Extraction of Phycobiliprotein from Microalgae Cultivated in a Novel Lab-Scale Raceway Pond using cost-effective Freeze and Thaw Approach

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Approval Sheet

This is to certify that the contents and forms of thesis titled as "Extraction of Phycobiliprotein from Microalgae Cultivated in a Novel Lab-Scale Raceway Pond using cost-effective Freeze and Thaw Approach" is the original work of author(s) and has been carried out under my direct supervision. I also certify that the thesis has been prepared under my supervision according to the prescribed format and I endorse its evaluation for the award of Bachelor of Engineering in Environmental Engineering Degree through the official procedure of the Institute.

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Abstract

Microalgae are gaining significant interest due to their intracellular components, including high-value phycobiliproteins (PBPs). PBPs are natural pigment-protein complexes with antioxidant and anti-inflammatory properties, making them beneficial for the food, nutraceutical, cosmetic, and biotechnology industries. However, large-scale commercial exploitation remains hindered by the high cost associated with PBP extraction from microalgal biomass. While the freeze-thaw method has been reported as an effective extraction technique, further optimization is crucial for industrial viability. This study investigates the efficiency of the freeze-thaw method for PBP extraction from Nostoc sp. cultivated in a novel lab-scale raceway pond system. This research aims to evaluate the impact of this cultivation method on microalgal yield compared to conventional techniques. The findings will contribute to the development of cost-effective and sustainable strategies for large-scale PBP production from microalgae

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Keywords: cyanobacteria, Nostoc sp., extraction, freeze-thawing process

Chapter: 01

1. Introduction:

1.1 Microalgae

Microalgae are photosynthetic microorganisms, a diverse group of single-celled or simple multicellular organisms, they play a fundamental role in both the chemistry and ecology of our planet. They utilize sunlight to fuel a process called photosynthesis, transforming carbon dioxide and water into organic matter and releasing oxygen. This not only provides them with energy but also significantly impacts the global carbon cycle and the very atmosphere we breathe. Understanding the classification of these vital microbes based on their pigments and cell structure is crucial for harnessing their potential. Furthermore, microalgal cultivation techniques are raceway ponds and photo-bioreactors that offer controlled environments to optimize their growth and exploit their remarkable capabilities for a range of applications.

1.2 Cultivation Approach

In literature one of the common and relatively cheaper methods to produce microalgal biomass is cultivating in open ponds. Open ponds include natural lagoons, raceway type ponds, etc., and was used initially for expanding microalgae culture. Raceway ponds are a well-established and cost-effective technology for cultivating microalgae. These shallow, artificial ponds offer a large surface area exposed to sunlight, making them ideal for large-scale production of these microscopic powerhouses.

Raceway ponds are relatively inexpensive to build and maintain compared to more complex cultivation systems like photo-bioreactors. They can easily scaled up or down to meet production needs, making them suitable for both small-scale research and large-scale commercial operations. Their open design allows for natural air exchange, simplifying gas management and reducing operational costs. Raceway ponds can be adapted to various climates and environmental conditions.

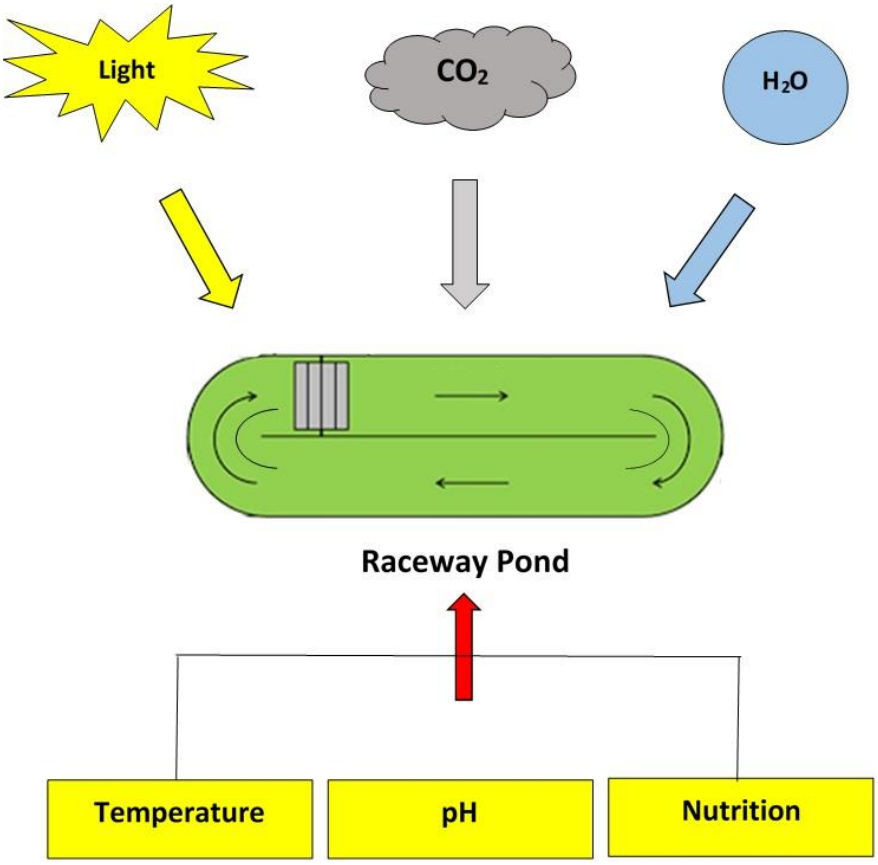

Figure 1. Cultivation of Microalgae in a Lab-scale Raceway Pond

1.3 Phycobiliproteins

Phycobiliproteins (PBPs) are pigment protein naturally produced by cyanobacteria, red algae, and some cryptophytes. This pigment complex is a key member of photosynthesis in algae and act as a photosynthetic light-harvester, with which the efficiency of light capture in visible spectrum can be enhanced [1]. PBPs consists of deacylated protein and phycobilins bound by covalent bonds [2], and can be classified specifically into four categories in spectral property, namely, phycoerythrin (PE; λ_{max} = 490–570 nm), phycocyanin (PC; λ_{max} = 610–625 nm), allophycocyanin (APC; λ_{max} = 650–660 nm), and phycoerythrocyanin (PEC; λ_{max} = 560–600 nm) [3]. As a type of natural pigment, PBPs are safer and more commercially valuable than synthetic colorants. Synthetic colors have been shown or suspected to increase the risk of cancer and allergic reactions, have begun to uses of artificial colorants in foods have been restricted by many organizations in the world [4]. In contrast, the Food and Drug Administration (FDA) has approved PBPs use in food and cosmetic industries [5]. PBPs are strongly fluorescent and can thus be developed for novel immunofluorescent probing [6].

A wide range of extraction methods including homogenization, sonication, lysozyme digestion, heat shock, nitrogen lysis and freezing and thawing (freeze–thaw) have been utilized to obtain phycobiliproteins [7,8,9]. Among these methods, the freezing–thawing extraction method had been reported as being the best for yielding the most phycobiliproteins [10].

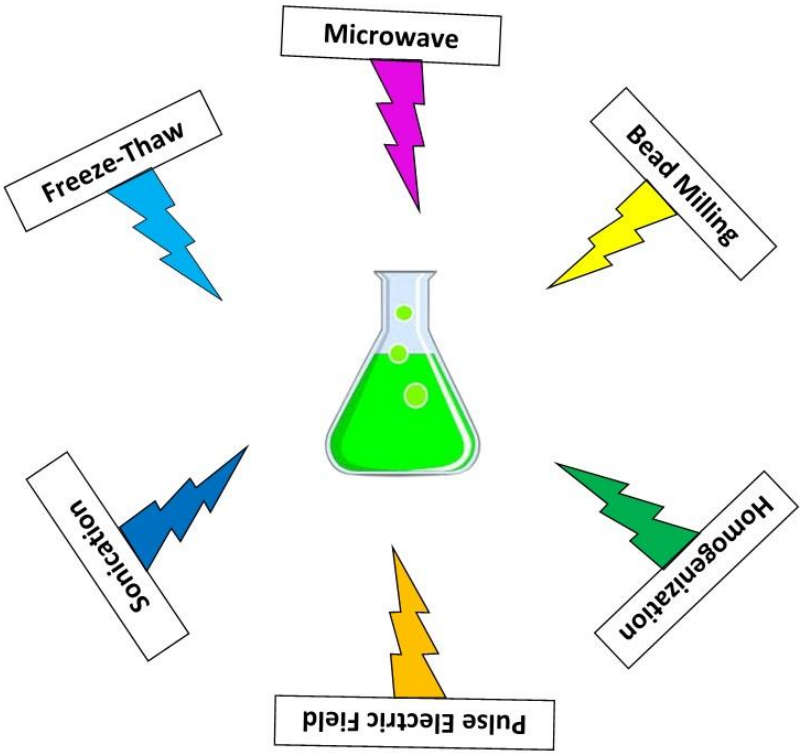

Figure 2. Different Extraction Method of Phycobiliprotien from Microalgae

Objectives:

The Objectives of this study were as follows:

1. Design and Construction of a Laboratory-Scale Raceway Pond for Enhanced Microalgal Cultivation
2. Comprehensive Study of Microalgal Growth Dynamics in a Controlled Raceway Pond Environment

3. Extraction of Phycobiliprotein from Cultivated Microalgae
4. Characterization and Process Optimization for Phycobiliprotein Production

Innovation:

1. Implemented a pressure flow motor to replace the conventional paddle wheel, thereby enhancing energy efficiency and providing more consistent and controlled water circulation within the pond.
2. Designed double slits at each end of the raceway pond to improve flow dynamics, increase turbulence, and enhance the dissolution and distribution of CO_2, thereby optimizing the photosynthetic efficiency of microalgae.
3. Installed solar panels to power the pressure flow motor, ensuring a sustainable and environmentally friendly energy source that reduces the operational carbon footprint.

Scope:

The scope of our project encompasses the design and construction of an energy-efficient lab-scale raceway pond, utilizing locally available components and materials sourced from NUST labs. We aim to develop an effective extraction method for Phycobiliprotein from microalgae, optimizing the process through controlled environmental conditions within the raceway pond. By replacing the traditional paddle wheel with a pressure flow motor and incorporating double slits for enhanced flow mixing and turbulence, we ensure efficient CO_2 distribution. Additionally, the integration of solar panels for motor operation highlights our commitment to sustainable and eco-friendly design.

Chapter: 02

2. Literature Review

Literature review forms a part of research as a solid base for future investigations and gathering relevant information to organize the research process with clear objectives hence the investigations proceed in the right way. It is an important part of the research since it provides a foundation for future research and helps to gather the relevant information to do the research correctly with a clear direction. The article collection of mine is comprised of a few of the subjects studied to be able to derive a sound analysis and obtain the information required in this research. It provides a common trend that highlights the recent studies done in the field of microalgae and raceway pond design by presenting the findings and implications, respectively, of the most significant ones.

2.1 Finding 01

This study (Sawant et al., 2022) focuses on utilizing Computational Fluid Dynamics (CFD) modeling to optimize the design of open raceway ponds for microalgae cultivation. By promoting optimized fluid flow patterns within the pond, the design is expected to reduce the power requirements for paddlewheel operation which is a major energy consumer in raceway ponds. This translates to a more cost-effective approach to cultivating algae. The CFD model allows researchers to analyze and predict the behavior of the culture medium within the pond, enabling them to refine the design for optimal performance.

2.2 Finding 02

This study (Marzorati et al., 2020) focuses to enhance culture mixing in the reactor, a baffle system was implemented due to the observed tendency of microbial culture to settle at the bottom, negatively impacting growth. Effective mixing, both axially and radially, is crucial for optimal culture development. The implementation of the baffle system aimed to address this issue by promoting more uniform distribution of the culture throughout the reactor. This ensures that the microorganisms are consistently exposed to nutrients and oxygen, thereby supporting their growth and metabolic activities. By improving the homogeneity of the culture environment, the baffle system helps to maximize the overall efficiency and productivity of the reactor.

2.3 Finding 03

This Study (Fanxue Zeng et al., 2015) investigates that Computational Fluid Dynamics (CFD) simulations have illustrated the effectiveness of a novel raceway pond design, featuring 15° inclined blades and semi-circular slits. This innovative design configuration has demonstrated a significant improvement in algal productivity, achieving a remarkable 17% increase compared to conventional raceway pond designs. The inclined blades and semi-circular slits work synergistically to enhance the mixing dynamics within the pond, promoting more uniform distribution of nutrients and light, which are crucial for optimal microalgae culture growth.

2.4 Finding 04

The study (Supenya Chittapun et al., 2020) demonstrates that the freeze-thaw method significantly outperforms the pulsed electric field (PEF) technique in the extraction of Phycobiliproteins (PC) content. This finding highlights the superior efficiency of the freeze-thaw method in breaking down cell membranes to release PC. The repeated cycles of freezing and thawing create ice crystals that disrupt cellular structures more effectively, leading to a higher yield of extracted PC compared to the PEF technique. In contrast, the PEF technique, while innovative and less labor-intensive, does not achieve the same level of cell disruption and PC release as the freeze-thaw method. Consequently, for applications requiring high PC content extraction, the freeze-thaw method is preferred due to its proven efficacy and reliability.

2.5 Finding 05

This study (Jaeschke et al., 2021) Phycocyanin extraction from Spirulina sp. cells can be efficiently achieved under specific conditions that ensure the purity and yield of the extracted product. The process is conducted at a moderate temperature of 25°C, which is optimal for maintaining the stability of phycocyanin and preventing its degradation. Additionally, the extraction is performed at a neutral pH, which further helps in preserving the integrity of the phycocyanin protein and avoiding any potential denaturation that could occur under more extreme pH conditions.

Chapter 03

3. Methodology

3.1 Media Preparation

Media preparation for microalgae culturing is a critical step that ensures the provision of essential nutrients required for optimal growth and productivity. The process begins with the selection of an appropriate culture medium, in our case its Zarrouk's Media, which typically includes a balanced mix of macro and micronutrients such as nitrogen, phosphorus, potassium, trace metals, and vitamins. These components are essential for cellular metabolism, photosynthesis, and overall physiological functions of the microalgae. Zarrouk's medium is prepared by dissolving the specific nutrients in distilled or deionized water, ensuring that the pH is adjusted to an optimal level for the particular microalgal species being cultured. Sterilization of the medium is then performed, commonly through autoclaving, to eliminate any potential contaminants that could interfere with the growth of the microalgae. Once prepared, the sterile medium is cooled and transferred under aseptic conditions to culture vessels. This meticulous preparation of the culture medium is paramount in providing a conducive environment for the microalgae, facilitating their growth and enhancing their metabolic activities, thereby supporting successful cultivation.

3.2 Microalgae Culturing

Nostoc sp., initially, the culture is transferred from a smaller volume of 50 ml to a larger 500 ml bottle to facilitate growth. This upscaling is essential for providing sufficient space and nutrients to support the proliferation of the microbial culture. The growth period for this experiment is designated as 7 days, during which the Nostoc sp. is expected to undergo significant growth and development. The cultivation process is conducted in

batch mode, a method where the microbial culture is grown in a closed system with a fixed volume of medium and no additional input or output of materials until the end of the growth period.

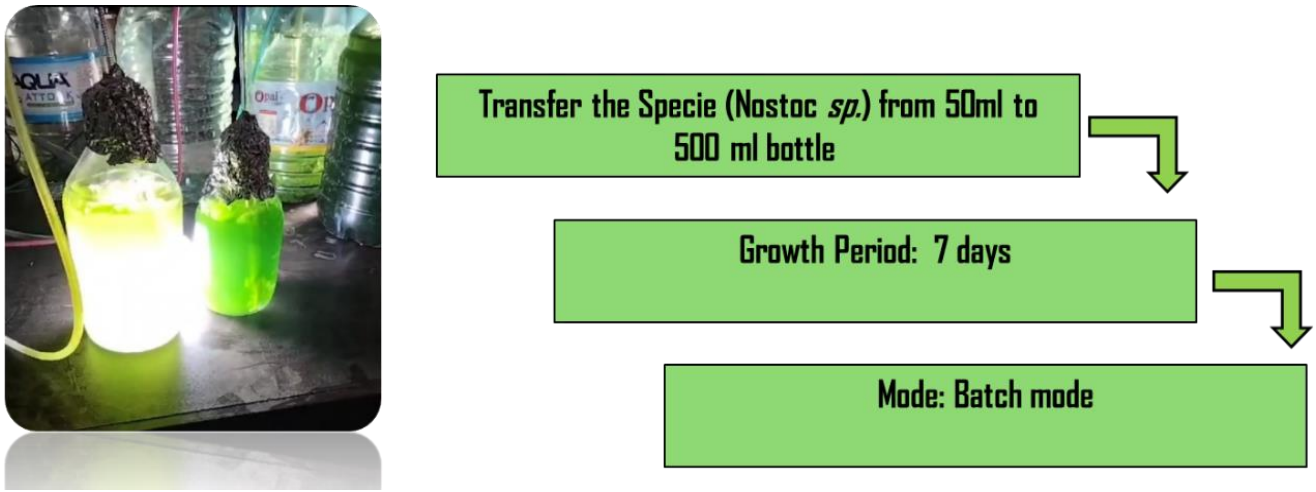

Figure 3. Culturing of Microalgae

3.3 Transferring of Culture to Raceway Pond

Once the raceway pond is prepared, the microalgal culture is transferred from smaller cultivation vessels, such as flasks or bioreactors, to the pond. After the transfer, the raceway pond is equipped with a flow motor to ensure continuous circulation and even distribution of the microalgal cells throughout the medium. This mixing helps maintain uniform light exposure and nutrient availability, which are critical factors for the efficient growth of microalgae. Additionally, the raceway pond is often exposed by artificial lighting, to provide the energy required for photosynthesis.

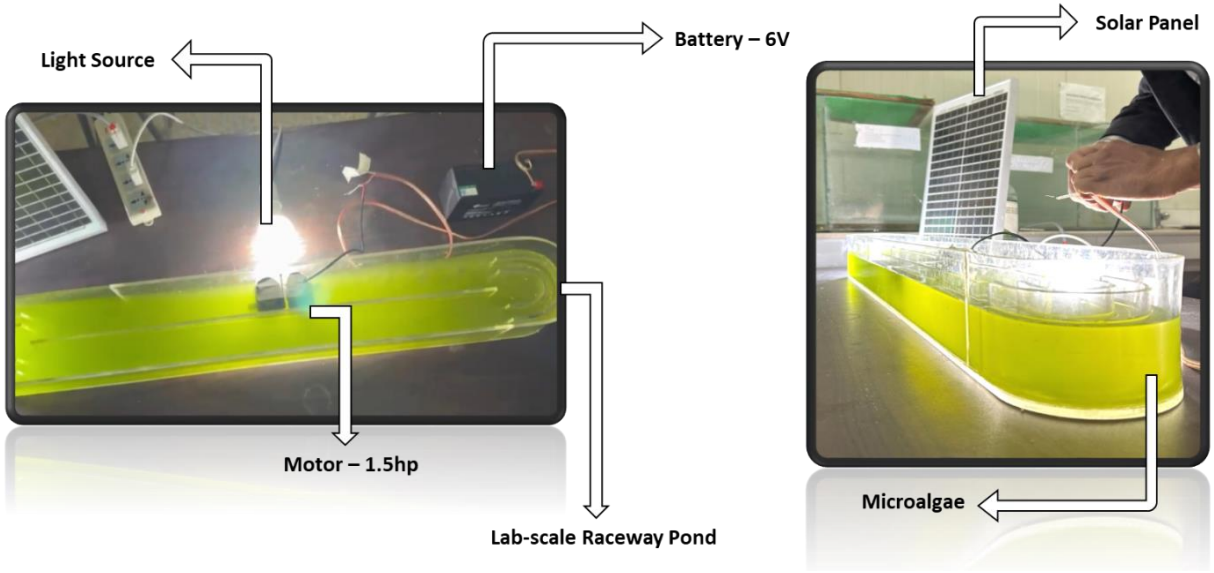

Figure 4. Cultivation of Microalgae in Lab-scale Raceway Pond

3.4 Factors Affecting Cultivation

3.4.1 Light

Light plays a crucial role in the growth and survival of microalgal species. Different wavelengths of light can affect the accumulation of photo biologically active compounds (PBPs) in algae. For example, blue light at 30 µmol $m^{-2}.s^{-1}$ or white light at 90 µmol $m^{-2}.s^{-1}$ has been found to be beneficial for the growth and accumulation of PBPs in certain microalgae species like Nostoc. Additionally, light intensity influences algal growth and PBPs synthesis, with low light intensities promoting PBPs accumulation in some species. Microalgae require a balance of light and dark periods during cultivation, with light–dark cyclic culture facilitating both growth and PBPs accumulation. Utilizing specific light sources and optimizing light–dark cycles can enhance PBPs production while reducing energy consumption.

3.4.2 Nitrogen Source

Microalgae exhibit varying abilities to utilize different nitrogen sources, such as ammonium, nitrate, and urea. The choice of nitrogen source can significantly impact PBPs accumulation in algal cultures. For instance, Arthrospira platensis and Nostoc shows the highest PBPs accumulation when supplemented with nitrate, while other species like Pseudoscillatoria sp. prefer ammonium supplementation. However, excessive nitrogen concentrations can inhibit algal growth and PBPs production. Thus, optimizing nitrogen source addition is essential for maximizing PBPs yield in microalgae cultivation.

3.4.3 Temperature

Temperature plays a critical role in PBPs production, as it influences the growth and metabolic activity of microalgae. Each algal strain has an optimal temperature range for growth and PBPs accumulation. Deviations from this range, either too low or too high, can lead to reduced PBPs content. For example, Cyanobacterium Arthronema africanum exhibits decreased PBPs content at temperatures below 15°C or above 47°C. Understanding the temperature preferences of specific algal strains is essential for optimizing PBPs production in microalgae cultivation systems.

3.4.4 Others factors

Apart from light, nitrogen source, and temperature, various other factors influence PBPs accumulation in microalgae cultures. These include the availability of essential nutrients and chemical elements like carbon, iron, potassium, and calcium. Optimal concentrations

of these components in the culture medium are crucial for maximizing PBPs yield. Additionally, factors such as pH and the presence of growth hormones can also affect PBPs production in algal cultures. Understanding and optimizing these factors are essential for enhancing PBPs accumulation and improving the efficiency of microalgae cultivation for PBPs production.

3.5 Extraction of Phycobiliprotein from Microalgae

The freeze-thaw method offers a unique way to extract Phycobiliprotein, vibrant pigments within microalgae. It works by exploiting the power of freezing. As temperatures drop, intracellular fluids crystallize, causing the cell to expand. Upon thawing, a fascinating reversal occurs. The cell contracts, generating pressure that damages the weakened cell wall. This ultimately releases the desired Phycobiliprotein into the surrounding solution.

A key advantage of this method is its gentleness. Unlike techniques using harsh chemicals or high temperatures, freeze-thaw avoids introducing elements that can degrade Phycobiliprotein. Studies suggest optimal extraction involves repeated cycles (6-7) of freezing for 4 hours at -20°C followed by thawing for 24 hours at 25°C, using distilled water as the solvent.

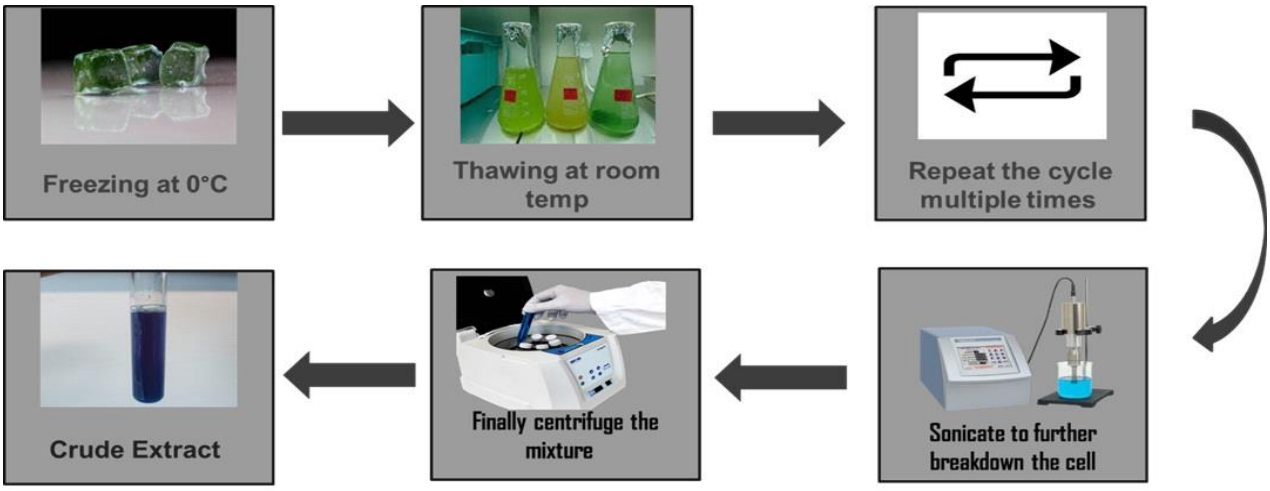

Figure 5. Different Extraction of Phycobiliprotien from Microalgae using Freeze-thaw approach

This method was applied to Nostoc sp., a microalgae known for its bioremediation abilities. Here, PC (phycocyanin) extraction was performed on lyophilized biomass using distilled water. Interestingly, cultures grown in a modified Zarrouk's medium yielded a higher PC content compared to those grown in wastewater.

3.6 Factor Affecting Extraction

The crucial physical and chemical parameters that majorly influence PC extraction include temperature, pH, solvent type, salt solution and biomass/solvent ratio etc.

3.6.1 Temperature

It is widely known that changes in cell membrane structure brought about by temperature have an impact on the extraction of intracellular compounds, basically enhancing the

mass transfer rates of internal compounds to the extraction medium. An increase in the PC extraction yield has been reported with an increase in temperature from 30 to 50 °C, however further rise in temperature can negatively impact PC yield as conditions started favoring cell degradation and denaturation. Furthermore, high temperatures can interfere with selective release of intracellular components. Most mechanical disruption techniques, including bead milling, ultrasound, and homogenization, are carried out between 25-35°C. The purity of the crude extract significantly depends on the temperature, as the temperature rises cytoplasmic proteins and other interfering substances are also released, lowering the purity of the PC. Moreover, the structure of the PC protein denaturize above 50 °C, as such high temperatures affect the stability of the chromophore, which then most likely involves changes to secondary, tertiary, and quaternary structures accompanied with a change in color.

3.6.2 Light, pH, solvents, and processing time

Illuminating conditions, favorable pH and processing time are the key factors that affect the aggregation and structure of PC, influencing its color profile and biological activity leading to instability. PC remains stable under normal light conditions for longer periods unless exposed to intense light conditions (> 4000 µmol m-2 s-1). When exposed to white fluorescent lamp (20 Watt) for a period of two months at pH 7.0, PC exhibits 10% degradation at 4 °C to almost 50% at 40 °C. The ideal pH range for stability of PC ranges from 6.0 – 7.0, where the hydrogen atom binds to the carboxylate groups resulting in monoanion formation. Below pH 5.0 and at pH > 8.0, the protein degrades and the quality of PC extract decreases. The pH values below 5.0 correspond to the isoelectric point of PC, which exists at a pH of around 4.6 to 5.2. At isoelectric point, the net charge on proteins is zero, the electrostatic repulsion between molecules decreases, proteins and water interact less promoting precipitation and thus making the extraction more difficult. Within the defined pH range for pigment stability, aqueous buffer solutions are typically used as a solvent to regulate the pH of the extraction medium. The treatment time can be a critical factor as combination of multiple approaches may enhance the extraction yield;

however, minimum downstream processing times are prerequisite for industrial approach. In extraction methods, longer processing times can ensure high yield for freezing and thawing approach whereas longer processing times can lead to PC degradation in high-pressure homogenization. As a result, optimization of the process parameters is important to improve the extraction yield of PC.

3.6.3 Biomass ratio and for

The impact of dried or fresh biomass on extract yield is still unclear. In general, the extraction yield increases with the biomass/solvent ratio when solvents are used for extraction purposes. A high biomass/solvent ratio (1:10) in sodium phosphate buffer (pH 6.8) treatment produced the highest extraction yield accompanied with a decrease in extract quality, as the increasing solvent availability also enhances the interfering proteins and debris. Whereas, reducing a biomass/solvent ratio (1:6), resulted in a low yield with the purest extract. In terms of a wet biomass effect on extraction via freezing and thawing, a wet biomass treatment constituting 75% wet biomass and 25% distilled water resulted in a fast and efficient extraction of PC compared to 100% wet biomass treatment that took five times longer while 50% wet biomass treatment resulted in a low PC yield. An understanding of the factors influencing PC stability could enhance extraction procedures and outcomes, however, the possible link between the factors bound stability and PC purity has not been studied as they do not appear to be associated.

4. Results

4.1 Microalgae Growth

The growth of microalgae, as illustrated in the provided growth curve, follows a typical sigmoidal pattern characterized by distinct phases. During the initial lag phase (Days 0-2), the Optical Density (OD) values remain close to zero for all conditions (C1, C2, and Avg), indicating that the microalgae are acclimating to their environment. This phase is followed by the exponential growth phase (Days 2-8), where there is a rapid increase in OD values, signifying vigorous cell division and growth. By Day 8, OD values reach approximately 2.5 for C1, 3.0 for Avg, and 2.0 for C2. As the growth continues into the stationary phase (Days 8-16), the rate of increase in OD slows down and begins to plateau due to factors such as nutrient depletion. By Day 16, OD values stabilize around 5.0 for C1, 5.5 for Avg, and 4.5 for C2. This data provides a clear quantitative depiction of the microalgae growth pattern over the 16-day period under the studied conditions.

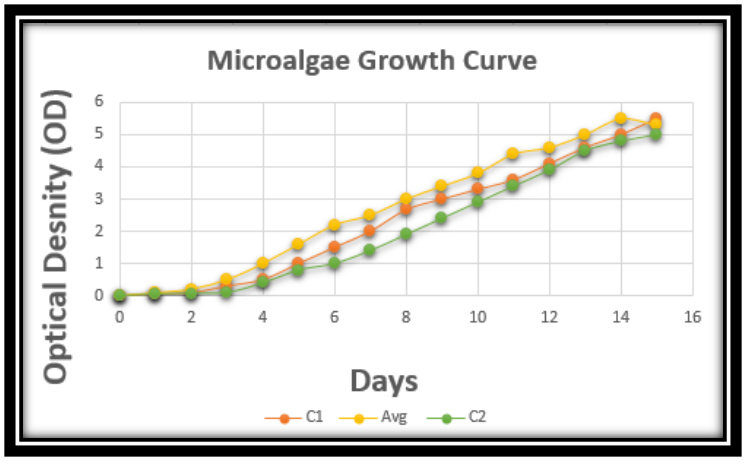

Figure 6. Optical Density of Microalgae

Table 1. Shows the Optical Density of Microalgae over 16 days Period

Days	C1	Average	C2
0	0	0	0
2	0.2	0.2	0.2
4	0.8	1.0	0.6
6	1.6	2.0	1.2
8	2.5	3.0	2.0
10	3.5	4.0	3.0
12	4.2	4.8	4.0
14	4.8	5.2	4.3
16	5.0	5.5	4.5

4.2 Extracted Phycobiliprotein

The amount of Phycobiliprotein extracted from the microalgae on the 16th day, considering the average across all conditions, is 55 mg/L. This value indicates the concentration of Phycobiliprotein in the culture medium after 16 days of growth. The average concentration provides a representative measure of the overall productivity of the microalgae cultures under the studied conditions, reflecting the potential yield of

phycobiliproteins that can be harvested at the end of the cultivation period. This extraction level is significant as phycobiliproteins are valuable for various applications, including as natural dyes, in fluorescent probes, and in nutritional supplements. Thus, achieving a concentration of 55 mg/L suggests a successful cultivation process with a good yield of phycobiliproteins.

5. Conclusion

The cultivation of microalgae in a raceway pond, followed by the extraction of phycobiliproteins using the freeze-thaw method, demonstrates a promising approach for efficient biomass production and valuable compound extraction. Over a 16-day period, the growth of microalgae showed a typical sigmoidal pattern with distinct lag, exponential, and stationary phases. The Optical Density (OD) measurements indicated successful cell proliferation, with the average OD reaching 5.5 by the 16th day.

Using conversion factor, the concentration of extracted phycobiliproteins was estimated to be 55 mg/L on the 16th day. This concentration reflects a substantial yield, highlighting the effectiveness of the cultivation and extraction processes. The raceway pond provided an optimal environment for microalgae growth, ensuring sufficient light exposure and nutrient availability, while the freeze-thaw method proved to be a simple and efficient technique for breaking down the cell walls to release phycobiliproteins.

Overall, this study underscores the potential of raceway pond systems for large-scale microalgae cultivation and the viability of the freeze-thaw method for extracting high-value phycobiliproteins. These findings support the feasibility of integrating these methods in biotechnological applications, contributing to the sustainable production of natural pigments and other bioactive compounds.

Chapter: 06

6. Commercial significance of Phycobiliproteins

In manufacturing industry, microalgae based PC have become increasing popular for their multiple and diversified beneficial functionalities. As an antioxidant and cytotoxic agent, PC have potential applications in health supplements, bioremediation and pharmaceutical industry. Due to potential health benefit as a natural blue colorant, PC can compete with artificial colorants in food and cosmetic industry through cost effective techniques for recovery and separation.

6.1 Food & Beverage Industry

PC is a naturally occurring blue pigment obtained from microalgae and cyanobacteria with potential for use as a value-added food colorant. The beverage and confectionary industry have a high demand for blue colorant, which are seldom produced in nature leading to the use of synthetic colors. In recent years, the health and safety issues associated with synthetic food colorants have caused the food and drug authorities around the world to restrict their use. For this reason, the food industry is now expressing a growing interest in the search, economical production, stabilization, and use of natural blue colorants and PC is an ideal candidate for meeting these benchmarks.

6.2 Health Supplements

PC is gaining recognition for its important role in health supplements. This naturally occurring compound is highly valued for its strong antioxidant properties, making it a valuable addition to dietary supplements and nutraceuticals. By scavenging harmful free radicals in the body as an antioxidant, PC provides protection against oxidative stress

and inflammation. PC recognition for its potential health benefits encompasses reducing inflammation, supporting cardiovascular health, and aiding in detoxification processes. Furthermore, its immune-modulating abilities enhance its appeal in health supplements by strengthening the body's defense mechanisms. These attributes position it as a vital component within health supplements, striving to enhance overall well-being. In current scenario where the consumers prioritize natural bio-based solutions for their health concerns, the inclusion of PC in dietary supplements represents a sustainable solution to cleaner and natural sources of nutritional support.

6.3 Pharmaceuticals

PC has garnered significant attention from the pharmaceutical industry due to its wide range of applications in the development of pharmaceuticals. Its ability to act as a carrier molecule represents its potential to augment drug solubility, stability, and targeted distribution by encapsulating various pharmaceutical compounds. This encapsulation ensures the efficient transportation to specific cellular targets and enhances drug efficacy, while minimizing undesirable side effects. Ongoing research trends continue to explore the transformative impact of PC on pharmaceutical industry by offering innovative solutions for complex healthcare challenges. The potential of PC-based pharmaceuticals extends to diverse medical treatments, including cancer therapy, immunotherapy, and regenerative medicine. Studies investigating PC potential for anti-cancer properties, indicating it exhibits cytotoxic effects on cancer cells and inhibits tumor growth through mechanisms such as apoptosis induction and anti-antigenic. Such valuable characteristics position PC as an important ingredient for the development of novel anticancer drugs. Researchers are also exploring its potential as an adjunct therapy or foundational component in innovative cancer treatments. In essence, PC multifaceted contributions in pharmaceuticals underscore its significance in driving advancements in renewable energy and therapeutic interventions.

6.4 Bioremediation

PC containing cyanobacteria plays a vital role in bioremediation by offering a sustainable solution for fighting environmental pollution. In the context of bioremediation processes, PC-rich microalgae are deployed to effectively combat a wide range of pollutants, including heavy metals and organic compounds found in water bodies and soil. One of the key mechanisms in the process is the ability of PC to chelate heavy metals. This forms stable complexes that are less toxic and easier to remove. Microalgae additionally produce enzymes and secondary metabolites that aid in degrading organic pollutants like hydrocarbons and pesticides. By harnessing the natural capabilities of PC, bioremediation practices contribute to sustainable environmental management, reducing the impact of pollution on ecosystems and human health.

6.5 Cosmetic Industry

PC has gained recognition and popularity as a versatile and natural ingredient in the cosmetic industry. It is harnessed to create visually appealing skincare and makeup items, and hair care products. The vibrant natural blue color of PC is its most notable pigment characteristics, adding a captivating hue to various cosmetic formulations. Additionally, PC offers potential skincare benefits with its soothing and moisturizing properties, making it a valuable addition to skincare formulations. PC bioactive compounds can provide multiple benefits for the skin, including soothing irritations, reducing redness, and enhancing hydration. These qualities make it a valuable ingredient in cosmetic products [49]. Its natural origin aligns with the growing demand for clean and sustainable beauty options displaying an industry wide shift towards environmentally conscious and skin friendly formulations.

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