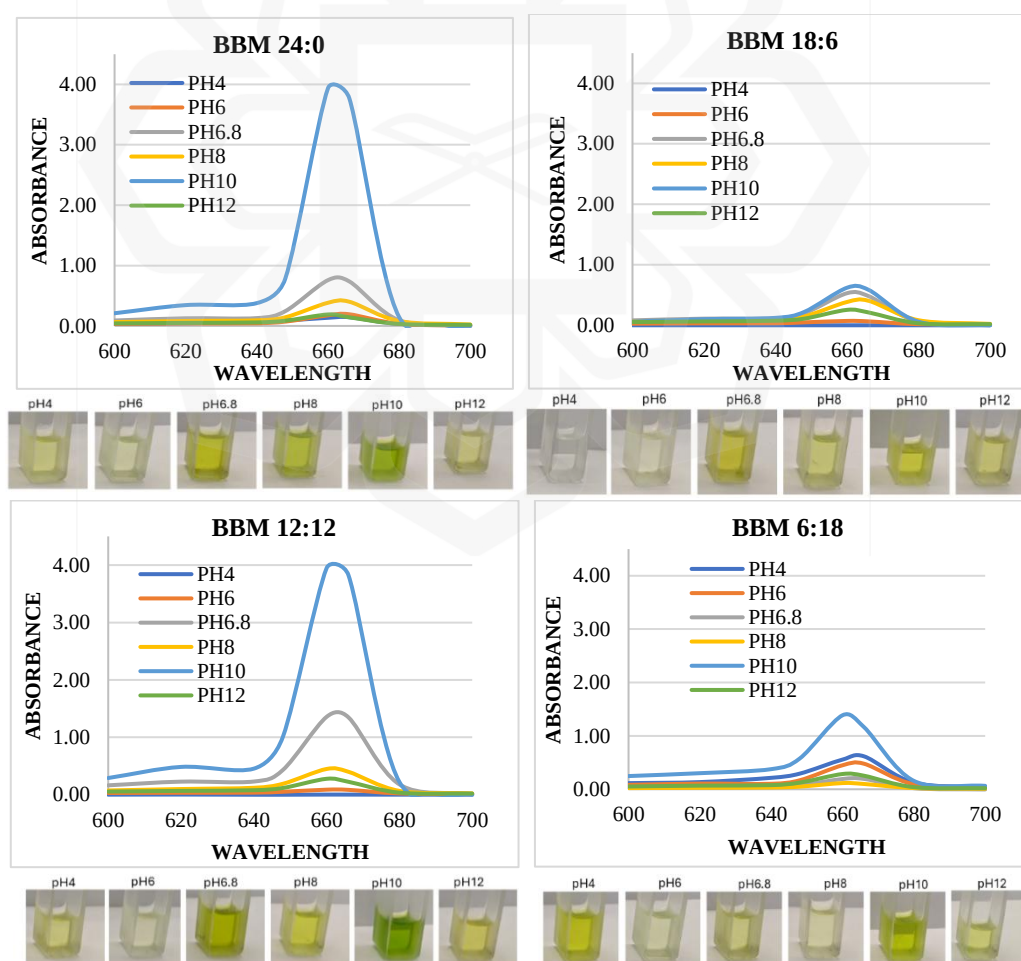


Figure 4.76 Effects of pH and photoperiod on chlorophyll content of *D. brasiliensis* cell culture in BBM medium after 2 weeks

Absorbance data indicates optimal chlorophyll production recorded at pH 10 (3.95) followed by (3.94) with peak supported by 24 hours. In contrast, acidic pH 4 and 6 conditions show significantly lower absorbance values, 0.09 and 0.13 respectively to all photoperiods. Overall, the data highlighting the role of pH 10 and longer light-dark cycles in promoting chlorophyll activity refer to Figure 4.76.

4.5.4 Effect of BBM Medium Formulation, pH and Photoperiod on *D. brasiliensis* Cell Culture Chromaticity

The data reveals that the highest green intensity (a*) was recorded at a 12-hours photoperiod with pH 10, reaching (46.32), while the lowest was observed at a 12-hours photoperiod with pH 4, at (0.03) among photoperiods, the pH 10 consistently exhibited the highest values, indicating it as the most positive for green intensity, while the pH 4 and 6 had the lowest values overall, particularly under 12 hours as per recorded in Figure 4.77 and Table 4.73.

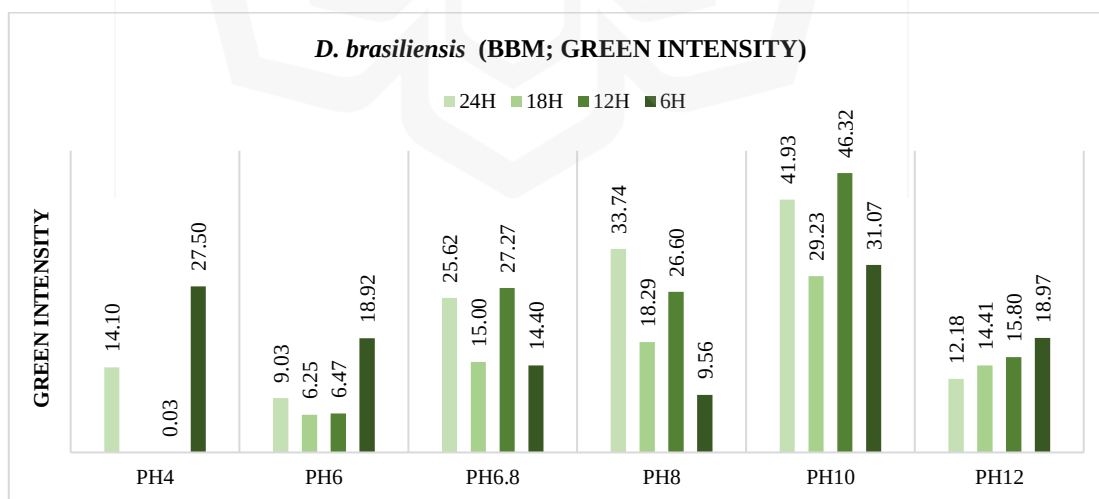


Figure 4.77 Effects of pH and photoperiod on green intensity values (a*) of *D. brasiliensis* cell culture in BBM medium after 2 weeks

Table 4.73 Green intensity (a*) distribution of *D. brasiliensis* cell culture in BBM medium at different pH and photoperiod after 2 weeks

Green Algae	Photoperiod	Peak pH	a*
<i>D. brasiliensis</i>	24:0	pH 10	41.93
	18:6	pH 10	29.23
	12:12	pH 10	46.32
	6:18	pH 10	31.07
<i>a*</i> , ranges from white (0) to green (100)			

The highest lowers value (L*) recorded was (79.47) at pH 10 under 6-hours photoperiod, indicating reduced light absorption, while the highest lightness value was (100.08) at pH 4 under a 12-hours photoperiod. Overall, the data trend demonstrates that balance photoperiods, particularly 12 hours, combined with neutral pH 10 are more promising for effective light absorption by the algae refer to Figure 4.78 and Table 4.74.

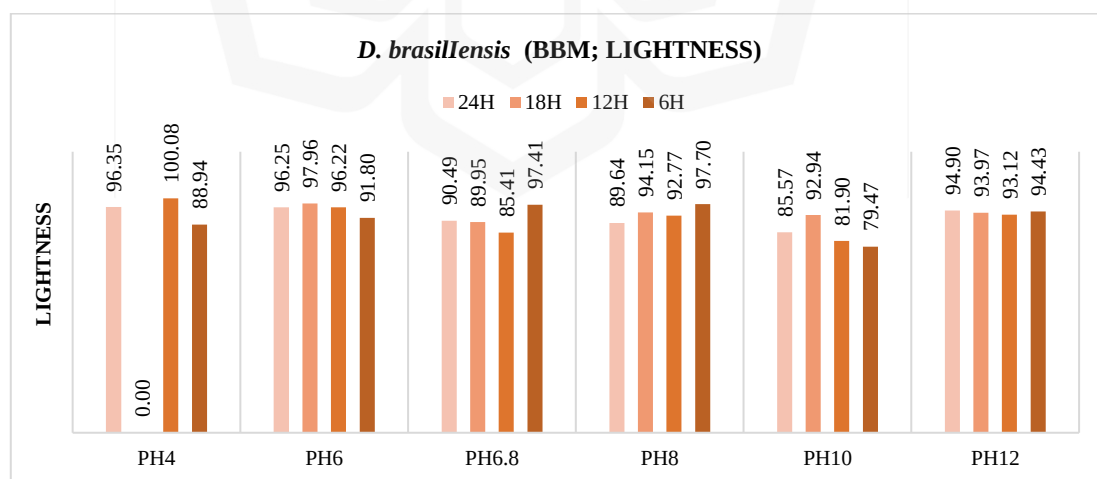


Figure 4.78 Effects of pH and photoperiod on lightness values (L*) of *D. brasiliensis* cell culture in BBM medium after 2 weeks

Table 4.74 Lightness (L*) values distribution of *D. brasiliensis* cell culture in BBM medium at different pH and photoperiod after 2 weeks

Green Algae	Photoperiod	Peak pH	L*
<i>D. brasiliensis</i>	24:0	pH 10	85.57
	18:6	pH 6.8	89.95
	12:12	pH 10	81.90
	6:18	pH 10	79.47
<i>L*</i> , ranges from black (0) to white (100)			

In conclusion, *D. brasiliensis* exhibited the highest growth (3300×10^6 cells/mL) and absorbance (3.20) at pH 6.8-8 under an 18-hours photoperiod, with optimal biomass (0.83 g/L) and CO₂ sequestration (1.30 g/L CO₂e) at pH 8. Lower growth was observed at pH 4. Chlorophyll production peaked at pH 10 (3.95×10^6 mL⁻¹), while green intensity (a*) and lightness (L*) were highest at pH 10 with 12-hours photoperiods. Overall, moderate pH levels (6.8-10) and longer light cycles favor growth and carbon sequestration.

4.5.5 Effect of BG11 Medium Formulation, pH and Photoperiod on *D. brasiliensis* Cell Culture Growth

D. brasiliensis cell counts in BG11 medium experience a significant increase after Day 6, with peak growth observed by Day 14 as demonstrated in Figure 4.79. Moderate light exposure 18:6 and 12:12 photoperiod promotes the fastest and highest cell growth, making it the most effective photoperiod for growth. The 24:0 light cycle also supports healthy growth, though slightly slower than continuous light. In contrast, the 6:18 cycles with reduced light exposure result in noticeably slower growth rates and much lower peak cell counts.

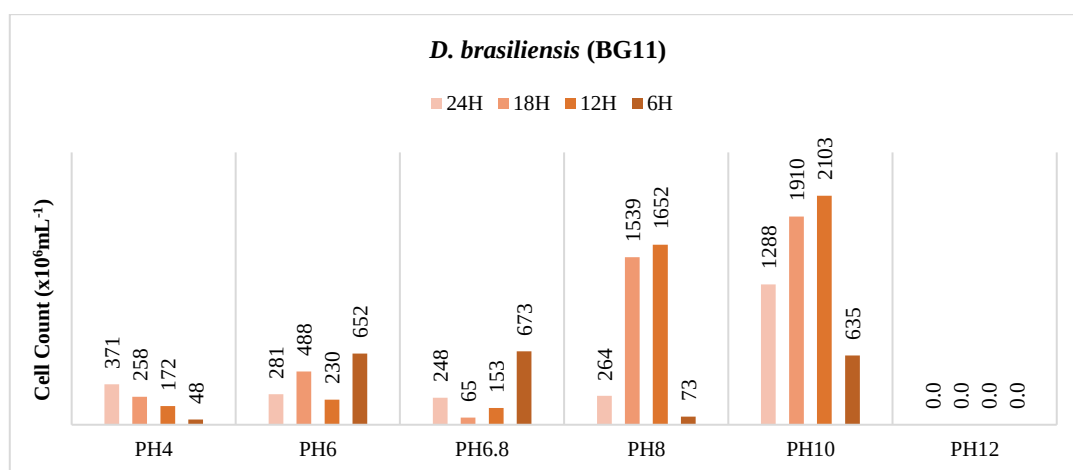


Figure 4.79 Cell counts of *D. brasiliensis* cultured in BG11 medium at different pH and photoperiod after 2 weeks

Table 4.75 The optimum cell counts distribution of *D. brasiliensis* cultured in BG11 medium at different pH and photoperiod after 2 weeks

Green Algae	Photoperiod	Peak pH	Cell Counts (x10 ⁶ mL ⁻¹)
<i>D. brasiliensis</i>	24:0	pH 10	1288
	18:6	pH 10	1910
	12:12	pH 10	2103
	6:18	pH 10	635

The highest cell counts under BG11 medium at 12 hours photoperiod, with a peak of (2103×10^6 cells/mL) at pH 10, followed by significant growth during 18 hours reaching (1910×10^6 cells/mL) as highlighted in Table 4.75. In contrast, the lowest growth was observed at pH 8 and 6 which are 8 cells under 6 hours. Overall, growth trends indicate that the optimal conditions at photoperiods of 18-12 hours and pH levels between 8 and 10 that showed longer photoperiods strong positive impact.

Absorbance graphs at 750 nm in BG11 medium over 14 days indicate that growth trends are influenced by light exposure and pH conditions. In the 24:0 and 18:6 photoperiod, absorbance steadily increases across all pH levels, with the highest readings observed at pH 8 and 10. For the 12:12 photoperiod, absorbance increases moderately, with pH 8 and 10 still supporting the highest growth but to a lesser extent than the previous conditions. The 6:18 photoperiod exhibits minimal absorbance increases, indicating limited growth under this light-dark cycle, regardless of pH refer to Figure 4.80.

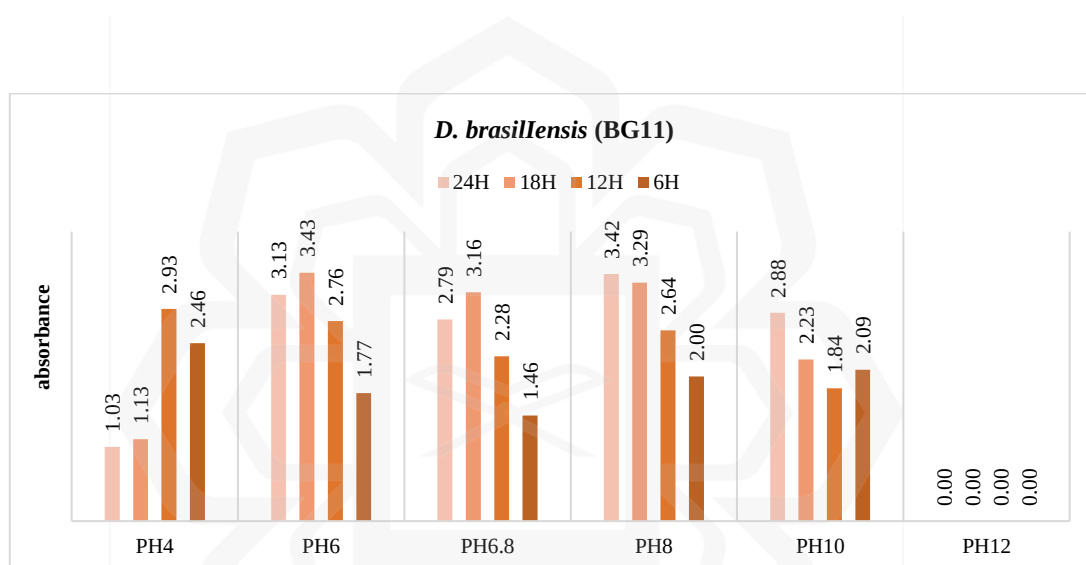


Figure 4.80 The effect of different photoperiod and pH on cell density measured at 750 nm (OD_{750}) of *D. brasiliensis* cultured in BG11 medium after 2 weeks

Table 4.76 The optimum cell density distribution measured at (OD_{750}) of *D. brasiliensis* in BG11 medium at different pH and photoperiod after 2 weeks

Green Algae	Photoperiod	Peak pH	Abs
<i>D. brasiliensis</i>	24:0	pH 8	3.42
	18:6	pH 6	3.43
	12:12	pH 6	2.76
	6:18	pH 4	2.46

Absorbance varies by photoperiod and pH, peaking at pH 6 and 8 under an 18 and 12-hours photoperiod on Day 14 (3.43 and 3.42). The lowest value is at pH 4 under a 24-hours photoperiod on day 14 (1.03) as highlighted in Table 4.76. Longer photoperiods (24H, 18H) support higher growth rates, while shorter ones (12H, 6H) show limited growth and pH 6, 6.8 and 8 generally promotes better absorbance.

4.5.6 Effect of BG11 Medium Formulation, pH and Photoperiod on *D. brasiliensis* Biomass and Carbon Sequestration Rate (CSR)

Optimal biomass (0.54 g/L) and CO₂ sequestration (0.85 g/L CO₂e) occur at pH 6 with a 6 hours photoperiod. pH 10 produces the lowest outcomes (biomass 0.06 g/L, CO₂ 0.09 g/L CO₂e) under 6 hours. Continuous light (24and18 hours) supports growth but is less effective than 6 hours, with biomass and CO₂ sequestration peaking at pH 8 (0.51 g/L and 0.79 g/L). Moderate conditions like pH 6 with an 12H photoperiod generate notable performance (biomass 0.52 g/L, CO₂ 0.82 g/L CO₂e), while shorter light exposure photoperiods limit results as per Figure 4.81 and Table 4.77.

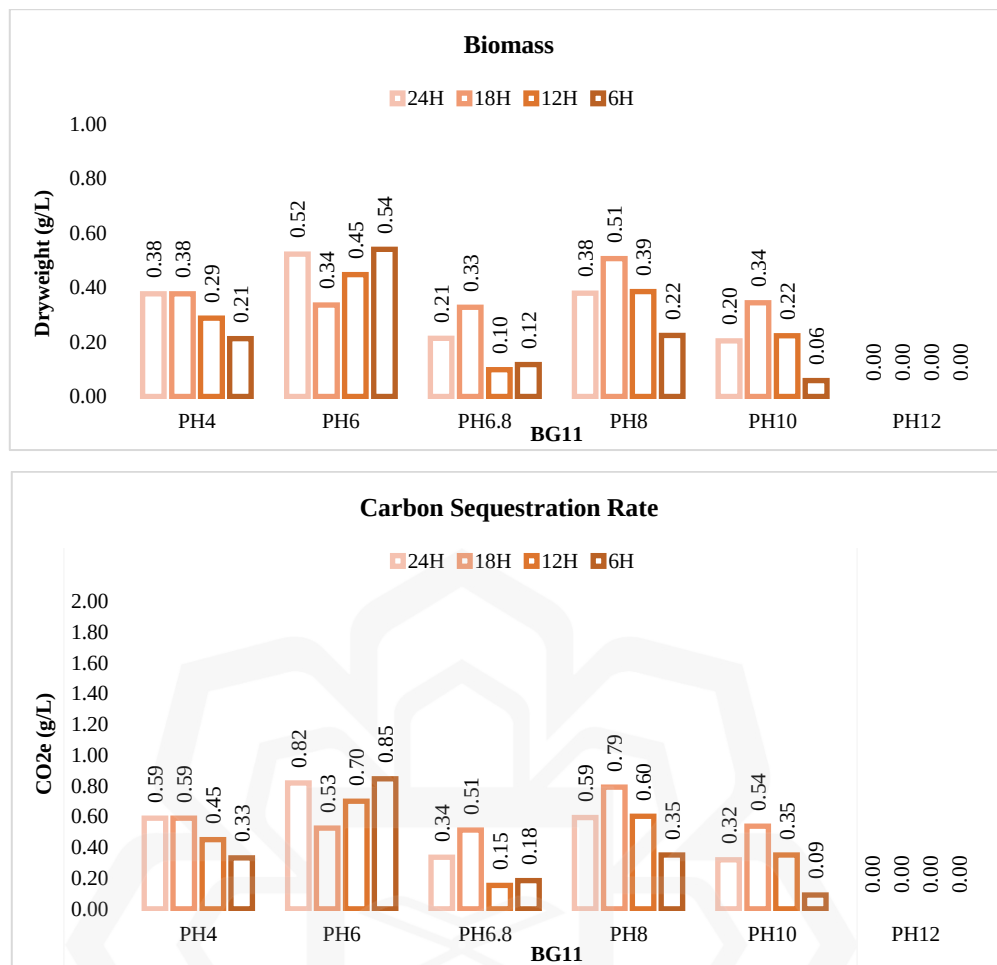


Figure 4.81 Biomass and CSR of *D. brasiliensis* cultured in BG11 medium at different pH and photoperiod after 2 weeks

Table 4.77 The optimum biomass and CSR distribution of *D. brasiliensis* cultured in BG11 medium at different pH and photoperiod after 2 weeks

Green Algae	pH	Photoperiod	Biomass (g/L)	CSR (CO ₂ e)
<i>D. brasiliensis</i>	pH 4	24:0	0.38	0.59
	pH 6	6:18	0.54	0.85
	pH 6.8	18:6	0.33	0.51
	pH 8	18:6	0.51	0.79
	pH 10	18:6	0.34	0.54

4.5.7 Effect of BG11 Medium Formulation, pH and Photoperiod on *D. brasiliensis* Chlorophyll Content

Figure 4.82 illustrates distinct patterns in the 600–700 nm wavelength range, showcasing variations in chlorophyll content influenced by light exposure and pH levels. The intensity of green colouration notably affects absorbance measurements. Graphs corresponding to light exposure ratios of 24:0 and 18:6 display a pronounced peak around 680 nm, particularly at pH levels 6, 8, and 10, indicating optimal chlorophyll activity under these conditions.

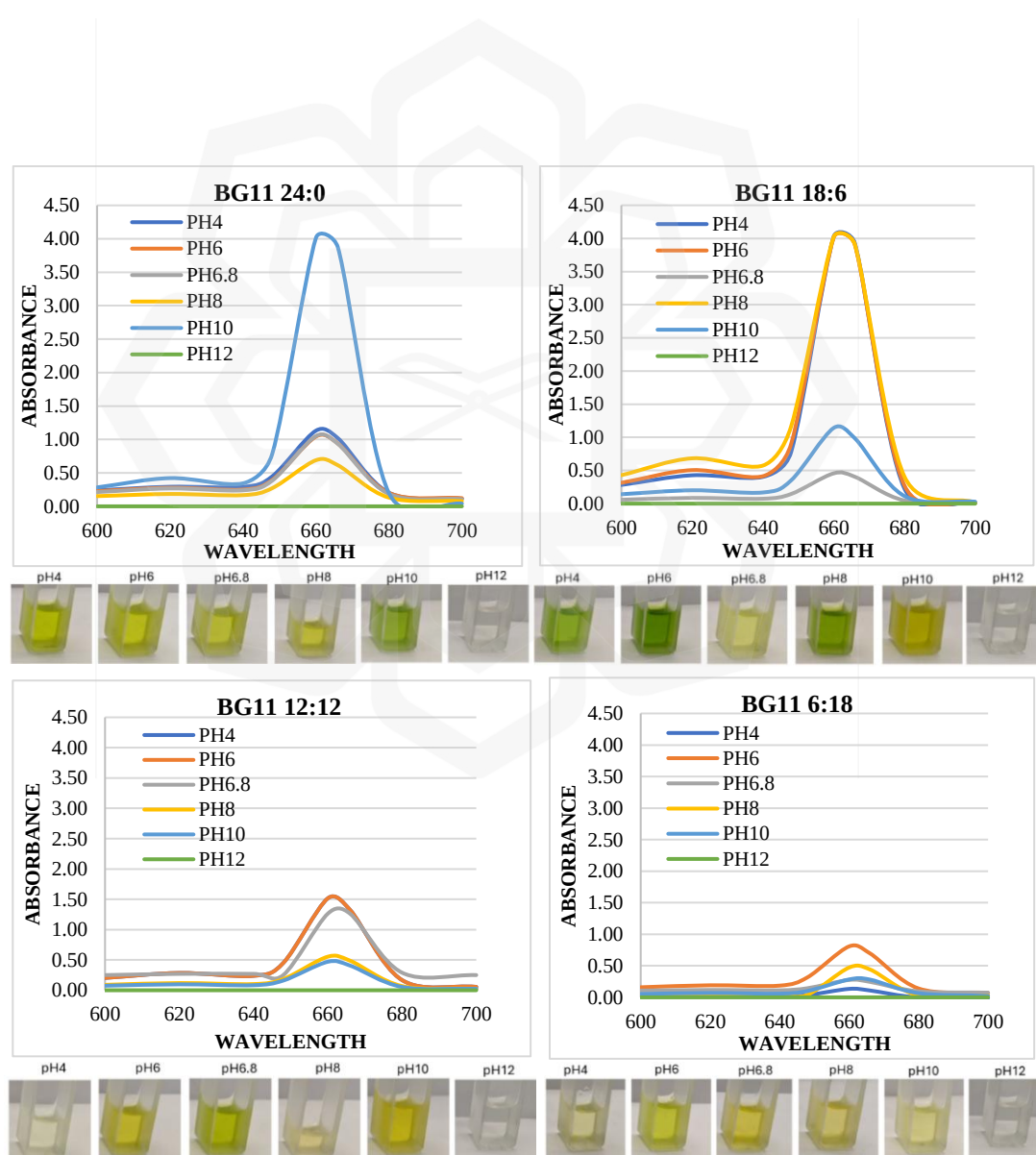


Figure 4.82 Effects of pH and photoperiod on chlorophyll content of *D. brasiliensis* cell culture in BG11 medium after 2 weeks

Chlorophyll absorbance production peaks at pH 4, 6, 8 and 10 with absorbance in the 660–666 nm range, with better results under 24H and 18H photoperiods recorded by (4.03 and 4.02). Limited exposure (6H) with all pH show the lowers result only (0.13 to 0.28). Light-dark cycles of 24:0 and 18:6 enhance algae growth as demonstrated in Figure 4.82.

4.5.8 Effect of BG11Medium Formulation, pH and Photoperiod on *D. brasiliensis* Cell Culture Chromaticity

Green intensity peaks at pH 8 under a 18H photoperiod 44.81, while the lowest values occur at pH 6.8 under 12-hours photoperiod 0.15. The 18H cycle consistently produces the highest intensity, while the 6H cycle produces the lowest as per highlighted in Figure 4.83 and Table 4.78.

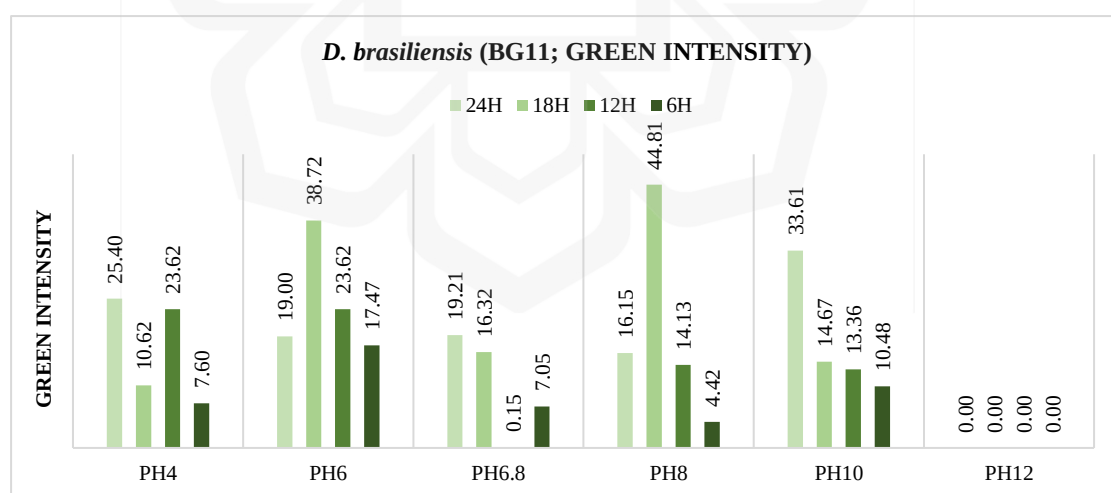


Figure 4.83 Effects of pH and photoperiod on green intensity values (a*) of *D. brasiliensis* cell culture in BG11 medium after 2 weeks

Table 4.78 Green intensity (a*) distribution of *D. brasiliensis* cell culture in BG11 medium at different pH and photoperiod after 2 weeks

Green Algae	Photoperiod	Peak pH	a*
<i>D. brasiliensis</i>	24:0	pH 10	33.61
	18:6	pH 8	44.81
	12:12	pH 4 and 6	23.62
	6:18	pH 6	17.47
<i>a*</i> , ranges from white (0) to green (100)			

Lightness the lowest at pH 6.8 under a 12-hours photoperiod (28.87) and highest at pH (97.93) under the 6-hours photoperiod, indicating reduced light absorption under these conditions. Longer photoperiods (24H, 18H) with pH 10 enhance light absorption, while shorter light exposure and acidic conditions reduce efficiency as showed in Figure 4.84 and Table 4.79.

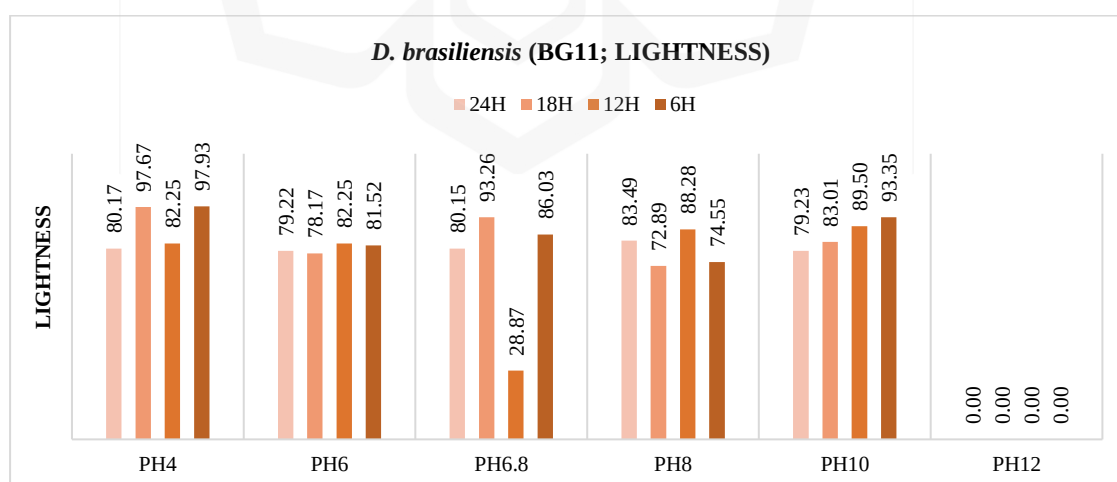


Figure 4.84 Effects of pH and photoperiod on lightness values (L*) of *D. brasiliensis* cell culture in BG11 medium after 2 weeks

Table 4.79 Lightness (L*) values distribution of *D. brasiliensis* cell culture in BG11 medium at different pH and photoperiod after 2 weeks

Green Algae	Photoperiod	Peak pH	L*
<i>D. brasiliensis</i>	24:0	pH 6	79.22
	18:6	pH 8	72.89
	12:12	pH 6.8	28.87
	6:18	pH 8	74.55
<i>L*</i> , ranges from black (0) to white (100)			

In conclusion, optimal growth peaks at pH 10 (2103×10^6 cells/mL) during a 12-hours photoperiod and (1910×10^6 cells/mL) at 18 hours, while minimal growth occurs at pH 6 and 8 under 6 hours. Absorbance is highest at pH 6 and 8 (3.43) with 18 and 12 hours, whereas biomass (0.54 g/L) and CO₂ sequestration (0.85 g/L CO₂e) are optimal at pH 6 with 6 hours. Longer photoperiods (24H, 18H) enhance chlorophyll and green intensity.

4.5.9 Effect of BRISTOL Medium Formulation, pH and Photoperiod on *D. brasiliensis* Cell Culture Growth

Figure 4.85 show that *D. brasiliensis* cell counts increasing significantly after Day 6 and peaking by Day 14 in Bristol medium. Overall result leads to the moderate growth, under 24:0 light followed by the 18:6 light cycle. Less light in the 12:12 which still supports good growth but at a slightly slower rate and 6:18 cycles slow growth visibly.

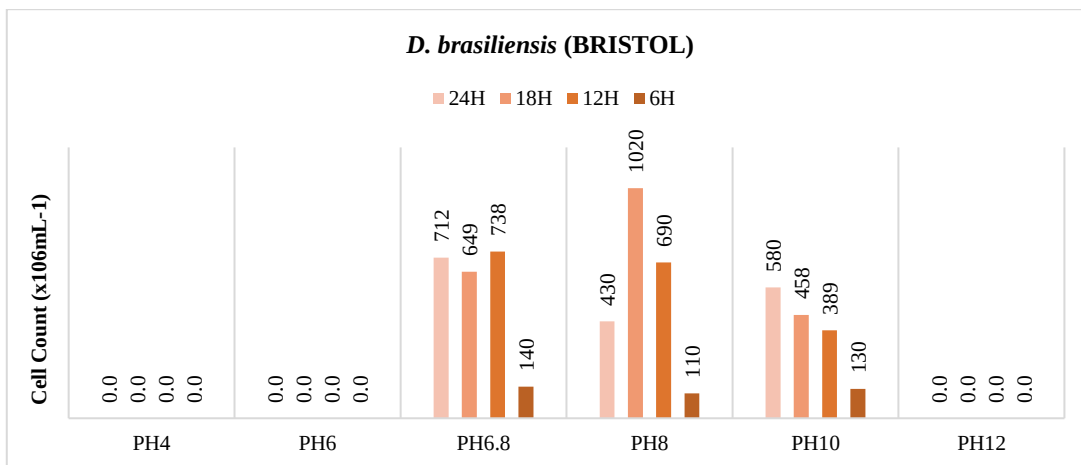


Figure 4.85 Cell counts of *D. brasiliensis* cultured in BRISTOL medium at different pH and photoperiod after 2 weeks

Table 4.80 The optimum cell counts distribution of *D. brasiliensis* cultured in BRISTOL medium at different pH and photoperiod after 2 weeks

Green Algae	Photoperiod	Peak pH	Cell Counts (x10 ⁶ mL ⁻¹)
<i>D. brasiliensis</i>	24:0	pH 6.8	712
	18:6	pH 8	1020
	12:12	pH 6.8	738
	6:18	pH 6.8	140

The data collected using Bristol medium highlights the influence of photoperiod and pH on cell growth. The highest cell counts were observed under an 18-hours photoperiod at pH 8, with a record of $(1020 \times 10^6 \text{ cells/mL})$, indicating this as the optimal condition for growth (Table 4.80). This is followed by pH 6.8 under a 12-hours photoperiod, yielding $(738 \times 10^6 \text{ cells/mL})$. On the other hand, the least growth occurred under a 6-hours photoperiod at pH 8, with only $(110 \times 10^6 \text{ cells/mL})$, reflecting the significant impact of reduced light exposure on cell production.

Continuous light exposure (24:0) supports steady but slow growth, followed closely by the 18:6 photoperiod, which show slightly reduced growth, as illustrated in Figure 4.86. The 18:6 photoperiod achieves the highest growth, peaking at pH 8, while the 6:18 photoperiod demonstrates the lowest absorbance, indicating minimal growth due to restricted light exposure.

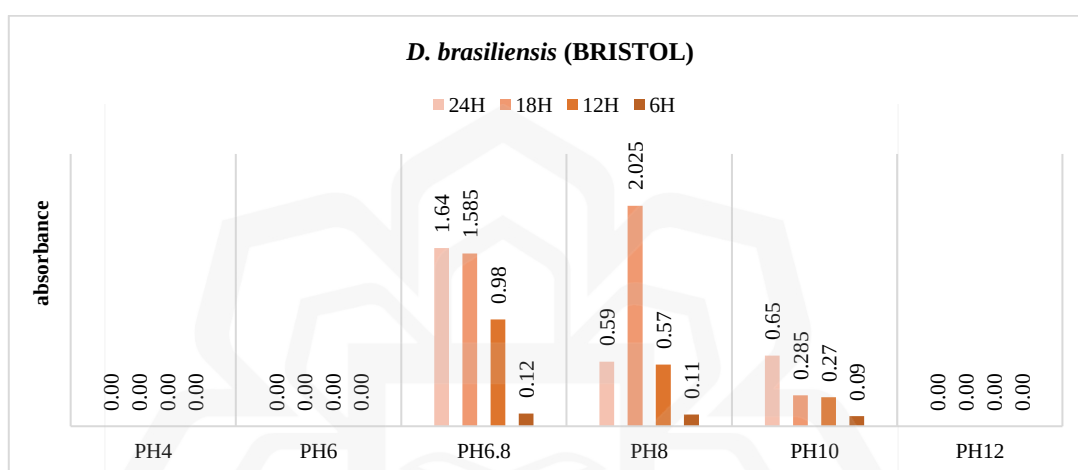


Figure 4.86 The effect of different photoperiod and pH on cell density measured at 750 nm (OD_{750}) of *D. brasiliensis* cultured in BRISTOL medium after 2 weeks

Table 4.81 The optimum cell density distribution measured at (OD_{750}) of *D. brasiliensis* in BRISTOL medium at different pH and photoperiod after 2 weeks

Green Algae	Photoperiod	Peak pH	Abs
<i>D. brasiliensis</i>	24:0	pH 6.8	1.64
	18:6	pH 8	2.03
	12:12	pH 6.8	0.98
	6:18	pH 6.8	0.12

The highest absorbance is recorded at pH 8 with an 18-hours photoperiod on Day 14 (2.03), while the lowest is at pH 10 with a 6-hours photoperiod (0.09) as showed in Table 4.81. Longer photoperiods (24 and 18 hours) and pH levels near neutral to slightly alkaline pH 6.8 and 8 support better growth.

4.5.10 Effect of BRISTOL Medium Formulation, pH and Photoperiod on *D. brasiliensis* Biomass and Carbon Sequestration Rate (CSR)

Highest result show under a 6-hours photoperiod at pH 6.8, biomass peaks at (0.38 g/L) and CO₂ sequestration at (0.59 g/L CO₂e). The lowest values are at pH 6.8 and 10 with same 6-hours photoperiod show biomass (0.05 g/L) and CO₂ sequestration (0.08 g/L CO₂e) as display in Figure 4.87.

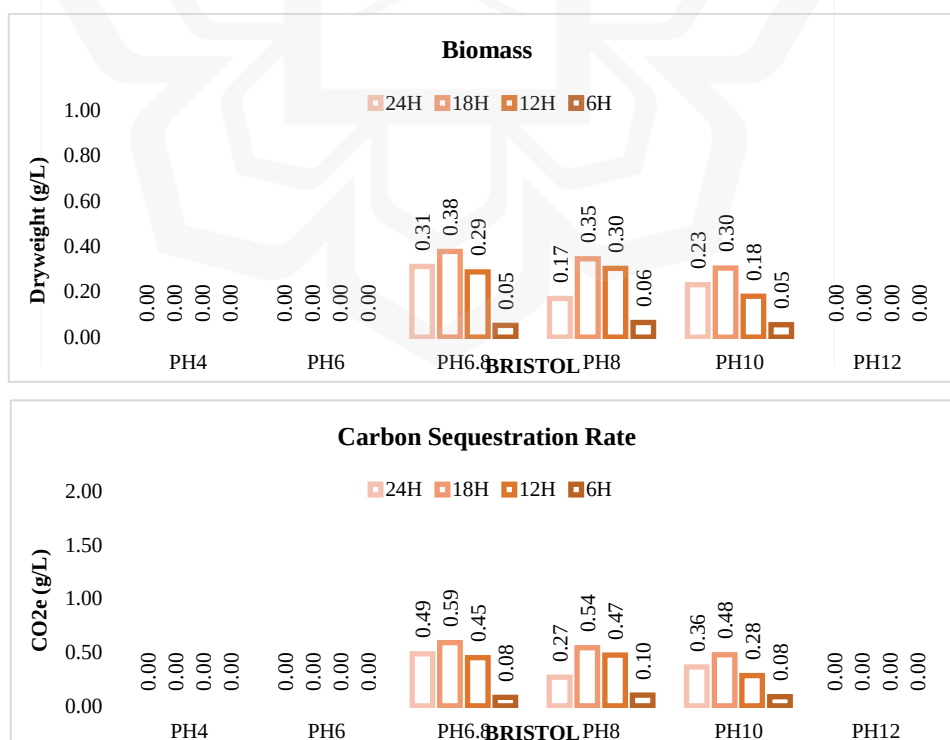


Figure 4.87 Biomass and CSR of *D. brasiliensis* cultured in BRISTOL medium at different pH and photoperiod after 2 weeks

Table 4.82 The optimum biomass and CSR distribution of *D. brasiliensis* cultured in BRISTOL medium at different pH and photoperiod after 2 weeks

Green Algae	pH	Photoperiod	Biomass (g/L)	CSR (CO ₂ e)
<i>D. brasiliensis</i>	pH 6.8	18:6	0.38	0.59
	pH 8	18:6	0.35	0.54
	pH 10	18:6	0.30	0.48

4.5.11 Effect of BRISTOL Medium Formulation, pH and Photoperiod on *D. brasiliensis* Chlorophyll Content

Figure 4.88 illustrates distinct patterns in the 600–700 nm wavelength range, reflecting variations in chlorophyll content influenced by light exposure and pH levels. The graphs for 24:0, 18:6, 12:12 and 6:18 photoperiods exhibit lower absorbance across all pH levels show rising peaks at pH 6.8 and 8, indicating increased chlorophyll activity under these specific conditions.

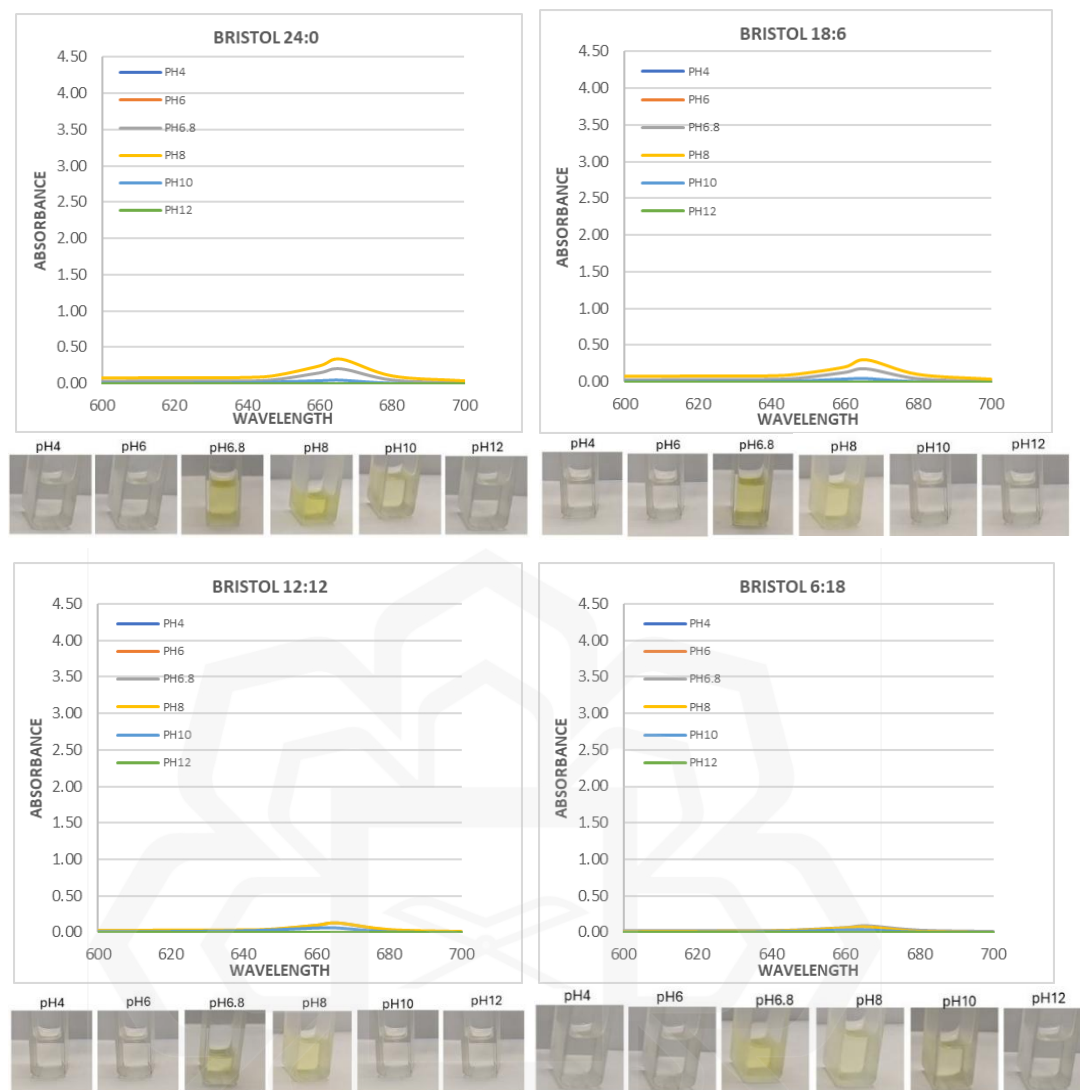


Figure 4.88 Effects of pH and photoperiod on chlorophyll content of *D. brasiliensis* cell culture in BRISTOL medium after 2 weeks

4.5.12 Effect of BRISTOL Medium Formulation, pH and Photoperiod on *D. brasiliensis* Cell Culture Chromaticity

Optimal chlorophyll absorbance production occurs at pH 6.8 and 8 under a 24 and 18-hours photoperiod, peaking same result (0.33 ± 0.32). The lowest is at pH 4 with 6-hours exposure, at (0.01). longer photoperiods 12 hours enhance chlorophyll synthesis refer to Figure 4.89.

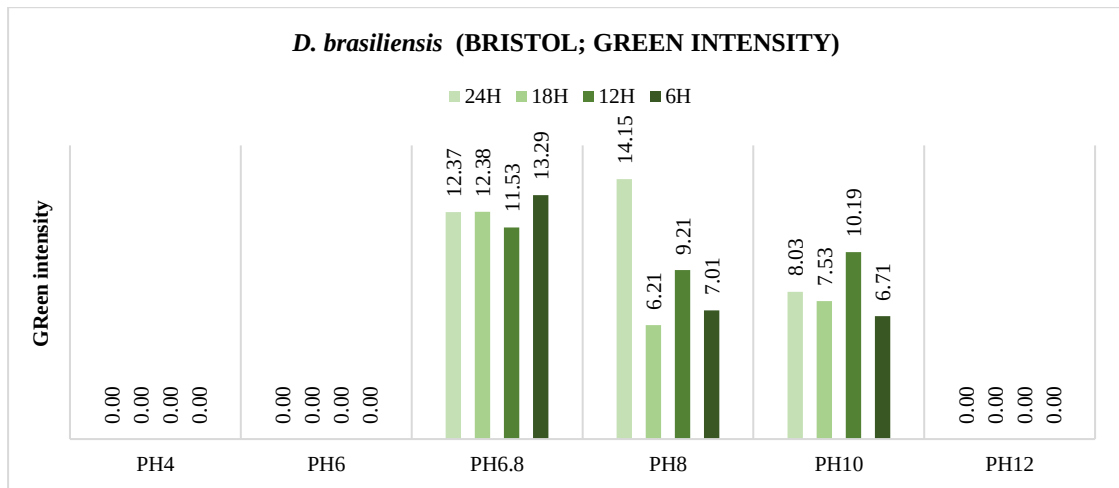


Figure 4.89 Effects of pH and photoperiod on green intensity values (**a***) of *D. brasiliensis* cell culture in BRISTOL medium after 2 weeks

Table 4.83 Green intensity (**a***) distribution of *D. brasiliensis* cell culture in BRISTOL medium at different pH and photoperiod after 2 weeks

Green Algae	Photoperiod	Peak pH	a*
<i>D. brasiliensis</i>	24:0	pH 8	14.15
	18:6	pH 6.8	12.38
	12:12	pH 6.8	11.53
	6:18	pH 6.8	13.29
<i>a*</i> , ranges from white (0) to green (100)			

The highest green intensity is observed at pH 8 with a 24-hours photoperiod (14.15), while the lowest is at pH 8 and with an 18-hours photoperiod share same result (6.21) as highlighted in Figure 4.89 and Table 4.83. The lowest lightness value, indicating better light absorption, is (13.58) under 18-hours photoperiod at pH 8. The highest lightness, indicating reduced absorption, is (99.07) at pH 10 with a 6-hours photoperiod refer to Figure 4.90 and Table 4.84.

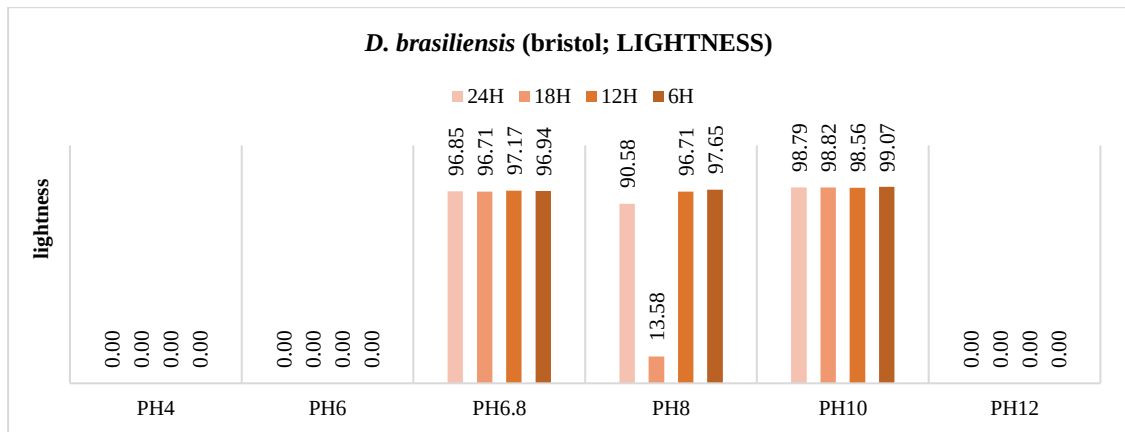


Figure 4.90 Effects of pH and photoperiod on lightness values (L^*) of *D. brasiliensis* cell culture in BRISTOL medium after 2 weeks

Table 4.84 Lightness (L^*) values distribution of *D. brasiliensis* cell culture in BRISTOL medium at different pH and photoperiod after 2 weeks

Green Algae	Photoperiod	Peak pH	L^*
<i>D. brasiliensis</i>	24:0	pH 8	90.58
	18:6	pH 8	13.58
	12:12	pH 8	96.71
	6:18	pH 6.8	96.94
<i>L*</i> , ranges from black (0) to white (100)			

In summarise, the result show optimal microalgae growth at pH 8 under an 18-hours photoperiod, with maximum cell counts (1020×10^6 cells/mL) and absorbance (2.03) on Day 14. Biomass (0.38 g/L) and CO₂ sequestration (0.59 g/L CO₂e) peak at pH 6.8 under a 6-hours photoperiod. Chlorophyll synthesis is enhanced at pH 6.8–8 with 24- and 18-hours photoperiods, peaking at (0.32). Green intensity is highest at pH 8 under a 24-hours photoperiod (14.15). Short photoperiods and extreme pH will reduce growth.

4.5.13 Effect of Chu Medium Formulation, pH and Photoperiod on *D. brasiliensis* Cell Culture Growth

The 4.91 show that *D. brasiliensis* cell counts lower increasing from Day 6 until by Day 14 in Chu medium. Overall result leads to the lower growth, under 24:0 light followed by the 18:6 light cycle. Less light in the 12:12 and 6:18 which still supports moderate growth but at a slightly slower rate with slow growth visibly.

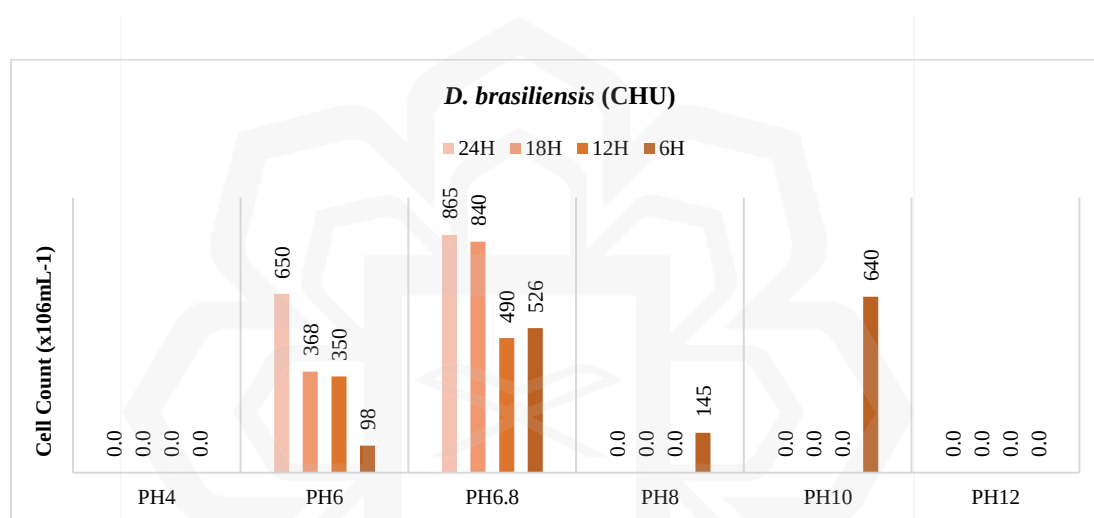


Figure 4.91 Cell counts of *D. brasiliensis* cultured in Chu medium at different pH and photoperiod after 2 weeks

Table 4.85 The optimum cell counts distribution of *D. brasiliensis* cultured in Chu medium at different pH and photoperiod after 2 weeks

Green Algae	Photoperiod	Peak pH	Cell Counts (x10 ⁶ mL ⁻¹)
<i>D. brasiliensis</i>	24:0	pH 6.8	865
	18:6	pH 6.8	840
	12:12	pH 8	490
	6:18	pH 10	640

The data collected using Chu medium demonstrates the critical role of photoperiod and pH in influencing cell growth. The highest cell counts (865×10^6 cells/mL), was recorded under a 24-hours photoperiod at pH 6.8, suggesting that continuous light exposure at this pH level provides optimal conditions for growth. On the other hand, the minimum growth was observed under a 6-hours photoperiod at pH 6, with only (98×10^6 cells/mL), indicating that shorter light exposure significantly limits cell proliferation. Refer to Figure 4.91 and Table 4.85 for detailed data.

The absorbance analysis of *D. brasiliensis* cultured in CHU medium reveals that pH 6.8 consistently supports optimal growth across all photoperiods, followed by pH 8 and 10. Continuous light (24:0) and extended light exposure (18:6) result in higher absorbance values and faster growth compared to shorter light periods (12:12 and 6:18). Growth peaks are generally observed between days 6 to 10 under encouraging condition as displayed in Figure 4.92.

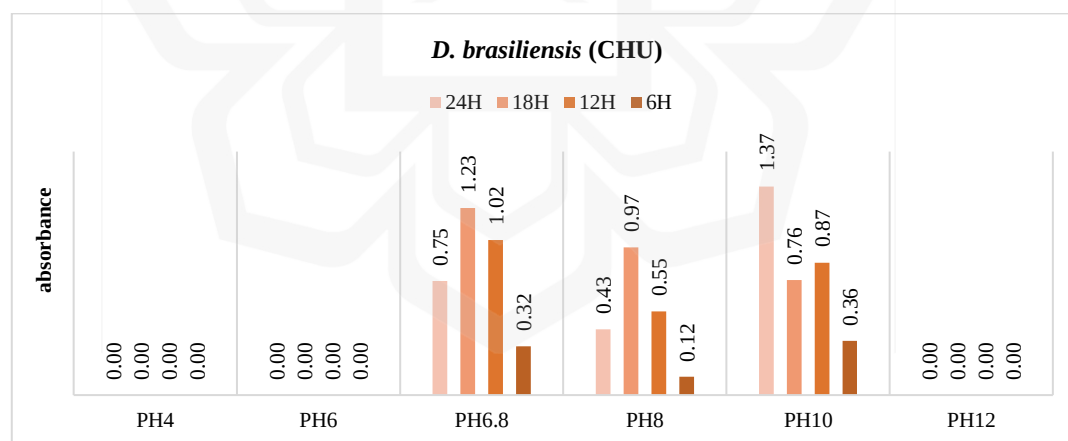


Figure 4.92 The effect of different photoperiod and pH on cell density measured at 750 nm (OD_{750}) of *D. brasiliensis* cultured in Chu medium after 2 weeks

Table 4.86 The optimum cell density distribution measured at (OD₇₅₀) of *D. brasiliensis* in Chu medium at different pH and photoperiod after 2 weeks

Green Algae	Photoperiod	Peak pH	Abs
<i>D. brasiliensis</i>	24:0	pH 10	1.37
	18:6	pH 6.8	1.23
	12:12	pH 6.8	1.02
	6:18	pH 10	0.36

Table 4.86 recorded the highest absorbance is recorded at pH 10 with a 24-hours photoperiod on Day 14 (1.37), while the lowest is at pH 8 with a 6-hours photoperiod (0.12). Longer photoperiods (24H and 8H) and pH 6,8, and 10 support better growth refer to Table 4.86.

4.5.14 Effect of Chu Medium Formulation, pH and Photoperiod on *D. brasiliensis* Biomass and Carbon Sequestration Rate (CSR)

The highest biomass result show under a 24-hours photoperiod at pH 6.8, biomass peaks at (0.38 g/L) and CO₂ sequestration at (0.59 g/L CO₂e). The lowest values are at pH 4 with 6-hours photoperiod: biomass (0.01 g/L) and CO₂ sequestration (0.02 g/L CO₂e) as highlighted in Figure 4.93 and Table 4.87.

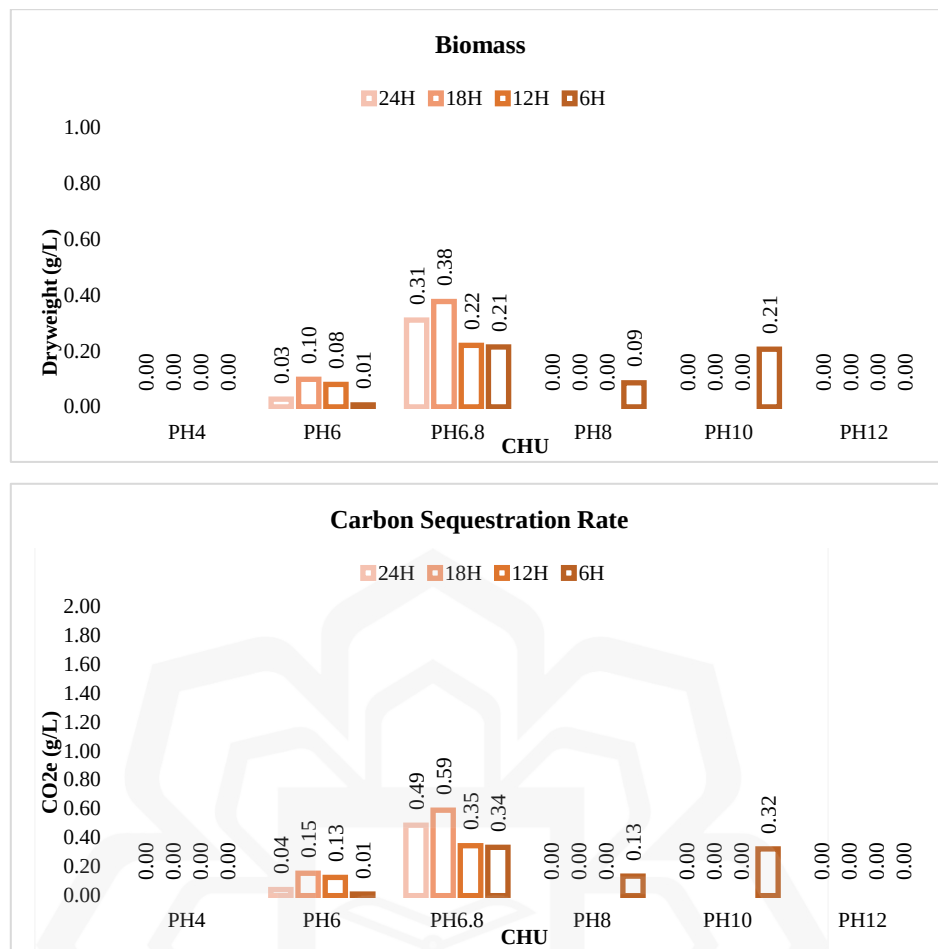


Figure 4.93 Biomass and CSR of *D. brasiliensis* cultured in Chu medium at different pH and photoperiod after 2 weeks

Table 4.87 The optimum biomass and CSR distribution of *D. brasiliensis* cultured in Chu medium at different pH and photoperiod after 2 weeks

Green Algae	pH	Photoperiod	Biomass (g/L)	CSR (CO ₂ e)
<i>D. brasiliensis</i>	pH 6	21:0	0.10	0.15
	pH 6.8	18:6	0.38	0.59
	pH 8	6:18	0.09	0.13
	pH 10	6:18	0.21	0.32

4.5.15 Effect of Chu Medium Formulation, pH and Photoperiod on *D. brasiliensis* Chlorophyll Content

Chlorophyll production peaks at pH 6.8 under a 6-hours photoperiod, reaching an optimal concentration of (0.15). This indicates that neutral to slightly acidic conditions and moderate light exposure are ideal for chlorophyll synthesis. Conversely, the lowest chlorophyll production, at just (0.02), occurs at pH 4 under extended light durations of 18 and 24 hours. These findings suggest that highly acidic environments and prolonged light exposure inhibit chlorophyll production, emphasizing the importance of balanced pH and photoperiod for optimal photosynthetic activity. Refer to Figure 4.94 for detailed trends.

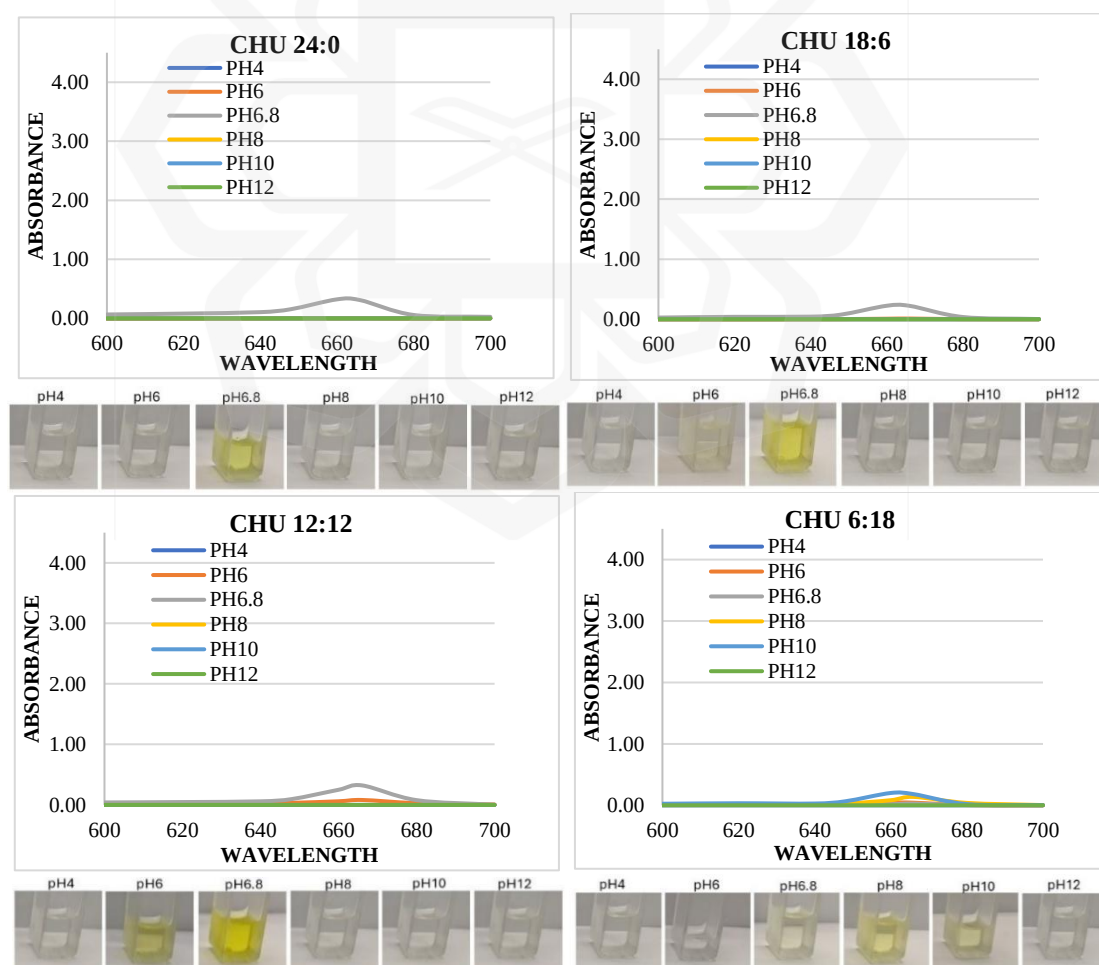


Figure 4.94 Effects of pH and photoperiod on chlorophyll content of *D. brasiliensis* cell culture in Chu medium after 2 weeks

4.5.16 Effect of Chu Medium Formulation, pH and Photoperiod on *D. brasiliensis* Cell Culture Chromaticity

The highest green intensity (a^*) is observed at pH 6.8 with a 12-hours photoperiod (23.26), while the lowest is at pH 6 with 24-hours photoperiod (1.54). Green intensity generally peaks at pH 6.8 across all photoperiods as per highlighted in Figure 4.95 and Table 4.88. The lowest lightness value (L^*), indicating better light absorption, is (92.86) at pH 6 under a 6-hours photoperiod. The highest lightness, indicating reduced absorption, is (100.21) at pH 6 with 6-hours photoperiod indicated in Figure 4.96 and Table 4.89.

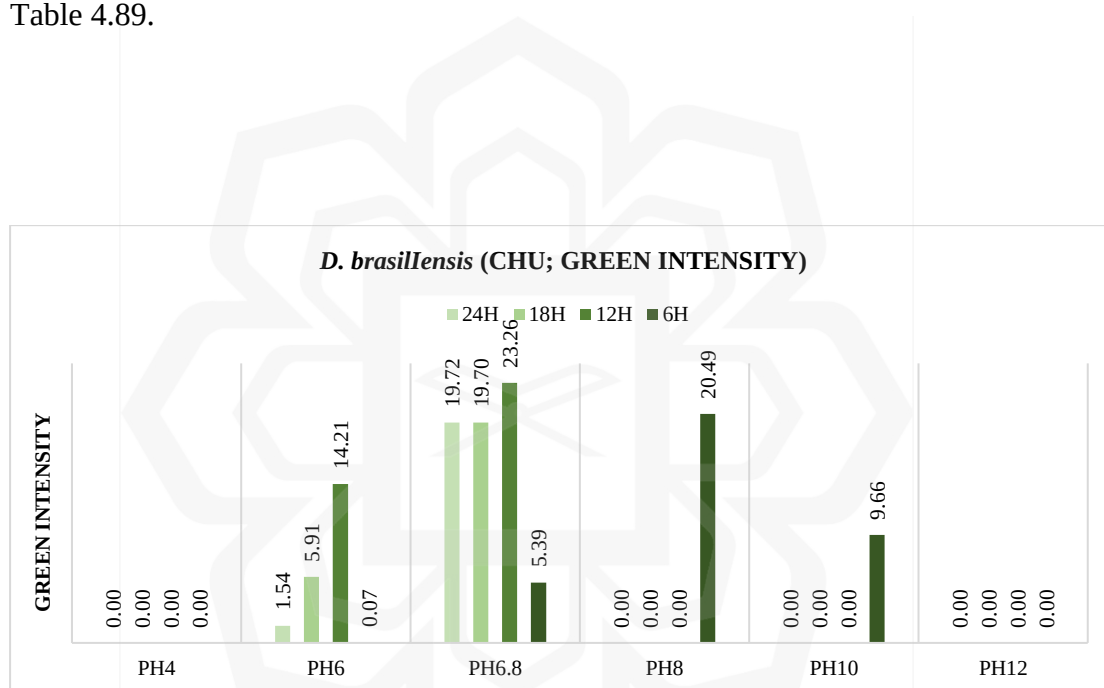


Figure 4.95 Effects of pH and photoperiod on green intensity values (a^*) of *D. brasiliensis* cell culture in Chu medium after 2 weeks

Table 4.88 Green intensity (a^*) distribution of *D. brasiliensis* cell culture in Chu medium at different pH and photoperiod after 2 weeks

Green Algae	Photoperiod	Peak pH	a^*
<i>D. brasiliensis</i>	24:0	pH 6.8	19.72
	18:6	pH 6.8	19.70
	12:12	pH 6.8	23.26
	6:18	pH 8	20.49
a^* , ranges from white (0) to green (100)			

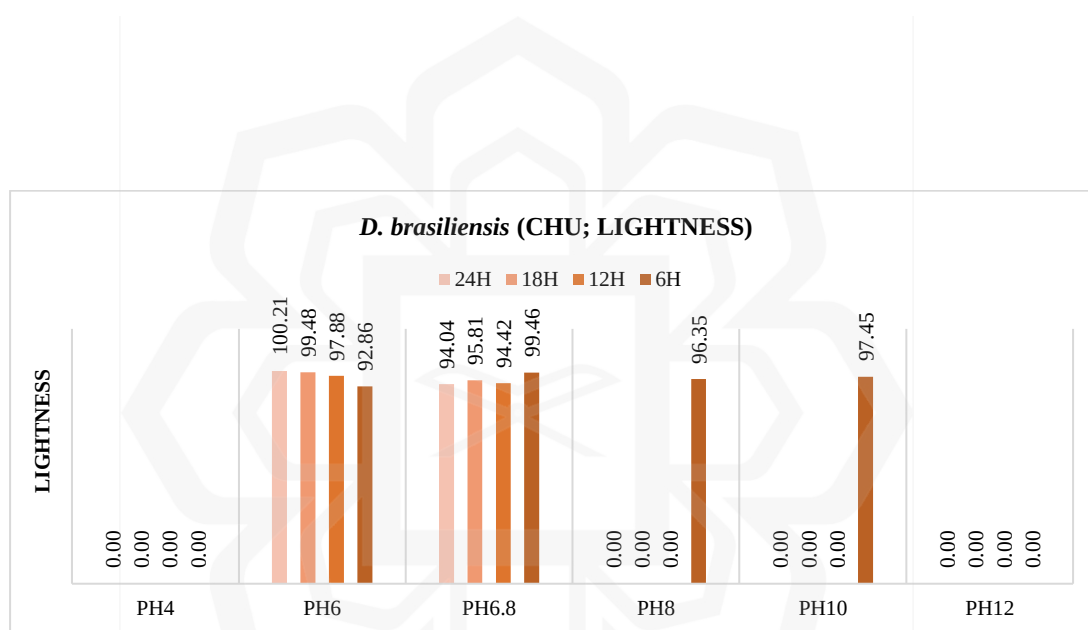


Figure 4.96 Effects of pH and photoperiod on lightness values (L^*) of *D. brasiliensis* cell culture in Chu medium after 2 weeks

Table 4.89 Lightness (L*) values distribution of *D. brasiliensis* cell culture in CHU medium at different pH and photoperiod after 2 weeks

Green Algae	Photoperiod	Peak pH	L*
<i>D. brasiliensis</i>	24:0	pH 6.8	94.04
	18:6	pH 6.8	95.81
	12:12	pH 6.8	94.42
	6:18	pH 6	92.46
<i>L*</i> , ranges from black (0) to white (100)			

In conclusion, the study using Chu medium show optimal growth and CO₂ sequestration at pH 6.8 with a 24-hours photoperiod: cell counts (865× 10⁶ cells/mL), biomass (0.38 g/L), and CO₂ sequestration (0.59 g/L CO₂e). Maximum absorbance (1.37) is at pH 10 with 24-hours exposure. Chlorophyll peaks (0.15) at pH 6.8 under a 6-hours photoperiod. Green intensity (23.26) is highest at pH 6.8 with 12-hours exposure, while lowest lightness (92.86) occurs at pH 6 with 6-hours photoperiod, indicating efficient light absorption.

4.5.17 Multivariate Data Analysis

4.5.17.1 Multivariate analysis

The KMO values for the 288 datasets yielded a score of **0.8628** (Table 4.90), indicating that the dataset falls within the "very good" category and is suitable for PCA analysis. Bartlett's Test of Sphericity was conducted to verify that the R-matrix is not equivalent to the identity matrix. The *p*-value for the *D. brasiliensis* datasets on cell growth, carbon sequestration, and chromaticity showed highly significant differences at 0.0001.

Table 4.90 Kaiser-Meyer-Olkin and Bartlett's test for *D. brasiliensis* Cell Growth, Carbon Sequestration, and Chromaticity stability

Kaiser-Meyer-Olkin Measure of Sampling Adequacy		0.8628
Bartlett's Test of Sphericity	Chi-square (Observed value)	5288.649
	DF	45
	<i>p</i> -value (Two-tailed)	<0.0001

Correlation coefficient matrix (r^2) in Table 4.91 established a very strong positive correlation among biomass and CSR ($r^2 = 1$). High positive correlations were observed in lightness, green intensity, Chlorophyll content, cell density, cell counts, biomass and CSR ($r^2 = 0.709$ to 0.846).

Table 4.91 Correlation coefficient matrix for the *D. brasiliensis* Cell Growth, Carbon Sequestration, and Chromaticity stability

Variables	L*	a*	Chl	CCt	CDt	BM	CSR	PH	PHPD	Day
L*	1									
a*	0.785	1								
Chl	0.492	0.753	1							
CCt	0.680	0.717	0.531	1						
CDt	0.593	0.672	0.544	0.709	1					
BM	0.837	0.846	0.609	0.711	0.689	1				
CSR	0.837	0.846	0.609	0.711	0.689	1.000	1			
pH	-0.052	-0.013	-0.017	0.017	-0.026	-0.037	-0.037	1		
PHPD	-0.033	0.039	0.058	0.040	0.128	0.017	0.017	0.000	1	
Day	0.659	0.543	0.361	0.500	0.508	0.572	0.572	0.000	0.000	1

Values in bold are different from 0 with a significance level $\alpha=0.01$

4.5.17.2 Principal Component Analysis (PCA)

The PCA analysis revealed two principal components (PCs) encompassing the 10 variables, which together accounted for a cumulative variability of 67.42%. The eigenvalues for PC1 and PC2 were 5.7 and 1.0, respectively, as shown in Table 4.5.23.

In principle, variables far away from the axes F1 and F2 had a strong factor loading (FL). Referring to the Table 4.92, L*, a*, CCt, CDt, BM, CSR and PHPD had strong FL ($FL > 0.75$) whereas Chl and Day had moderate FL ($0.500 < FL < 0.749$) and PH had a weak FL ($FL < 0.499$).

Table 4.92 The principal components factor loading and eigenvalues of the correlation matrix for *D. brasiliensis* Cell Growth, Carbon Sequestration, and Chromaticity

Variables	PC1	PC2
L* (Lightness)	0.880	-0.146
a* (green intensity)	0.920	0.013
Chl (Chlorophyll content)	0.721	0.108
CCt (Cell counts)	0.826	0.042
CDt (Cell Density)	0.801	0.166
BM (Biomass)	0.940	-0.052
CSR	0.940	-0.052
pH	-0.031	0.173
PHPD (Photoperiod)	0.046	0.962
Day	0.687	-0.104
Eigenvalue	5.708	1.034
Variability (%)	57.080	10.340
Cumulative (%)	57.080	67.420

The first principal component (PC1) explained 57.08% of the total variance, with strong factor loadings observed for L*, a*, CCt, CDt, BM and CSR. In contrast, the second principal component (PC2) accounted for 10.34% of the total variance, with PHPD identified as the only variable showing a strong association.

4.5.18 Summary of Results

1. There is a strong relationship between the cell growth, biomass, carbon sequestration, lightness and green intensity of the *D. brasiliensis* with time exposure in response to light and dark condition
2. BG11 medium is the optimal choice for cultivating *D. brasiliensis*, achieving the highest overall growth, biomass production, CO₂ sequestration, and chlorophyll content.
3. The best performance was observed at pH 8 under an 18-hours photoperiod.
4. BG11 medium is a strong alternative for applications focused on carbon capture, with the highest CO₂ sequestration (1.30 g/L) and robust biomass production (0.83 g/L CO₂e).
5. Algal growth is enhanced under mildly alkaline conditions (pH 6.8–8) and extended photoperiods (18–24 hours), emphasizing the importance of selecting appropriate media and environmental parameters.

4.6 DISCUSSION

4.6.1 Influence of Photoperiod on Algae Growth and Productivity

Photoperiod plays a critical role in regulating the growth rate and productivity of microalgae in a wide range of algal species (Krzemińska et al., 2014). The adjustment in the photoperiod encourages changes in the algae growth and productivity including cell growth rate, cell density, pigment, total lipid, nutrients utilization, fatty acid, protein, and biomass production (Beigbeder and Lavoie, 2022; Wahidin et al., 2013; Ruangsomboon 2012). The findings indicate that the highest cell concentration among optimal algae is (1,936 cells/mL) and cell density (3.58) were observed for *P. ampnigranulata* grown in BG11 medium under a 24:0 (light:dark) photoperiod. The result reported by Ruangsomboon (2012) also attained the total biomass concentration

of their studied algae was four times higher under 24:0 (light:dark) photoperiod compared to 12:12 photoperiod. Growth rate and biomass production increased when exposed much longer to light in terms of either light duration exposure (Gani et al., 2021; Krzemin'ska et al., 2014).

Next, the results also underscore species-specific variations in photoperiod sensitivity. As for this study, *P. ampnigranulata* in BBM medium achieved its best performance under a 12:12 photoperiod on biomass production 0.87 g/L and carbon sequestration 1.36 g/L. As studied by Amini Khoeyi et al. (2012), the growth rate and biomass productivity also varied based on algae species. For example, *C. vulgaris* under 12:12 photoperiod has obtained similar growth rate and biomass productivity with *B. braunii* and *S. obliquus* under continuous illumination (24:0). Their study also concluded that, higher light intensity decreased the *C. vulgaris* productivity. This is supported by Holdmann et al. (2018) which agreed the shorter photoperiods led to an improved biomass gross productivity compared to the continuous illumination.

Therefore, the productivity and growth rate of the algae not restricted to photoperiod factor but also to consider the species specification such as from similar taxonomic group. As revealed by Krzemin'ska et al. (2014), the algae may be group into two, which one group growing more efficiently at continuous illumination (24:0) and another group growing more efficiently under 12:12 regime. Additionally, Beigbeder and Lavoie (2022) also highlighting the key aspect in the selection of appropriate microalgae strains such as the strain with fast growing properties, high biomass productivity, high CO₂ resistance, and others, based on the applications to be developed.

Thus, this study has obtained the exceptional findings which proved comparable result with previous studies on the influence of photoperiod on algae growth and productivity. This study also has filled up the gaps of limited studies on the cultivation of algae species native to Malaysia since Malaysia only accounts for 1.1 % of global cultivated microalgae production (Rajkumar and Sobri Takriff, 2016).

4.6.2 Impact of pH on Algal Growth and Chlorophyll Pigmentation

The growth of microorganism like microalgae is significantly influenced by pH because of its direct impact on $\text{NH}_3/\text{NH}_4^+$ balance and nitrogen accessibility (Mathew et al., 2021). Also, pH of the culture medium plays important role which affecting the algal growth and pigmentation (Alkhamis et al., 2022; Yu et al., 2022). Among the cyanobacteria group, *P. ampnigranulata* exhibited optimal growth at pH 10 in BG11 medium with showed promising cell density value (3.58), followed by *Alkalinema* sp. thrived at pH 6 with cell density value (3.42). Meanwhile green microalgae group showed lower values than cyanobacteria result (± 3.29). These results indicate that cyanobacteria such as *P. ampnigranulata* can tolerate alkaline conditions better than green algae, which tend to prefer slightly acidic to neutral pH levels. This aligns with previous research suggesting that pH influences enzyme activity and nutrient availability in algal cells (Becker, 2004). In addition, cyanobacteria are able to growth in highly acidic or alkaline pH. However, pH level from 7.5 to 9 is the optimal pH range for higher growth rate for most of cyanobacteria while pH lower or higher than these range may significantly decline the growth of these algae species (Chandra and Rajashekhar 2016; Wangwibulkit et al., 2008).

Next, chlorophyll pigmentation analysis is a crucial aspect of understanding the photosynthetic efficiency and metabolic adaptability of algae species. From observation, the highest chlorophyll absorbance, recorded at (4.01 ± 4.02) occurred under alkaline conditions (pH 6–10) aligns with previous studies indicating that microalgae can thrive in moderately alkaline environments due to the enhanced availability of bicarbonate ions (CO_3^{2-}) at such pH levels (Smith et al., 2021). This result not only impacts algae biomass but also influences the synthesis of chlorophyll and other pigments. Optimal pH levels enhance pigment stability and production, which is vital for maximising light absorption and energy transfer within the photosynthetic apparatus (Chen et al., 2019).

Chorvatova et al. (2020) also explained the relation between pH, CO_2 , and photosynthesis. Water's pH is higher (alkaline) during the day due to a drop in CO_2 ,

whereas it is lower (acidic) at night when there is no sunlight. The strong photosynthetic activity of microalgae, which increases chlorophyll pigmentation when excited by light, was thus facilitated by the alkaline conditions during the day. Moreover, during photosynthesis, the function of carbon-fixing enzymes was optimally at pH 8. Changing the pH too high or too low will negatively affects the rate of photosynthesis as the enzymes in the plant can slow down, stop working, or denature (Snel and Dassen, 2000). Therefore, maintaining pH levels within the alkaline range ensures robust growth and pigment synthesis, which can significantly enhance the productivity of algal cultivation systems for applications in sustainable energy and carbon sequestration (Kumar and Eswari, 2023).

4.6.3 Influence of Medium Composition on Algal Growth as Carbon Capture and Light Reduction

Medium composition plays a key role in determining algae growth rates and biomass production. BG11 medium generally supported higher chlorophyll absorbance values (4.02) and cell densities (3.29 ± 3.58) compared to BBM, as evidenced by the performance of *P. ampnigranulata*, *Alkalinema* sp., and *D. brasiliensis*. The nutrient-rich composition of BG11, particularly its nitrogen content, including nitrate and phosphate may accounts for these results (Liu et al., 2021). This finding indicates that the composition of the medium plays a crucial role in producing the highest algae chlorophyll pigment content, which significantly contributes to absorbing light energy and reducing light intensity in the built environment. Their dense chlorophyll structure enhances photosynthetic efficiency, converting light into biomass and sequestering carbon dioxide effectively (Ramanna et al., 2017). By mitigating lowering indoor light levels up to 70% (model system) and lowering heat gain, these algae contribute to energy savings and sustainable climate control.

Meanwhile, BBM medium is rich in essential nutrients like nitrogen, phosphorus, and trace elements which important for algae growth. Thus, BBM

demonstrated better performance for *P. ampnigranulata*, achieving the highest biomass yield of 0.80 ± 0.87 g/L. This highlights BBM's efficiency in promoting microalgae growth, crucial for carbon sequestration. The robust cell growth through photosynthesis contribute to biomass accumulation directly enhance the algae's capacity to capture and store atmospheric CO₂, contributing to carbon reduction (Li and Yao, 2024; Smith and Jones, 2020). These results indicate BG11 and BBM as an optimal medium for sustainable applications in carbon sequestration, aligning with goals for energy-saving solutions and environmental sustainability in the built environment.

Apart from medium used, the effectiveness of carbon capture and light reduction also depend on the specific algae species including the distinct classes of microalgae (i.e., autotrophic, heterotrophic, and mixotrophic) and growth condition provided by the medium (Li and Yao, 2024; Shareefdeen et al., 2023). As reported by Shareefdeen et al. (2023), the microalgae from mixotrophic able to yield higher biomass even with lower light intensity, thus making it more energy effective than purely autotrophic and/or heterotrophic microalgae. Therefore, by integrating all the potential key aspect, the aim of providing carbon capture and light reduction agent will be achieved.

4.6.4 Interconnections Between Algae Biomass, Chlorophyll Content, and Carbon Sequestration for Optimising Photosynthetic Efficiency for Sustainable Applications

Development of sustainable applications from organism based such as microalgal biomass, chlorophyll content, and carbon sequestration capability were promising resources due to their advantages such as higher growth rate compared to terrestrial plants and higher atmospheric carbon dioxide sequestering capability without requiring of specific arable land for cultivation (Cho et al., 2019; Mata et al. 2010). The relationship between algae biomass, carbon sequestration, and chlorophyll content is interconnected through photosynthesis, where algae use chlorophyll to absorb light and convert CO₂ into organic material, resulting in biomass growth (Ahmad et al., 2024;

Ashours et al., 2024; Prasad et al., 2021). As showed in previous chapter, *P. ampnigranulata* displayed the highest chlorophyll absorbance (4.01) and lead to highest biomass (0.87 g/L) carbon sequestration (1.36 g/L CO₂e). The highest correlation was between biomass and carbon sequestration and chlorophyll content.

Chlorophyll is the pigment accountable for absorbing light energy during photosynthesis. Thus, optimising the chlorophyll content led to expand the overall efficiency of photosynthesis. This is due to the higher chlorophyll content indicates greater photosynthetic efficiency which enhance the capability of algae to capture light, leading to increased CO₂ uptake and enhanced biomass production (Alami et al., 2021; Singh and Dhar, 2019). Moreover, algae with increased chlorophyll levels typically appear darker (lower lightness or L*) and greener (more negative a*), depending on the presence of other pigments like carotenoids (Mondal et al., 2022). These chromaticity measurements provide a straightforward method to estimate chlorophyll levels, aiding in the assessment of algae growth, health, and density (Cadondon et al., 2022). Previous multivariate analysis has shown a strong positive correlation between chlorophyll content and chromaticity. For instance, *C. radiosa* exhibited high chlorophyll absorbance (3.95), resulting in the lowest lightness (L*) value of 61.30 and a green intensity of 43.54. This relationship is not only useful for monitoring environmental conditions but also for designing algae-based applications with specific visual and functional properties, such as reducing light intensity (Talaie and Prieto, 2024).

Furthermore, the relation between chlorophyll absorbance and the cell density of microalgae generally studied in spectrophotometric methods to evaluate the concentration of microalgae in a culture. As reported by Rodrigues et al. (2011), higher chlorophyll absorbance shows higher cell density in microalgae culture. As referred to this study, the absorbance of chlorophyll was highest (4.02) in *P. ampnigranulata* and *Alkalinema* sp. under their respective optimal conditions that have high positive correlation to cell density that showed values (3.42-3.58). The strong correlation between chlorophyll content and cell density observed in this study supports the hypothesis that light absorption efficiency directly impacts algal productivity (Ho et al., 2010). In addition, there are four key aspects that contributed to the light absorption

efficiency that affect the algae productivity which are photosynthetic efficiency, light quality and intensity, light distribution, and photoinhibition. Optimising the photosynthetic and light quality and intensity help to improved growth rates and biomass productivity whereas designing proper photobioreactor support in enhancing light distribution to increase productivity. Meanwhile, balancing light intensity aid in avoiding photoinhibition caused by excessive light, which at the same time optimising light absorption for maximum algae growth (Hong et al., 2023; Parveen et al., 2023; Al-Qasmi et al., 2012).

4.7 ALGAE PANEL DESIGN MODEL SYSTEM ASSESSMENT USING CYANOBACTERIA AND GREEN ALGAE CELL CULTURE TO REDUCE LIGHT INTENSITY FOR ENERGY SAVING

Two algae species from cyanobacteria and two from green algae were selected based on their adaptability to external facade applications and ability to filter light. The selected species, growth mediums, and environmental conditions for the experiment were as Table 4.93.

Table 4.93 Selected algae species, growth mediums, and environmental conditions

Algae	pH	Photoperiod	Medium
<i>P. amphigranulata</i>	10	12:12	BBM
<i>Alkalinema sp.</i>	8	18:6	BBM
<i>D. brasileensis</i>	10	24:0	BG11
<i>C. radiosa</i>	8	12:12	BBM

The prototype facade panels (Figure 4.97) containing the selected algae species were exposed to controlled environmental conditions (2000 lux) with room temperature (24 °C). Light intensity measurements were taken at regular intervals using a calibrated lux meter. The readings were recorded on days 0, 2, 4, 6, 10, 12, and 14. The objective was to assess the algae's effectiveness in reducing light intensity over time.

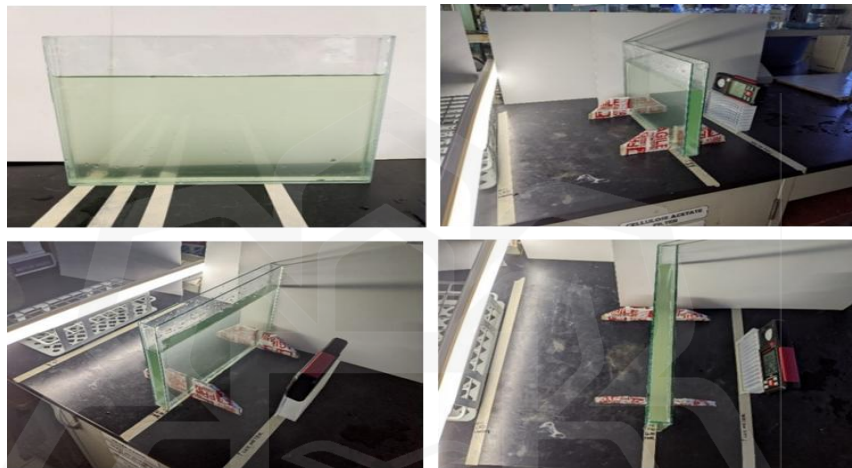


Figure 4.97 Algae facade panel prototype design set up

The light intensity reading from day 0 to day 14 of cyanobacteria and green algae species (Table 4.93) show encouraging result which exhibit decreasing trends of light intensity over the period of time with the escalating of percentage.

Table 4.94 Light Intensity (Lux) and percentage of light reduction distribution in cyanobacteria and green algae species after 2 weeks

Species	Day 0	Day 2	Day 4	Day 6	Day 10	Day 12	Day 14
<i>P. amphigranulata</i>	1550	960	900	800	740	640	620
	0%	38%	42%	48%	52%	59%	60%
<i>Alkalinema sp.</i>	1550	990	940	790	770	650	600
	0%	36%	40%	49%	50%	58%	61%
<i>C. radiosa</i>	1550	960	790	750	730	580	500
	0%	38%	49%	52%	53%	63%	68%
<i>D. brasileensis</i>	1550	990	970	840	830	700	680
	0%	36%	37%	46%	46%	54%	56%

The results from Table 4.94 can be simplified as below:

1. *C. radiosa* recorded the highest light intensity reduction of 1050 lux (68%) by day 14. Consistently maintained balance light intensity levels, indicative of robust growth.
2. *P. amphigranulata* showed a steady decline in light intensity, with a total reduction of 930 lux (60%) by day 14. Demonstrated moderate light filtering efficiency.
3. *Alkalinema sp.* achieved a reduction of 950 lux (61%) by day 14. Performed slightly better than *P. amphigranulata* in filtering light.
4. *D. brasileensis* exhibited the lowest light intensity reduction of 870 lux (56%) by day 14. The continuous light exposure might have influenced growth patterns.

4.7.1 Discussion

The results highlight the potential of algae-based panels in modulating light intensity within building façades. Variations in light reduction across species indicate that specific growth conditions, including light cycles and pH levels, play a crucial role in performance.

1. Growth Medium and pH: BBM medium with *C. radiosa* enrichment and higher pH levels (PH8) enhanced light filtering capabilities.
2. Light Cycle: balance light exposure (12:12) showed mixed results, suggesting that optimal light-dark cycles may vary between species.

The growth medium and pH can affect the nutrient availability and overall growth potential of algae since each species has optimal pH range for better nutrient intake and maximum growth performance (Chowdury et al., 2020; Gatamaneni et al., 2018). Moreover, different algae species also have dissimilar light requirements (Fuente et al., 2017; Cleuvers et al., 2002). Some might bloom under continuous light while others need alteration of light and dark cycles for their growth. Thus, by optimising the photoperiod helps to enhance the growth rates and at the same time improve photosynthetic efficiency (Parveen et al., 2023; Chiarini and Quadrio, 2021).

Accordingly, the application of algae-based panels as building façade can dynamically alter the environmental condition such as to provide adaptive shading by adjusting the algae density within the panels in which the grown algae help to reduce penetrating light into the building concurrently promote cooling effects and leading to energy savings. Moreover, algae-based panels also excellent in capturing CO₂ thus they help in reducing greenhouse gas emissions and the added value of these panels are they can be designed to enhance the aesthetic appeal such as a green wall (Çelekli et al., 2024; Jingshi, 2022).

4.8 ALGAE VERTICAL TUBULAR DESIGN MODEL SYSTEM ASSESSMENT USING CYANOBACTERIA AND GREEN ALGAE CELL CULTURE AS CARBON SEQUESTRATION AGENT

The implementation process involves three key steps: system setup, biomass cultivation, and carbon sequestration analysis. The close cultivation vertical tubular prototype (Figure 4.98) and carbon capture modules are assembled, calibrated, and tested to ensure optimal functionality for biomass growth and CO₂ capture under photoperiod 12:12, pH 8 and using 10L media BG11 and BBM within 14 days.



Figure 4.98 Vertical tubular prototype setup from day 1 (left) to day 14 (right)

Two algae species from cyanobacteria and green algae were selected based on their adaptability to external facade applications and ability to filter light. The selected species, growth mediums, and environmental conditions for the experiment were as in Table 4.95.

Table 4.95 Biomass and carbon sequestration rate distribution of cyanobacteria and green algae after 2 weeks

Algae	Dry Weight g/L	Biomass g/L	CO ₂ e g/L
<i>C. radiosa</i> (BG11)	0.77	5.13	8.04
<i>P. amphigranulata</i> (BBM)	1.025	5.83	10.70

The results presented in Table 4.95 compares two types of algae, *C. radiosa* (green algae) and *P. amphigranulata* (cyanobacteria), under specific conditions, analysing their dry weight, biomass, and CO₂ equivalent (CO₂e) production.

Dry Weight (g/L):

- *P. amphigranulata* (1.025 g/L) has a higher dry weight compared to *C. radiosa* (0.77 g/L).

Biomass (g/L):

- *P. amphigranulata* (5.83 g/L) again show a greater biomass than *C. radiosa* (5.13 g/L).

CO₂e (g/L):

- *P. amphigranulata* (10.70 g/L) exhibits a significantly higher CO₂ equivalent than *C. radiosa* (8.04 g/L).

4.8.1 Discussion

P. amphigranulata accumulates more solid biomass under the given conditions, indicating a higher growth rate or more efficient nutrient utilization. While both species exhibit good growth, *P. amphigranulata* show a slightly better yield, as reflected in its higher dry weight and biomass. Additionally, its greater CO₂ equivalent value suggests that it is more effective at capturing and fixing carbon dioxide from the environment,

making it a potentially more suitable candidate for biomass production and carbon sequestration. As stated by Elrayies (2018), algae are the oldest organisms which potentially in solving various environmental issues as they able to grow into a biomass, produce oxygen, good in sequestering CO₂ from atmosphere, and also optimally in filtering water and air as well.

The prototype demonstrates the potential of integrating biomass conversion with carbon capture technologies to mitigate climate change and contribute to sustainable environmental management. It enhances CO₂ absorption and converts it into stable oxygen through advanced biological processes. Prioritizing sustainability, this system reduces environmental impact while maintaining scalability for industrial applications. By integrating microalgae in the green technologies, its help in highlighting their passive performance as photosynthetic machines since the efficiency of microalgae are ten times greater than other grasses and large trees (Ratti and Belleri 2020; Elrayies 2018). Current green technology application used flat panel or flat plate reactors which act as illuminator for photosynthesis. This panel have cubelike shape and can be organized vertically or horizontally. Their high surface to volume ratio offers excellent illumination for photosynthesis, has drawn fascination for them. Literally, horizontal flat panel collects greater light, but it occupies more space. Therefore, vertical flat panel is more effective considering the land usage but requires more rigid and need higher cost to develop (Junying et al., 2013). However, this panel reactor offers numerous benefits, such as elevated photosynthetic efficiency, minimal oxygen buildup, and reduced energy consumption (Shareefdeen et al., 2023)

One of the vertical flat panel technologies has used algae-based that act as external facades. It holds significant potential for sustainable urban architecture, combining carbon sequestration and light modulation functionalities as shown in Figure 4.99. Through photosynthesis, algae efficiently absorb atmospheric carbon dioxide (CO₂) and release oxygen, contributing to the mitigation of urban carbon emissions (Mata et al., 2010). Research highlights the capability of microalgae to capture and store CO₂, making them a vital component in reducing the carbon footprint of cities. Additionally, these facades can regulate sunlight intensity, filtering and diffusing light

to enhance indoor comfort while reducing dependency on artificial lighting (Jiang et al., 2017).

This dual role positions algae facades not only as a transformative innovation in eco-friendly building design, but at the same time creating healthy and liveable buildings which likely transform the envelopes of buildings into factories of energy (Elrayies, 2018). Advancements in biotechnological systems, such as algae panel, further support the integration of algae into architectural facades. These systems provide controlled environments for algae growth, enhancing both functionality and aesthetic appeal in urban landscapes (Pavlik et al., 2017). Beyond their ecological benefits, algae-based facades can reduce operational energy costs and potentially contribute to renewable biofuel production. As cities face growing environmental pressures, these facades present a resilient and adaptive approach to sustainable development (Nwoba et al., 2019). As figure 4.99 shown, the outdoor and indoor CO₂ intake will capture the carbon emission directly dan can produce biomass and filtered the CO₂ indoor emission. These will affect the health quality of user inside the building.

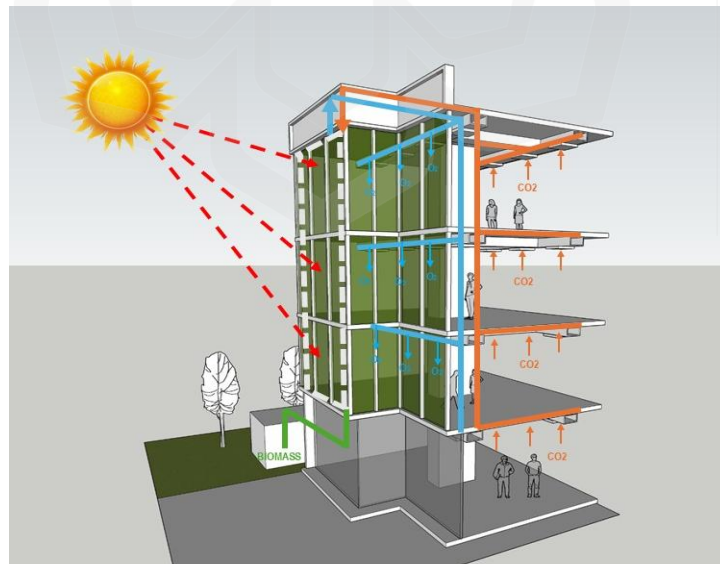


Figure 4.99 Algae panel system as external façade for carbon sequestration and reducing light intensity

The application of algae in building façade systems has gained significant attention due to its potential to enhance sustainability. Algae-based façade panels offer benefits such as carbon sequestration, light filtering, and aesthetic appeal. This chapter focuses on the performance evaluation of an algae-based external façade prototype. Specifically, the study investigates light intensity modulation through selected algae species within façade panels using a lux meter over 14 days. Extreme light intensity from sun can be filtered through algae panel that will reduce light intensity and will create cooling effects and reducing indoor temperature as shown in Figure 4.100.

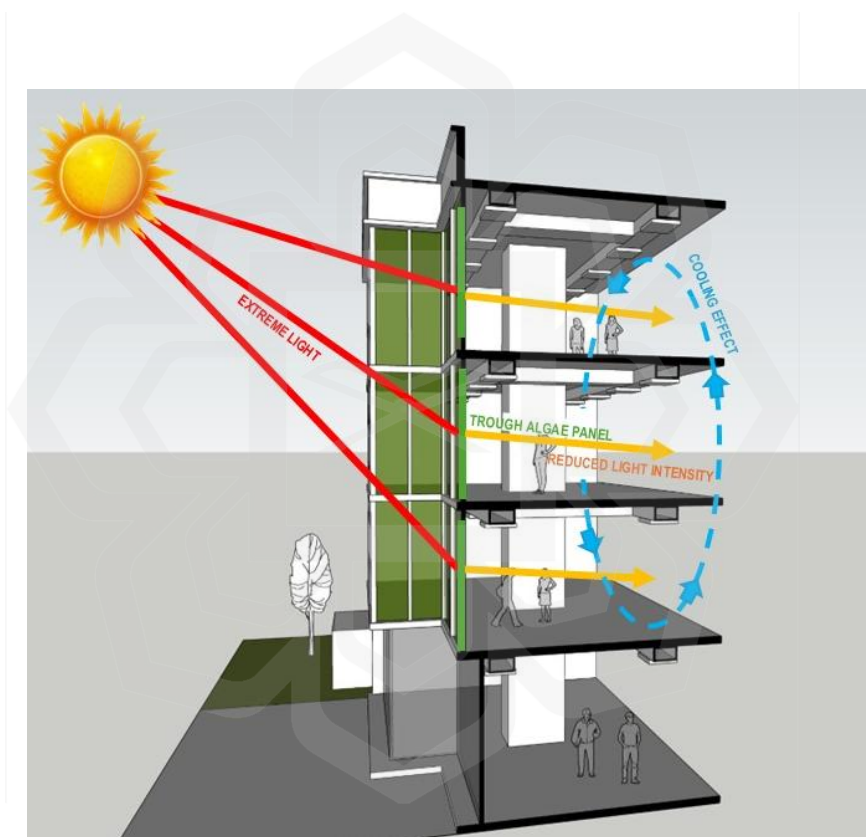


Figure 4.100 Algae panel that can create cooling effect inside the building by reducing light intensity

As explained by Çelekli et al. (2024), the photosynthetic activities of algae which convert sunlight and CO₂ into biomass in concurrently producing renewable energy while shading the interior part of the building. This resulted in enhancing the

thermal insulation, regulating indoor air quality and giving a healthier indoor environment and its surrounding. Furthermore, the integration of algae in building façade technology also helps in mitigating urban air pollution, reducing carbon footprint of the building itself, and tangibly way out for atmospheric carbon depletion. The efficiency of algae in sequestering CO₂ are proven to be better than other terrestrial plants as algae able to sequester approximately 1.83 kg of CO₂ per kilogram their dried weight (Huseien and Shah, 2021; Brennan and Owende, 2010).

This study highlights the potential of algae-based model system as carbon sequestration agent and managing light intensity in buildings. Among the tested species, *C. radiosa* (green algae) cultured in BBM at pH 8 under a 12:12 light-dark cycle demonstrated the highest effectiveness in reducing light intensity by 68%, lowering it from 1550 to 500 lux. This finding aligns with the results from the previous chapter, which highlighted *C. radiosa*'s outstanding chlorophyll absorbance of 3.95 and lightness value of 61.30. Overall, the tested algae species were able to filter approximately 60-70% of light intensity, as detailed in Table 9.2. It's indicated that most of algae can filter light according to their abilities and performance. By filtering excess light, algae panels can help reduce dependence on natural extreme and artificial lighting. The selection of algae species and their growth conditions can be customized to meet specific design needs, making these panels a versatile solution. Incorporating algae panels into building designs supports sustainable practices by harnessing the power of natural systems (Biloria et al., 2020). Moreover, *C. radiosa* show promising on biomass production and lead to highest carbon sequestration. Its show that, tubular design can be potential design for rapid growth of algae carbon capture that supported from the research, the highest photosynthetic efficiencies reported were 4.2% for the vertical tubular photobioreactor, 3.8% for the flat-panel reactor, 1.8% for the horizontal tubular reactor, and 1.5% for the open raceway pond (De Vree et al., 2015). Prioritizing sustainability, this system reduces environmental impact while maintaining scalability for industrial applications. The success of this prototype could pave the way for larger-scale implementation, helping industries, governments, and communities meet climate goals while promoting the use of renewable resources.

4.8.2 Recommendation for Algae Panel Application in Real Building

In the proposed algae panel system as show in Figure 4.101, the cost analysis estimation indicates that installing a 175 m² panel on the five-storey tropical office building would require an estimated capital expenditure ranging from RM 140,000 to RM 525,000 depending on system specifications, with the mid-range cost at approximately RM 262,500. Annual operational expenses, including maintenance and circulation pump energy, are projected at 5–10% of the initial investment, equivalent to RM 13,000–26,000 per year. Although financial payback from electricity savings alone appears lengthy, the system delivers added value through its contribution to sustainability initiatives, biomass valorisation potential, and enhancement of environmental performance ratings for green building certification. Importantly, the algae panel has been positioned predominantly on the east-facing façade to maximise morning solar exposure, which supports higher algae productivity while reducing direct heat gain into the building during peak hours.

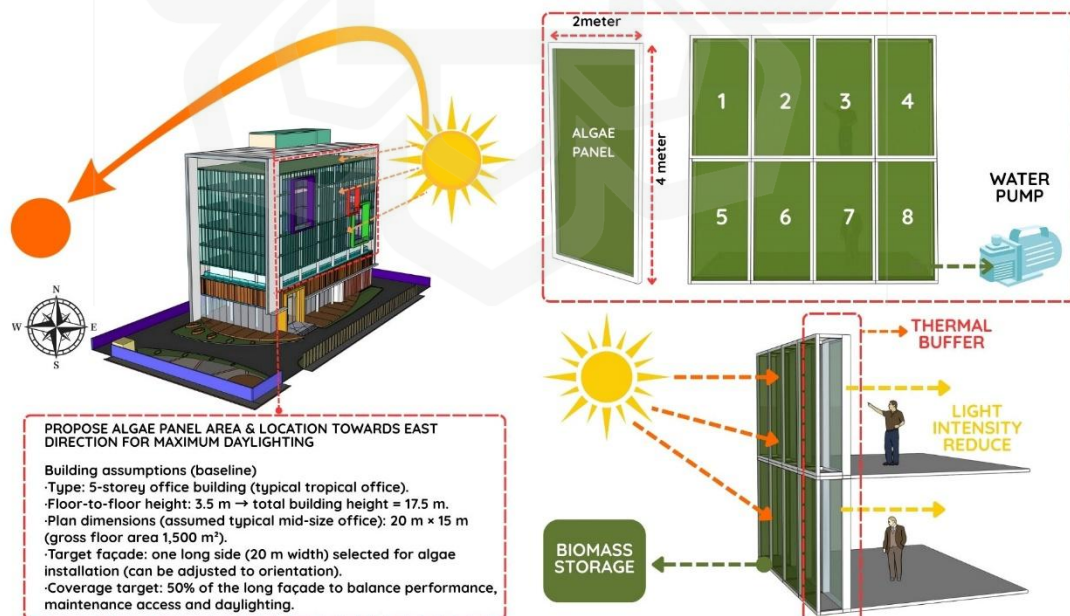


Figure 4.101 Conceptual design of an algae panel system for an office building

From a performance perspective, the system demonstrates strong potential both in biomass production and energy efficiency. With a measured yield of 0.6 g/L/day, the east-facing façade can produce between 383–1,533 kg of biomass annually depending on panel depth, creating opportunities for utilization in bio-based products. In terms of energy performance, the algae façade is estimated to reduce cooling demand by 5–15%, translating into net annual electricity savings of RM 1,200–5,700 after accounting for system operation. Additionally, the generated biomass provides a natural carbon sequestration benefit, as each kilogram of dry algal mass typically represents the fixation of around 1.8–2.0 kg of CO₂, meaning that the façade could capture approximately 690–3,000 kg of CO₂ per year depending on culture volume. While direct financial recovery may be limited, the orientation toward the east allows the façade to balance productivity with indoor comfort, while simultaneously mitigating carbon emissions. Hence, the combined benefits of reduced energy use, CO₂ sequestration, and sustainable biomass production strongly support the adoption of algae panel facade as a long-term green building strategy.

4.9 SUMMARY OF RESULTS

4.9.1 Effect of medium, pH and Photoperiod towards Algae Cell Culture Growth

The effect of medium, pH and photoperiod on algae cell culture growth are presented in Table 4.96.

Table 4.96 Summary of finding the best cell culture growth

Algae	Best Medium	Best pH	Best Photoperiod
<i>P. amphigranulata</i>	BG11	pH8	18H
<i>Alkalinema sp</i>	BG11	pH8	18H
<i>C. radiososa</i>	BG11	pH8	18H
<i>D. brasiliensis</i>	BG11	pH6	18H

1. Table 4.95 shown, Algae exhibit better growth under moderate pH conditions. Continuous light exposure enhances their cell growth
2. *P. amphigranulata* Indicating it is the most efficient in photosynthetic activity.
3. *Alkalinema sp.* Considerable absorbance values at first across all conditions. Reflecting considerable growth but have a continuous growth.
4. *C. radiosa* less specialized but can grow in varying conditions.
5. *D. brasiliensis* lower absorbance values at first across all conditions. Reflecting slower growth but have a continuous growth.

4.9.2 Effect of medium, pH and Photoperiod towards Biomass and Carbon Sequestration

The effect of medium, pH and photoperiod on biomass and carbon sequestration are presented in Table 4.97.

Table 4.97 Summary of effect pH and photoperiod toward biomass and carbon sequestration rate

Algae	Best pH	Best Photoperiod	Dry Weight	Biomass (g/L)	Carbon Sequestration Rate (g/L CO ₂ e)
<i>P. amphigranulata</i>	pH8	12H	0.13	0.87	1.36
<i>Alkalinema sp</i>	pH8	18H	0.11	0.76	1.19
<i>C. radiosa</i>	pH10	24H	0.11	0.75	1.18
<i>D. brasiliensis</i>	pH8	24H	0.12	0.83	1.30

1. Different algal species exhibit distinct responses to environmental conditions, offering valuable insights into their potential applications for carbon sequestration within the built environment as shown in Table 4.97.
2. *Pseudanabaena* (cyanobacteria) show has a stronger adaptability and growth response under optimised BBM conditions at pH 8 and photoperiod 12H, making it a promising candidate for biomass and carbon sequestration applications.

4.9.3 Effect of medium, pH and Photoperiod towards Green Intensity, Lightness and Chlorophyll

The effect of medium, pH and photoperiod on green intensity, lightness and chlorophyll are presented in Table 4.98.

Table 4.98 Summary of effect pH and photoperiod toward green intensity, lightness and chlorophyll

Algae	Best pH	Best Photoperiod	Green Intensity (a*)	Lightness (L*)	Chlorophyll
<i>P. amphigranulata</i>	pH8	12H	52.27	65.43	4.02
<i>Alkalinema sp</i>	pH8	18H	47.05	77.23	4.01
<i>C. radiosa</i>	pH10	24H	42.47	79.84	3.95
<i>D. brasiliensis</i>	pH8	24H	46.32	81.90	3.75

1. Table 4.98 show, the variations in L*, a* across different algae species highlight how colour properties can serve as light filtration and reduction.

2. *Pseudanabaena* (cyanobacteria) show has a stronger adaptability response under optimised BBM conditions at pH 8 and photoperiod 12H, making it a promising candidate for light intensity reduction application.

4.9.4 Summary of Findings

The summary of findings shows that *D. brasiliensis* records the highest cell density (3.20 at 750 nm), indicating its rapid proliferation capacity under the tested conditions. However, *P. amphigranulata* demonstrates superior overall performance, with the highest dry weight (0.13%), biomass yield (0.87 g/L), and carbon sequestration rate (1.36 g/L CO₂e), supported by its strong chlorophyll absorbance (4.02 at 666 nm). These results highlight that although *D. brasiliensis* is efficient in cell multiplication, *P. amphigranulata* is more effective in biomass accumulation and carbon capture. This finding is significant as microalgae with higher biomass and sequestration efficiency are recognized as strong candidates for carbon management strategies in urban environments (Wang et al., 2021).

Table 4.99 Summary of finding on cell growth, biomass and carbon sequestration and chromaticity

Algae	Cell Denisty	Dry Weight	Biomass	CSR	Chlorophyll	Chromaticity	
Unit	750mm	%	g/L	g/L CO ₂ e	666 nm	a*	L*
<i>P. amphigranulata</i>	2.72	0.13	0.87	1.36	4.02	52.27	65.43
<i>Alkalinema sp</i>	3.02	0.11	0.76	1.19	4.01	47.05	77.23
<i>C. radiosa</i>	2.97	0.11	0.75	1.18	3.95	42.47	79.84
<i>D. brasiliensis</i>	3.20	0.12	0.83	1.30	3.75	46.32	81.90

Chromaticity analysis further emphasises functional applications, with *P. amphigranulata* showing the strongest pigmentation intensity (a* = 52.27), indicating

potential use as a natural pigment source, while *D. brasiliensis* demonstrates the highest brightness ($L^* = 81.90$). From a sustainable design perspective, microalgae systems integrated into building façades or photobioreactors can simultaneously reduce carbon emissions, enhance indoor thermal performance by filtering solar radiation, and produce valuable biomass co-products (Koyande et al., 2019). Therefore, the superior performance of *P. amphigranulata* as shown in Tabel 4.99, not only establishes it as the most efficient carbon sequestration agent among the tested species but also underscores its potential in advancing sustainable building design through dual benefits of environmental mitigation and bioresource valorisation.

The comparative assessment illustrates that *P. amphigranulata* achieves “High” ratings across most parameters, indicating strong capability and high effectiveness as a carbon sequestration agent and a contributor to energy efficiency in the built environment as shown in Table 4.100. Its high pigmentation stability and resilience to environmental stress demonstrate reliable chlorophyll and biomass maintenance, even under fluctuating conditions. In terms of energy efficiency, *P. amphigranulata* records superior biomass production and carbon sequestration rates, confirming its role in reducing CO₂ emissions. Additionally, its capacity to filter light effectively (high a^* values) reflects excellent potential for regulating indoor thermal performance by reducing solar heat gain, thereby lowering the need for artificial cooling. These multiple “High” indicators emphasise that *P. amphigranulata* is not only biologically effective but also environmentally valuable, making it the strongest candidate for integration into algae-based building systems.

Table 4.100 Summary of finding on algae as potential carbon sequestration agent and energy saving in built environment.

Parameter	Sub-Parameter	<i>P. amphigranulata</i>	<i>Alkalinema sp</i>	<i>C. radiosa</i>	<i>D. brasiliensis</i>
Pollution Reduction	Pigmentation Stability (<i>Chlorophyll</i>)	High	High	Considerable	Moderate
	Sensitivity to Environmental Stress (<i>Inferred from consistent chlorophyll and biomass</i>)	High	Considerable	Moderate	Considerable
Energy Efficiency	Biomass Production (<i>g/L & Dry Weight</i>)	High	Moderate	Moderate	Considerable
Carbon Sequestration	Carbon Sequestration Rate (<i>CSR</i>)	High	Considerable	Low	Moderate
Light Performance	Light Intensity (<i>Inferred from L values</i>) *	High	High	Considerable	Moderate
	Light Filtration (<i>a values, higher = more green absorbed</i>)*	High	Considerable	Moderate	Considerable
Environmental Growth	Growth under Varying pH (<i>Inferred from biomass & chlorophyll stability</i>)	High	Considerable	Moderate	Considerable
	Growth under Varying Photoperiod (<i>Inferred from cell density & biomass</i>)	Considerable	Moderate	Moderate	High

In contrast, *Alkalinema sp.* and *C. radiosa* demonstrate “Considerable” performance across several parameters, representing above-average capability but with limitations under specific conditions. For example, *Alkalinema sp.* show stable pigmentation but only moderate biomass production, which may reduce its long-term efficiency for large-scale CO₂ mitigation. Similarly, *C. radiosa* displays considerable carbon sequestration yet struggles under environmental stress and light management, restricting its consistency in dynamic urban environments. Meanwhile, *D. brasiliensis* performs “High” only under varying photoperiods yet remains “Moderate” in other

critical aspects such as carbon sequestration and pigmentation stability, implying a narrower applicability. These findings highlight that while other species possess useful traits, their effectiveness is conditional. Overall, by aligning with the performance scale, *P. amphigranulata* emerges as the most reliable species, demonstrating strong capability and high effectiveness across diverse parameters, making it highly suitable as a dual-function agent for carbon sequestration and energy-saving in sustainable building design.

Furthermore, these results align with real-world applications of algae-based systems in architecture. Projects such as the BIQ House in Hamburg have demonstrated the feasibility of photobioreactor façades in capturing CO₂ and improving building energy performance. The consistent “High” effectiveness of *P. amphigranulata* indicates that its integration into similar systems could provide even greater benefits by combining high biomass productivity, efficient carbon capture, and effective light management. This suggests that future sustainable building designs could adopt *P. amphigranulata*-based façades to achieve synergistic benefits of environmental mitigation, renewable biomass production, and improved indoor comfort, strengthening its role in advancing green architecture and low-carbon cities.

CHAPTER FIVE

CONCLUSION

5.1 CONCLUSION

This research was structured around three core objectives aimed at evaluating the potential of selected microalgae and cyanobacteria as multifunctional bio-based materials for sustainable built environments. Through systematic experimentation involving *Pseudanabaena amphigranulata*, *Alkalinema* sp., *Chlamydomonas radiosa*, and *Desmodesmus brasiliensis*, the study successfully addressed each objective, yielding robust empirical evidence that supports the integration of algae-based systems into climate-responsive architectural design.

The first objective sought to examine the effects of growth medium, pH, and photoperiod on the growth performance and chromatic stability of the selected species. The findings revealed that both medium composition and environmental parameters significantly influence cellular proliferation and pigment retention. Among the tested media—BBM, BG11, Bristol, and Chu—BG11 demonstrated superior support for cyanobacterial growth, particularly for *P. amphigranulata* and *Alkalinema* sp., while BBM favoured green algae such as *D. brasiliensis*. Optimal pH ranged between 6.8 and 10, with peak performance consistently observed at pH 8–10 under moderate to high light exposure. Photoperiod analysis further indicated that balanced light-dark cycles (e.g., 12:12 or 18:6) generally outperformed continuous illumination (24:0) in sustaining stable chlorophyll content and preventing photoinhibition. Notably, *P. amphigranulata* exhibited exceptional pigment stability across varying pH and light regimes, maintaining high chlorophyll absorbance (>3.9) and consistent green intensity ($a^* > 50$), which underscores its resilience and suitability for long-term architectural applications. These results confirm that species-specific tuning of culture conditions is essential to maximise both biological productivity and visual consistency key requirements for building-integrated algae systems.

The second objective focused on evaluating the carbon sequestration efficiency of the selected strains under controlled environmental stresses. Results demonstrated a strong positive correlation ($r^2 = 1.0$) between biomass accumulation and carbon sequestration rate (CSR), affirming that higher biomass directly translates to greater CO₂ fixation. *P. amphigranulata* emerged as the top performer, achieving a CSR of 1.36 g CO₂e/L and biomass of 0.87 g/L under pH 8 with an 18:6 photoperiod in BG11 medium. *Alkalinema* sp. followed closely with a CSR of 1.19 g CO₂e/L, while *D. brasiliensis* and *C. radiosa* recorded moderate to low sequestration capacities (1.30 and 1.18 g CO₂e/L, respectively). Crucially, extreme conditions such as pH 4 or 12 combined with minimal light (6 hours) led to near-complete growth inhibition and negligible carbon uptake, highlighting the sensitivity of microalgae to suboptimal environments. These findings validate that microalgae can function as active carbon sinks in urban settings, provided that cultivation parameters are carefully optimised. Moreover, the study establishes a quantitative benchmark for CSR performance, enabling future comparisons and scalability assessments in real-world building applications.

The third objective assessed the capacity of algae-based materials to modulate light intensity for energy savings. Using CIELAB colour space metrics (L* for lightness and a* for green intensity) and lux meter measurements, the research quantified light attenuation across cultures over a 14-day growth period. *C. radiosa* achieved the highest light reduction—1,050 lux (68%) followed by *Alkalinema* sp. (950 lux, 61%) and *P. amphigranulata* (930 lux, 60%). Lower L* values (e.g., 61.30 for *P. amphigranulata* at pH 8) correlated strongly with higher chlorophyll content and greater light absorption, confirming that pigment density directly influences shading efficacy. This light-filtering capability has direct implications for reducing solar heat gain and artificial lighting demand in buildings, thereby lowering cooling loads and energy consumption. The data further revealed that optimal light management occurs under conditions that also favour carbon sequestration namely, neutral-to-alkaline pH and balanced photoperiods suggesting synergistic co-benefits rather than trade-offs.

Collectively, these findings demonstrate that algae-based systems can simultaneously deliver carbon mitigation, thermal regulation, and visual functionality—aligning with the principles of regenerative and biophilic design. The study also identified clear species-specific roles: *P. amphigranulata* is best suited for high-performance façades requiring robust carbon capture and consistent green aesthetics; *Alkalinema sp.* offers moderate but reliable performance for general applications; *C. radiosa* excels in external shading due to its superior light attenuation; and *D. brasiliensis* show promise for rapid biomass generation in controlled environments. Despite these advances, the research acknowledges several limitations. Experiments were conducted under controlled laboratory conditions, which may not fully replicate the dynamic stresses of real-world urban environments (e.g., temperature fluctuations, air pollution, seasonal light variation) (Othman et al., 2024). Additionally, long-term durability, contamination risks, and economic feasibility of large-scale algae façades remain to be validated through pilot-scale implementations. Nevertheless, this study provides a foundational framework for selecting species, media, and operational parameters based on desired building performance outcomes.

In conclusion, this research successfully bridges biological science and sustainable architecture by demonstrating that microalgae are not merely passive greenery but active, multifunctional components of the built environment. By fulfilling all three research objectives, the study offers empirical validation for the use of algae-based materials as dual-purpose solutions for carbon sequestration and energy efficiency. As cities intensify their efforts to achieve net-zero emissions and climate resilience, integrating living systems like microalgae into building envelopes represents a viable, nature-based strategy that transforms architecture from a source of emissions into a platform for ecological regeneration. Future work should focus on full-scale prototyping, life cycle assessments, and policy integration to accelerate the transition from laboratory innovation to build reality.

5.2 RECOMMENDATIONS FOR ALGAE-BASED CARBON SEQUESTRATION AND ENERGY-EFFICIENT APPLICATIONS

The growing importance of sustainable and eco-friendly technologies in urban architecture has brought attention to algae as a viable solution for carbon sequestration and energy-efficient designs. This section provides recommendations based on the analysis of various microalgae species, their adaptability, carbon sequestration efficiency, energy efficiency, and light management potential, as summarised in Table 5.1 and 5.2.

5.2.1 Cyanobacteria (*Pseudanabaena*)

Pseudanabaena exhibits the highest overall performance in terms of adaptability, carbon sequestration efficiency (CSR), energy efficiency, and light management potential. With high adaptability across all culture modes, this species shows the highest CSR (1.36) and biomass production (0.87 g/L), making it a strong candidate for carbon capture applications. Its stability in both pigment and biomass production further enhances its suitability for integration into algae-based facades. Additionally, the species' high green absorbance (a^* 52.27) and excellent lightness filtration (L^* values) make it highly efficient in managing sunlight, reducing glare, and enhancing energy efficiency in building facades.

Recommendation: Given its superior attributes, *Pseudanabaena* is best suited for CO₂ sequestration and energy-efficient facade integration. It can be employed as a key component in bio-reactive facades for carbon capture and energy saving, especially in urban environments seeking to achieve sustainability targets.

5.2.2 *Alkalinema*

Alkalinema demonstrates moderate adaptability and carbon sequestration efficiency. Although its CSR (1.19) and biomass production (0.76 g/L) are lower than *Pseudanabaena*, it still performs well in a variety of settings. The species' pigment stability is moderate, but it remains suitable for applications requiring a balanced approach to light filtration and carbon capture. With a balanced green absorbance (a^*) and lightness (L^*), *Alkalinema* provides a stable and adaptable solution for buildings requiring moderate CO₂ reduction without extreme energy-saving needs.

Recommendation: *Alkalinema* is recommended for modest CO₂ reduction and general green facade use. It would be ideal for applications in areas where aesthetic considerations are balanced with the functional need for energy-efficient designs. This species is suited for more diverse or moderate-scale projects where high energy efficiency is not the sole priority.

5.2.3 *Carteria* (Green Algae)

Carteria is less resilient compared to other species, with low CSR (1.18) and biomass production (0.75 g/L). However, it exhibits strong light filtration capabilities, making it ideal for external shading applications. Its ability to reduce light intensity (68%) and moderate light absorption properties (a^* and L^*) make it an effective component for light-filtering elements in building facades. Despite its low carbon sequestration efficiency, *Carteria* can still contribute to energy efficiency by reducing indoor cooling demands through shading.

Recommendation: *Carteria* should be optimised for external shading panels and light-filtering elements. Its ability to reduce light intensity without compromising

airflow or natural light makes it an excellent choice for facades requiring shading or light filtering in buildings, particularly in regions with high solar exposure.

5.2.4 *Desmodesmus*

Desmodesmus stands out for its strong adaptability and relatively high carbon sequestration potential. With a good CSR of 1.30 and strong cell density, *Desmodesmus* is highly efficient in carbon capture. The species show considerable biomass and pigment production, which helps maintain its energy efficiency. Additionally, its high lightness (L^* 81.9) and good green absorbance make it well-suited for applications where energy regulation and light management are necessary. *Desmodesmus* is ideal for projects that prioritise rapid biomass growth for large-scale carbon sequestration.

Recommendation: *Desmodesmus* is ideal for rapid biomass growth and large-scale carbon sequestration. Its performance makes it suitable for integration into systems that require high biomass production and continuous CO₂ uptake, particularly in larger buildings or district-scale systems aimed at addressing carbon neutrality.

5.2.5 Summary of Recommendations

The key to optimising algae-based systems lies in selecting species based on the specific needs of the application, whether it is for carbon sequestration, energy efficiency, or light management. Here are a summary of the best-suited species and their applications as shown in Table 5.1 and 5.2.

Table 5.1 Comparative analysis of algae species for carbon sequestration, energy

	Species	Growth Adaptability (Culture Modes)	Carbon Sequestration Efficiency (CSR + Biomass)	Energy Efficiency (Biomass + Pigment)	Light Management Potential (Chromaticity + Light Filtration)	Recommended Application
Cynobacteria	<i>Pseudanabaena</i>	High – Adaptable in all modes	High – Highest CSR (1.36), biomass (0.87 g/L)	High – Strong pigment & biomass stability	High – High green absorbance (a^* 52.27) and best lightness filtration L^*	Best candidate for CO ₂ sequestration and energy-efficient facade integration
	<i>Alkalinema</i>	Considerable – Moderate adaptability	Considerable – Moderate CSR (1.19), biomass (0.76)	Moderate – Stable but lower pigment	Considerable – Balanced a^* and L^*	Suitable for modest CO ₂ reduction and general green facade use
Green Algae	<i>Carteria</i>	Moderate – Less resilient	Low – Lowest CSR (1.18), biomass (0.75)	Moderate – Stable pigment, lower biomass	High – Reduced light intensity (68%), moderate a^* & L^*	Optimised for external shading panels and light filtering elements
	<i>Desmodesmus</i>	High – Strong adaptability	Moderate – High cell density, good CSR (1.30)	Considerable – Good biomass & pigment	Considerable – lightness (L^* 81.9), considerable green absorbance	Ideal for rapid biomass growth

Table 5.2 Recommended algae parameters for carbon sequestration and energy saving applications

Parameter	Sub-parameter	Unit	Quality Index	Energy Saving Agent
Cell growth	Absorbance	Abs	> 2.0	Good growth and productivity
Carbon Efficiency	Dry Weight	%	> 0.1	Efficient carbon storage
	Biomass	g/L	> 0.7	Strong carbon fixation
	CSR	g/LC02e	> 1.0	Effective in mitigating climate change
	Chlorophyll	Abs	> 3.0	High photosynthetic activity
CIELAB Component	Lightness	L*	< 65.0	Significant decrease in light intensity
	Green-intensity	a*	> 50.0	Strong photosynthesis and light absorption

5.3 FUTURE DIRECTIONS

To enhance the effectiveness of algae in urban architecture, future developments should focus on scalability, cost reduction, and integration with other sustainable technologies such as solar panels and green roofs. The development of hybrid systems that combine algae-based facades with photovoltaic systems can further increase energy efficiency while contributing to carbon sequestration. Additionally, efforts to improve strain engineering and optimise culture conditions will increase the overall efficiency of algae systems in achieving climate-positive goals. In conclusion, algae-integrated systems have significant potential to improve both the environmental performance and aesthetic quality of urban buildings. By choosing the appropriate species based on specific needs and leveraging technological advancements, algae can be a key player in the creation of sustainable and energy-efficient urban environments.

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