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Photobioreactor – A Sustainable Approach to Algal Biotechnology and Biofuel Production

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Abstract: The increasing demand for environmentally friendly and sustainable energy sources worldwide has placed microalgae at the center of biotechnological research. Compared to traditional methods for producing biomass, algal photobioreactors (PBRs) have emerged as promising technologies for efficiently cultivating cyanobacteria and microalgae. This review thoroughly explores the biology, classification, design, technological advancements, and diverse applications of photobioreactors, highlighting their important role in addressing current industrial and environmental challenges. Starting with the biological foundation, the study outlines the key metabolic features of microalgae that make them ideal for industrial use. These features include their ability to accumulate lipids, their high photosynthetic efficiency, and their specific nutritional needs. The paper then analyzes the structural designs, working principles, advantages, and limitations of PBRs, categorizing them into open, closed, and hybrid systems. Algal productivity is significantly influenced by operational factors such as light intensity, carbon dioxide supply, mixing, temperature control, and contamination management, all of which are carefully optimized. The review also examines recent technological innovations, such as the use of smart materials, IoT-based automation, AI-driven monitoring, 3D printing, and biofilm growth techniques, which can enhance the performance and scalability of PBRs. It covers a wide range of applications, including the production of biofuels like biodiesel, bioethanol, and biogas, the treatment of wastewater, carbon capture, and the creation of valuable bioproducts such as pigments, antioxidants, and biofertilizers. The environmental advantages, such as reduced greenhouse gas emissions, minimal land use, and the ability to remove pollutants, are highlighted. Additionally, an economic comparison is made between PBR technologies and conventional methods in terms of cost-effectiveness, scalability, and market potential. While the benefits of PBRs are clear, the study also notes challenges that hinder their widespread commercial use, including high initial costs, complex operations, and regulatory constraints. The review recommends further research into biorefinery models, genetic engineering, and integration with renewable energy systems to fully unlock the potential of algal PBRs. Finally, the study calls for interdisciplinary collaboration, supportive legislation, and financial backing to accelerate the transition to a circular, bio-based economy driven by innovations in algal technology.

Keywords: *Photobioreactor, Algae, Bioindustry, Biofuel, Sustainability.*

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I. INTRODUCTION

➢ *Background on Microalgae and their Importance*

Moment about 80 of global energy demand is produced from fossil energies. still, expansive application of fossil energies has led to global climate change, environmental pollution, and health problems. numerous countries are therefore turning their attention to the development of new, clean, and sustainable energy sources. Among the colorful implicit sources of renewable energy, biofuels are of utmost interest and are anticipated to play a pivotal part in the global energy structure in the future. Biodiesel, one of the most generally used biofuels, is honored as an ideal recyclable energy carrier, and therefore also as a possible primary energy source. marketable biodiesel is presently produced from beast fat, waste frying oil painting and vegetable canvases, whose competition with comestible vegetable oil painting for agrarian land is still a controversial issue. Accordingly, microalgae that can grow fleetly and convert solar energy to chemical energy via CO_2 obsession are now being considered a promising oil painting source for making biodiesel. Under suitable culture conditions, some microalgae species are suitable to accumulate up to 50 – 70 of oil painting/ lipid per dry weight. The adipose acid profile of

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microalgae oil painting is suitable for the conflation of biodiesel. The major magnet of using microalgae oil painting for biodiesel is the tremendous oil painting product capacity by microalgae, as they could produce up to 58,700 L oil painting per hectare, which is one or two bulks advanced than that of any other energy crop. still, mass product of microalgae oil painting faces a number of specialized hurdles that render the current development of the algal assiduity economically unfit. In addition, it's also necessary, but veritably delicate, to develop cost-effective technologies that would permit effective biomass harvesting and oil painting birth. nonetheless, since microalgae product is regarded a doable approach to alleviate global warming, it's clear that producing oil painting from microalgae biomass would give significant benefits, in addition to the energy. Microalgae have thus been widely recognized as the feedstock for the third generation of biofuels. This review critically evaluates the literature regarding the cultivation, photobioreactor design, and harvesting of microalgae for biodiesel production. [1]

Promoting and embracing sustainable ways of producing and consuming goods is a major global issue. Issues related to climate change and energy availability show that the world needs to adopt more sustainable living habits to decrease the use of natural resources and lower air pollution emissions. It is necessary to develop specific strategies that enhance the environmental performance of products and services, save energy, create more efficient technologies, and guide consumers towards making more sustainable purchasing choices. This is essential to ensure that economic growth does not come at the cost of harming the environment. [2].

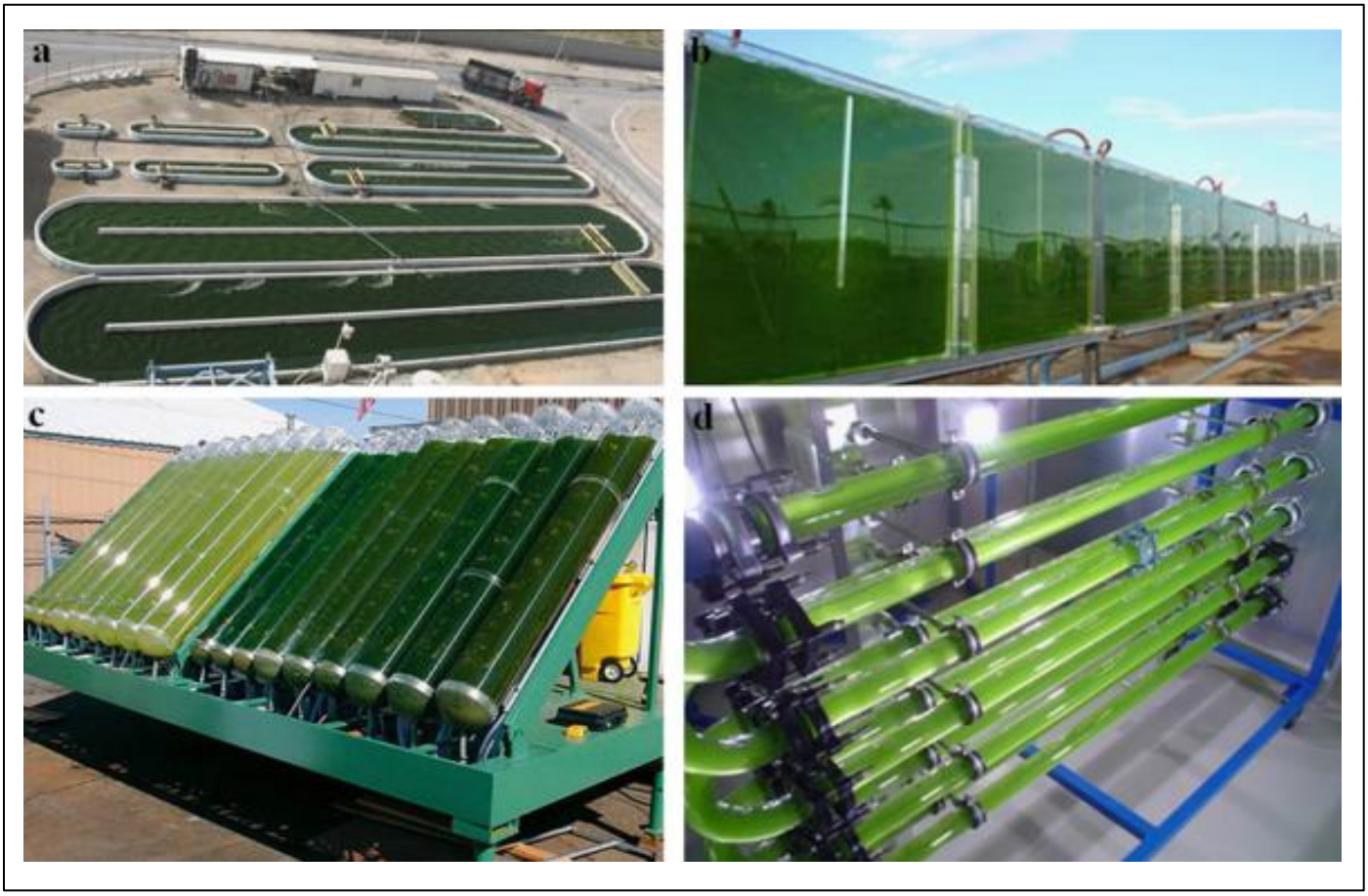

Fig 1 (a)Raceway Pond [Open System], (b)Flat Plate Photobioreactor [Closed System],(c)Tubular Photobioreactor [Outdoor,Angled Tubes], (d)Tubular Photobioreactor (Indoor,Horizontal Coils) [3]

➢ *Need for Sustainable Technology*

The building's energy usage and the comfort of its occupants in terms of temperature and visibility are greatly affected by the building's outer layer. In response to this, façade-integrated microalgae photobioreactors have recently been explored as an innovative eco-friendly approach for sustainable buildings. However, there are still important gaps in knowledge, especially concerning how well this system performs. This study aims to examine the main issues related to the performance of these photobioreactors when used on building façades. It also highlights the lack of a detailed and comprehensive review of existing research that considers the different performance aspects of microalgae photobioreactor façades (PBRF), along with various technical factors that might influence their application. The findings confirm the notable benefits of PBRFs. Additionally, the study addresses existing research gaps and challenges in applying this technology. Some of the major gaps include high costs for installation and maintenance, limited research on the visual, energy, thermal, and daylight performance of PBRFs,

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structural design considerations, user engagement, and the absence of relevant regulations.[4].

II. BIOLOGY AND METABOLISM OF ALGAE RELEVANT TO PHOTOBIOREACTOR APPLICATIONS

➢ *Types of Algae Used in PBRs (Microalgae, Cyanobacteria)*

Microalgae are rich in lipids, which can be transformed into liquid transportation biofuels, such as biodiesel, and sustainable aviation fuels (SAF). Cultivating microalgae for biofuel production has the potential to offer a carbon-neutral alternative to traditional fossil fuels, provided that the productivity and efficiency of different production systems can be further improved. This can be achieved by enhancing the performance of microalgal species and/or optimizing photobioreactor (PBR) designs. Certain microalgae species, such as *Arthrospira* and *Chlorella*, are rich in proteins, vitamins, and essential fatty acids, making them valuable nutritional supplements for the food and feed industries, thus contributing to human and animal health. Additionally, high-value compounds derived from microalgae, such as pigments and antioxidants, are used in cosmetics and pharmaceuticals due to their antioxidant, anti-aging, and anti-inflammatory properties, among others. On the other hand, microalgae can be used in lower-value applications, such as wastewater treatment, to remove nutrients and contaminants. They have the ability to absorb pollutants, thereby aiding in water purification. Moreover, microalgae play a significant role in carbon sequestration by capturing CO_2 during photosynthesis. Integrating microalgae cultivation with industrial processes has the potential to reduce greenhouse gas (GHG) emissions. However, there are still several challenges to overcome, including the limited robustness of microalgal strains to CO_2-rich environments, low product yields, difficulties in biomass harvesting and processing, limitations in product formation and purification, the lack of stable liquid CO_2 sources, and the effective utilization of all biomass fractions to create an economically viable biorefinery system. These challenges are largely linked to the selection of PBR designs for microalgae cultivation. Furthermore, certain microalgal species are capable of absorbing heavy metals and other contaminants from the environment, making them valuable for bioremediation efforts in polluted areas. [**5]**. *Cyanobacteria*, also known as blue-green algae, are the earliest photosynthetic organisms on Earth, appearing around 2.6 to 3.5 billion years ago. It is believed that the photosynthetic organelle found in eukaryotic cells may have originated through endosymbiosis, where a phagotrophic host engulfed a *cyanobacterium.* These microorganisms display a wide range of morphological forms, such as unicellular, filamentous, planktonic, benthic, or colonial (coccoid) structures.*Cyanobacteria* have a photosynthetic system that allows them to take carbon dioxide and convert it into a reduced form, making them ideal for the sustainable production of various chemicals and biofuels. Unlike heterotrophic bacteria, which rely on organic carbon sources, cyanobacteria only need sunlight, carbon dioxide, water, and minimal nutrients for growth, eliminating the need for costly carbon sources and complex growth media. Sunlight, being the most accessible and affordable resource on Earth, makes *cyanobacteria* a promising option for producing fine chemicals and biofuels using solar energy, thereby offering a more environmentally friendly synthesis method. *Cyanobacteria* are capable of efficient photosynthesis and have higher biomass production rates compared to plants. For example, they can convert up to 3 to 9% of solar energy into biomass, whereas crops like corn and sugar cane achieve only 0.25 to 3%. Recent advancements in genetic and metabolic engineering, along with the availability of over 300 cyanobacterial genome sequences, have led to significant progress in research aimed at fully realizing the potential of these photosynthetic bacteria.[6].

Table 1 Various Type Algae Used from 1890s to 2020s[7]

Era Algae	Use in PBRs
1890s	*Chlorella vulgaris* – physiological studies
1900s–1940s	*Chlorella pyrenoidosa, Scenedesmus, Nitzschia* – open-pond lipid assays
1950s–1960s	*Cyanobacteria, C. sorokiniana* – CO_2 capture, mass cultivation
1980s–1990s	*Spirulina, Dunaliella, Haematococcus, Chlorella, Scenedesmus* – pigment, supplements, wastewater
2000s	*Chlamydomonas, Anabaena* – biohydrogen research
2010s	Diverse green microalgae in outdoor PBRs, biofilm systems
2020s	*Auxenochlorellaprotothecoides* Advanced species in heterotrophy, industrial diatoms, wastewater bioremediation

➢ *Growth Requirements (Light, C0₂, Nutrients)*

For microalgae as photosynthetic microorganisms, the intensity and duration of light, as well as the CO_2 attention, are the main environmental parameters that significantly affect the societies' growth. Under natural conditions, the duration of light is determined by seasonal and diurnal oscillations, while operation of artificial light sources makes it possible to control the light and dark cycles or to cultivate microalgae under nonstop light.In a liquid medium, gassy inorganic carbon passes into a dissolved form, available to algal cells in the form of CO_2(aq) or HCO_3 −. The degree of dissolution, and hence the effectiveness of CO_2 obsession by algal cells, depends on the size of the gas bubbles and the hearthstone time in the liquid. The degree of CO_2 biofixation is determined by the difference between the attention of gas entering and exiting a photobioreactor, by the quantum of carbon in the biomass, and by other styles using sophisticated logical outfit. Parameters similar as light intensity, temperature, and pH have a significant impact on photosynthetic carbon obsession degree. It has preliminarily been shown that a variety of microalgae of the family *Scenedesmaceae* can be used as agents for removing

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inorganic nutrients from defiled waters, promising sources of precious products, CO_2 obsession agents, and as feed backups. nonetheless, a lot of exploration has either optimised their growth using a single parameter or used a limited range of settings. *Tetradesmus bajacalifornicus*, an indigenous species, was thus cultivated in Kaliwala's trial at varying CO_2 attention while maintaining a constant light intensity of 180µmol m −2 s −1. The growth and metabolic makeup of the cells were shown to be significantly impacted by CO_2 attention, according to the authors. In a different study, *Tetradesmus obliquus* and members of the *rubric Chlorella* were grown in a glass bubble column photobioreactor at different CO_2 attention and 74µmol m −2 s −1. *T. obliquus* displayed high growth criteria and lipid product situations among the microalgae studied, and the scientists observed that *T. obliquus* shown high forbearance to adding CO_2 situations. There are not numerous exploration that examine the goods of light on *Scenedesmaceae* microalgae that test for high PPFD values. The PPFD values in several trials are infrequently advanced than 150 µmol m −2 s −1, making it insolvable to adequately assess the algae's implicit.[8]

III. CLASSIFICATION OF ALGAL PHOTOBIOREACTOR

➢ *Open Systems*

One of the most traditional and straightforward methods for producing microalgae in large quantities is open pond cultivation. Open ponds are widely used in the industry because they are less expensive to build, maintain, and operate. They also offer advantages such as simple handling, low energy requirements, and the ability to scale up production. In these systems, paddle wheels and baffles are often used to ensure proper mixing, similar to how they are used in raceway ponds. *Figure 2* provides a schematic illustration of an open photobioreactor system, which is a type of raceway pond. While open ponds are the most cost-effective option for growing microalgae compared to closed systems, they do come with certain challenges. These systems are influenced by environmental factors, making it difficult to control light, temperature, and evaporation. Although they can produce large amounts of biomass, they require a significant amount of space, which can lead to contamination. Additionally, the low concentration of carbon dioxide—typically between 0.03% and 0.06%—can limit the transfer of gases and slow down algae growth. Despite these drawbacks, open systems are still preferred for commercial microalgae production because they are easy to clean, suitable for large-scale cultivation, and offer high productivity at a lower cost.

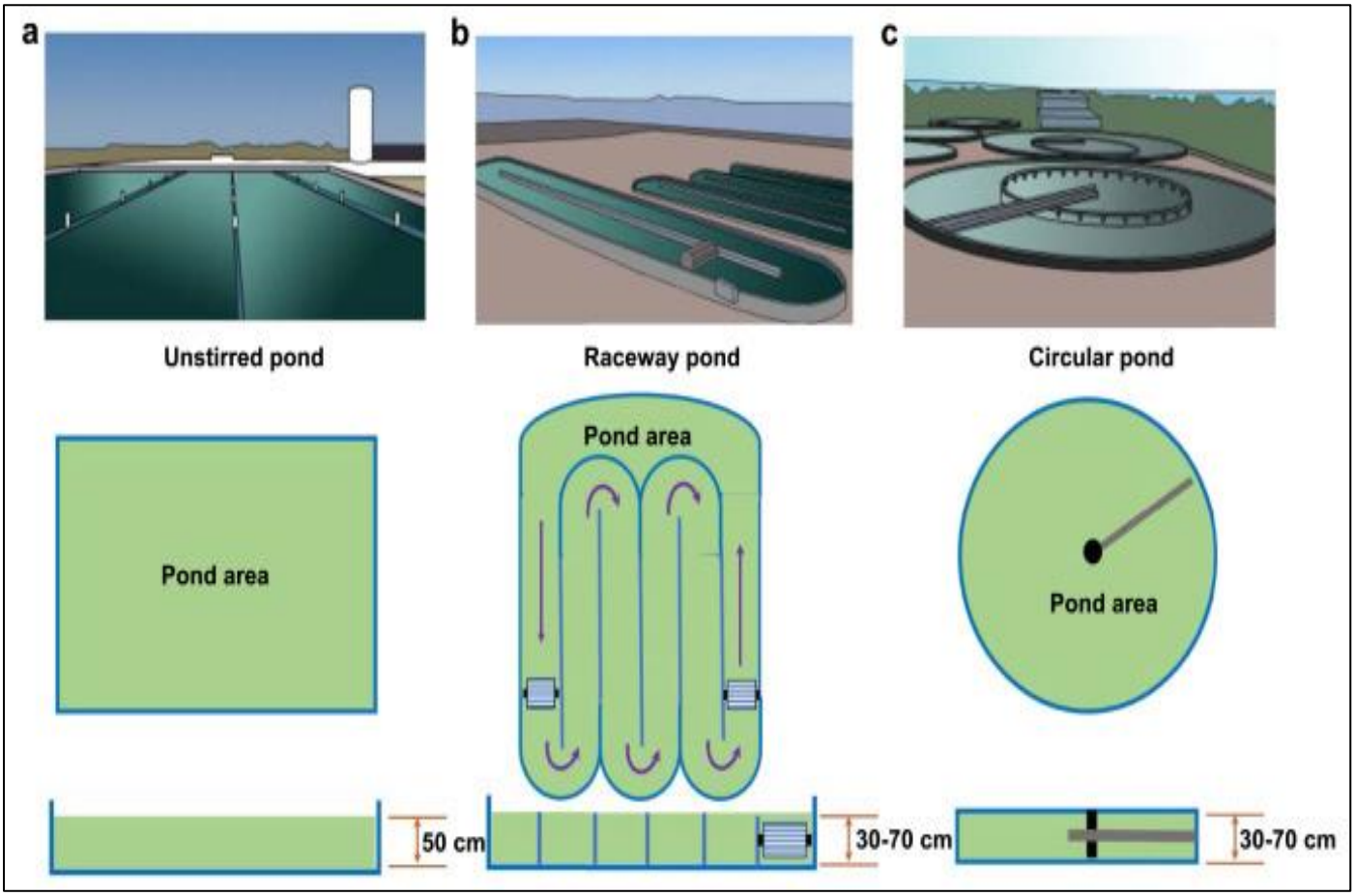

Fig 2 Open Cultivation Systems: (a) Solix Biofuel's Open, Undisturbed Pond for Growing Chlorella in Colorado, USA; (b) Carbon Corporation's Paddle Wheel Racing Pond in California, USA; (c) Circular Pond in Taiwan, China.

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Open-air farming methods are often used to grow microalgae for biomass production. These methods include natural and man-made ponds, raceway-style ponds, and inclined systems that use paddle wheels to move the water. These systems are generally easy to design and manage, but they come with several challenges and limitations that have been recognized over the past five decades of research. Some of these issues include the limited ability to grow only a few types of microalgae, the presence of harmful predator species, problems with water supply due to evaporation, inefficient use of carbon dioxide, the need for large spaces that can only be used on unused land, lower biomass output compared to enclosed systems, and the high cost of harvesting microalgae. Despite these difficulties, open culture systems are still used for producing microalgae biomass, and there are ongoing efforts to enhance their performance and address their shortcomings.

➢ *Closed System*

The maximum productivity of open pond systems has been reached, and increasing their output is not financially viable. Consequently, a number of academics have proposed that closed reactor systems are necessary for large-scale biomass generation in the future. Closed reactors are anticipated to become the most widely used microalgae rearing technologies as their cost declines over time. To improve growth control and operational conditions, several closed photobioreactor designs have been created. Horizontal tubular reactors, bubble column vertical tubular reactors, and flat plate or panel (FP) type photobioreactors are the three most used varieties for larger-scale growth systems.The closed photobioreactors schematic diagram is displayed in Figure .3

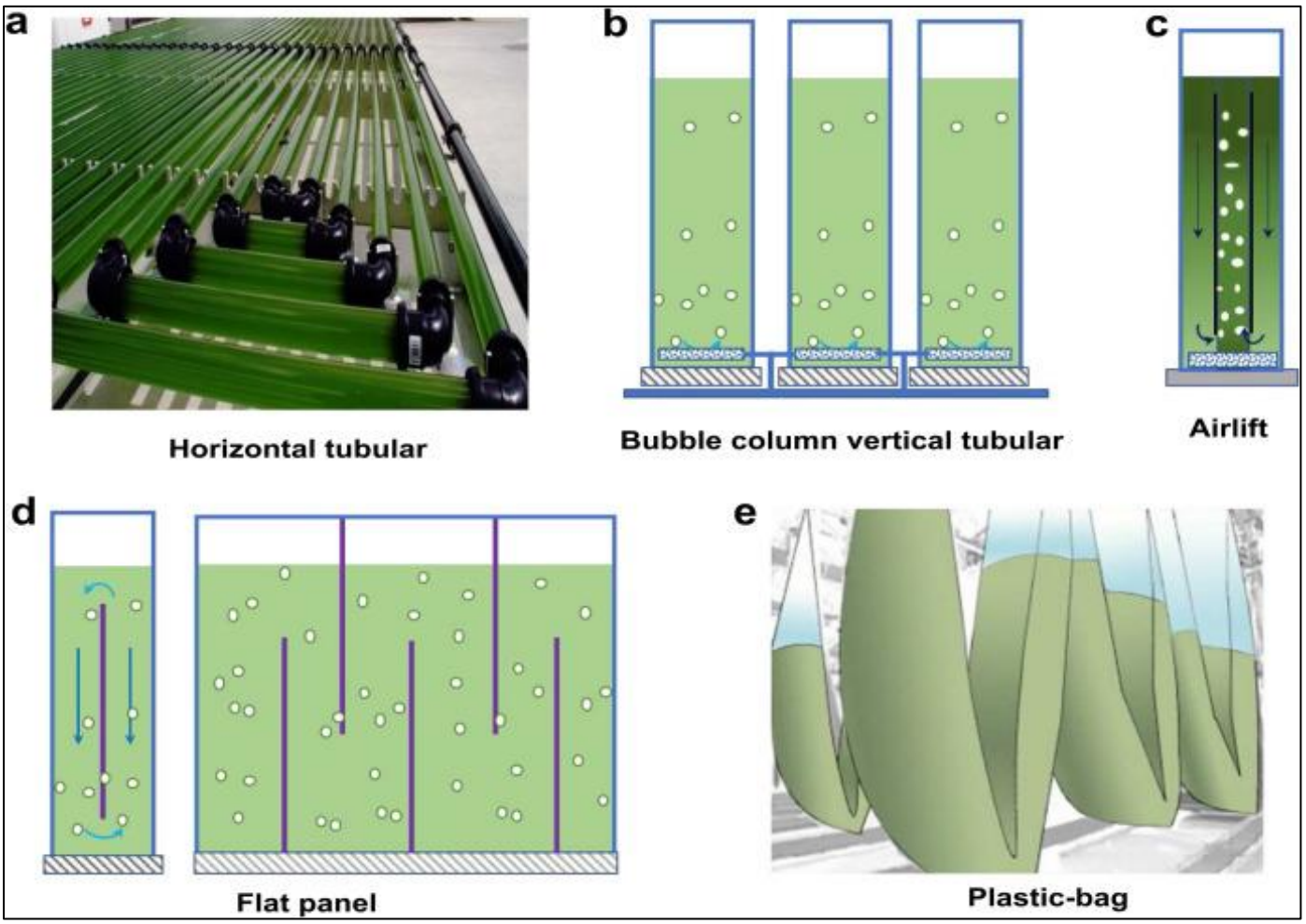

Fig 3 Closed Cultivation System: (a) Horizontal Tubular; (b) Bubble Column Vertical Tubular; (c) Airlift Tubular; (d) Flat Panel; (e) Large-Scale Plastic-Bag Photobioreactors.

Closed systems were created to get around the drawbacks of open systems. The main goal of the closed system is to create an environment where a monoculture of microalgae may be grown with very little contamination in order to produce high-value and biochemical compounds. The reactor's fundamental structure consists of a closed vessel where the microalgae are grown using either direct sunlight or artificial illumination. Closed photobioreactors are several times more efficient than open systems due to a high surface area to volume ratio, however the process is not cost-effective. The geometric configuration of the closed-system photobioreactors is used to categorise them; this is covered in more detail below. The closed system is more costly even if it produces higher concentrations of higher-quality biomass.To evaluate, the advantages and disadvantages of these systems are illustrated.

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A closed system offers several benefits, including the ability to manage microalgae growth, avoid contamination, limit the exchange of gases or bacteria between the inside and outside, provide control over the system, and help optimize its performance. In addition, closed photobioreactors (PBRS) are preferred when microalgae need to grow slowly, as they allow for better control over the species present. Closed photobioreactors are efficient in photosynthesis and offer excellent control. They can be designed vertically rather than horizontally, which helps save space and reduces water loss due to evaporation. However, this type of reactor also has several disadvantages, such as high costs for construction and operation, the risk of oxygen buildup, challenges in scaling up the system, and the possibility of cell death caused by the materials used in the photo process.

- *Horizontal Tubular*

Horizontal tubular photobioreactors are made with transparent materials and are set up in outdoor areas where they receive sunlight (as shown in Fig. 3a). These types of cultivation systems are designed to have a large surface area relative to their volume, which helps microalgae get more sunlight exposure. The tubes are usually less than 10 cm in diameter to allow sunlight to reach the microalgae inside. In a standard tubular microalgae system, the growth medium flows through the tubes where the microalgae use sunlight for photosynthesis. The medium is then returned to a storage tank using either a mechanical pump or an airlift pump. This keeps the flow inside the reactor highly turbulent, which helps prevent the algal cells from settling at the bottom. Some of the algae are collected after they pass through the solar collection tubes, which makes the system operate continuously. However, most of the tubular photobioreactors that have been studied using artificial light have been built at a small or laboratory scale, with capacities ranging from 0 to 20 liters. There is not much research available on large-scale closed photobioreactors. James and Al-Khars looked at how well Chlorella and Nannochloropsis grow in a translucent vertical airlift photobioreactor. They found that Nannochloropsis had productivities between 109 and 264 grams per cubic meter per day, while Chlorella had productivities between 32.5 and 95.3 grams per cubic meter per day.

- *Bubble Column Vertical Tubular*

Bubble column vertical tubular reactors, as shown in Figure 3b, are designed with a height that is twice its diameter. This design provides a high surface-to-volume ratio, which supports efficient heat and mass transfer within the reactor. An internal lighting system is often preferred because it helps reduce the energy needed for photosynthesis. The rate at which gas is introduced into the reactor, along with the light and dark cycles, are important factors that influence biomass production and the effectiveness of photosynthesis.Used a vertical glass tube that was 5 cm in diameter and 2.3 meters tall, giving a total volume of 4.5 liters. The bubble column setup allows for ample light exposure. However, it is still uncertain whether this system can be effectively used on a large commercial scale. In such reactors, production rates of up to 23 grams per cubic meter per day of monoraphidium have been recorded.

- *Airlift*

Airlift photobioreactors, as shown in Figure 3c, use a baffle or a draft tube to split the fluid inside the vessel into two connected areas, forming large circulation currents. These reactors offer several benefits, including high mass transfer, efficient mixing with minimal shear stress, low energy use, and easy operation under sterile conditions. However, scaling them up is challenging due to their complex flow patterns. The alternating conditions between lighter and darker sections make these reactors suitable for both single-species algae cultures and mixed cultures with wastewater. They also provide a high surface area relative to their volume and can support high cell densities. Mixing is accomplished either by air bubbles or mechanical rotation in a perforated tube, which aids in thorough mixing, effective nutrient delivery, proper light distribution, and prevents the buildup of excess oxygen.

- *Flat Panel*

Vertical flat panel photobioreactors, as shown in Fig. 3d, which use air bubbling, are more effective than bubble columns in terms of productivity and ease of operation. These systems provide a large surface area for light exposure, are suitable for use outdoors, and are effective for immobilizing algae, resulting in good biomass productivity. They are cost-effective and easy to clean. These reactors can be used in units with a capacity of 1000–2000 liters and have been successfully used for several days. Closed flat panels with air bubbling can achieve high productivity in volume-based cultivation. A 500-liter unit with a 440-liter culture capacity was able to produce 0.27 grams per liter per day using a flat plate glass photobioreactor. Although these systems have some challenges, such as difficulty in managing temperature and hydrodynamic stress, they have a lower risk of oxygen buildup and higher photosynthetic efficiency compared to other types of photobioreactors. Flat plate photobioreactors are recommended for the large-scale production of microalgae in both indoor and outdoor setups because they offer high light exposure on their surfaces, low accumulation of dissolved oxygen, and a modular design that makes scaling up easier. Pulzl and others developed a large-scale flat plate photobioreactor module with a capacity of 6000 liters, where one layer is used for culture circulation and the other for temperature-controlled water circulation. This design achieved high productivity due to the high surface-to-volume ratio. However, issues such as photo-inhibition and temperature control can affect the biomass yield.

- *Plastic-Bag*

By placing transparent polyethylene bags in sunlight and allowing air to mix at the bottom of the bags, microalgae can be grown (Fig. 3e). Transparent polyethylene sleeves are commonly used to prevent cells from settling, and these bags can be hung or placed in a cage for cultivation. Cultures using 50 L of polyethylene bags have been successfully used in turbidostats. However, it is important to carefully consider potential issues such as photo-inhibition and cell settling.[9]

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IV. DESIGN AND OPERATIONAL PARAMETER

➢ *Light Availability and Optimization*

Light is a key factor in photosynthesis, the process through which microalgae transform light energy into chemical energy, which supports their growth and biomass production. The strength, length, and type of light have a major effect on how microalgae grow. Proper light exposure helps photosynthesis to happen effectively, while too much or too little light can cause problems like reduced growth or damage to the cells. The amount of light that reaches the surface of the culture, measured in micromoles of photons per square meter per second (μmol photons m−2 s−1), helps determine the intensity of the light. The amount of light absorbed by the cells depends on factors such as cell concentration, how light interacts with the cells, mixing within the culture, and how deeply the light penetrates into the reactor. Any light that is not absorbed is either reflected away or turned into heat. Light-driven growth follows a pattern known as saturation kinetics, where growth speeds up until a certain light intensity level is reached. At this point, the growth rate stabilizes, and further increases in light intensity might harm or kill the cells, such as through a process called photoinhibition. While higher light intensity can increase microalgae growth up to a certain level, which varies by species, too much light can lead to photo-inhibition. Light is essential for microalgae growth as it serves as their energy source when they grow as phototrophic organisms. However, only about 10% of the light is converted into chemical energy, while the rest is released as heat. Some research estimates this conversion rate to be as low as 2%. Microalgae use light to generate adenosine triphosphate (ATP), which is vital for maintaining cellular functions and producing new molecules. However, very intense light can interfere with the photosynthetic process. The relationship between light intensity and growth has been studied. As light intensity increases, it eventually reaches a saturation point where growth becomes stable. Further increases in light could damage the cells, like through photoinhibition, or even cause cell death. To imitate natural conditions, microalgae are often grown in low light levels, ranging from 60 to 400 μmol m−2 s−1. For the species *Chlorella vuygaris*, the highest growth rate was observed at a light intensity of 80 μmol m−2 s−1. Light intensity of 50 μmol m−2 s−1 is not enough to support growth, while an intensity of 110 μmol m−2 s−1 can cause photo-inhibition. For the production of lipids, different microalgae species and strains need varying light intensities, ranging from 60 to 700 μmol m−2 s−1. High light intensity can cause triacylglycerol content to rise more sharply. The level of light also influences the production of fatty acids, carotenoids, including carotene, lutein, and astaxanthin. [10].

➢ *Mixing and Aeration*

High microalgal growth rates rely on proper solution mixing, so mass transfer can be improved by adding baffle structures to photobioreactor (PBR) systems. In this study, butterfly-shaped baffles were added to a double-column photobioreactor (DC-PBR) to reduce mixing time, increase the mass transfer coefficient, and boost the growth rate of *Arthrospira platensis*. By increasing the size of the baffles and the angle between their wings, the mixing time was reduced by 20%, and the mass transfer coefficient was improved by 32%. The vertical flow vortices created by the butterfly baffles enhanced the light and dark cycles between the inner and outer columns in DC-PBRs, which led to a 19% increase in chlorophyll-a content, a 20% improvement in photochemical efficiency and electron transfer rate during photosynthesis. The addition of a butterfly baffle to the PBR increased the biomass growth rate of A. platensis by 33%, while also causing the helix pitch and trichome length to increase by 15–16%. [11]

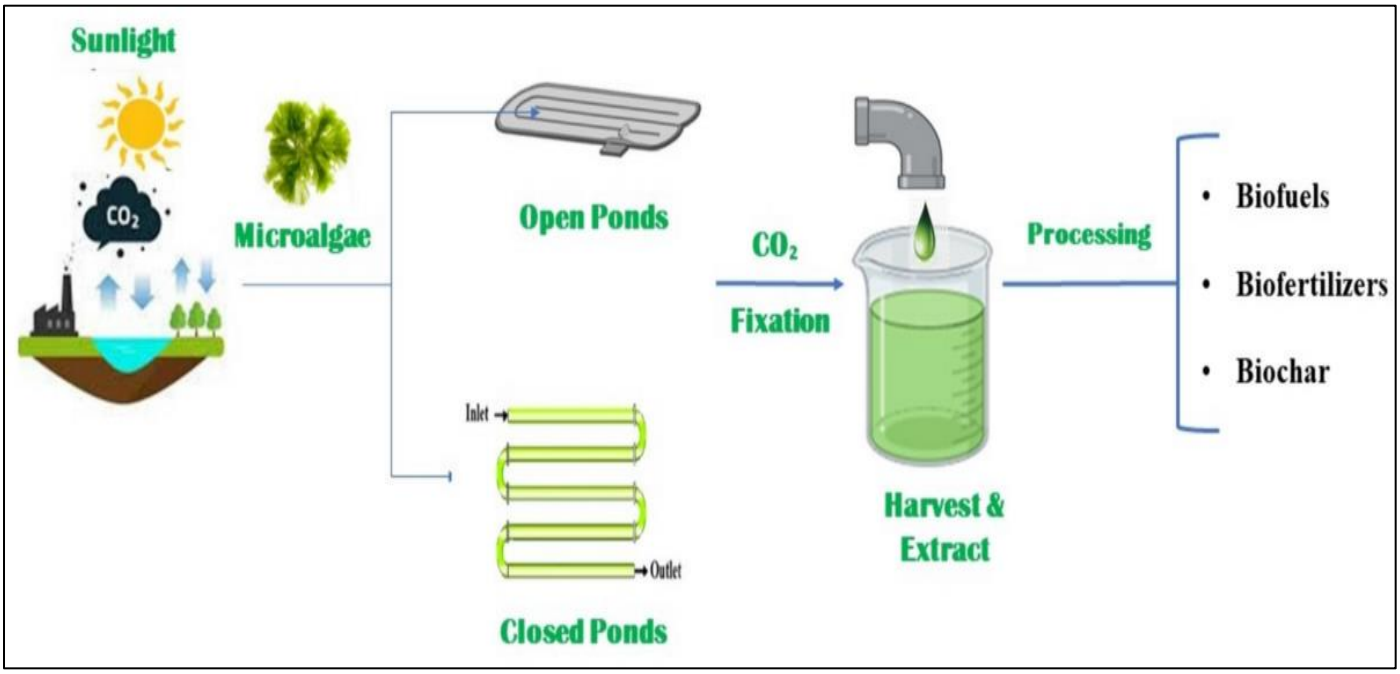

Fig 4 This Figure is a Schematic Representation of co_2 Bio-Fixation Process Using (Open & Close) PBR with Butterfly Baffles to Cultivate Microalgae.

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➢ *Temperature Control*

The growth and metabolic processes of microalgae and other photosynthetic microorganisms are significantly influenced by temperature. The majority of algae species grow best in certain temperature ranges, usually between 20°C and 30°C. Cell death or decreased biomass production might result from departures from these ideal circumstances. Furthermore, the biochemical makeup of algal cells is impacted by temperature. For example, temperature changes can affect microalgae's lipid content, which is a crucial factor in the creation of biofuel.Temperature variations can also affect the synthesis of important secondary metabolites as antioxidants and pigments. Thus, it is essential to keep PBR temperatures steady in order to maximise output and guarantee constant product quality. [12]

The microalgae *Scenedesmus abundans* was grown in five identical airlift photobioreactors (PBRs) using both batch and fed-batch methods under outdoor tropical conditions. The strain S. abundans was found to be able to withstand high temperatures (35–45 °C) and high light intensities (770–1690 µmol m−2 s−1). The highest biomass production rates were observed with the fed-batch method, reaching 152.5–162.5 mg L−1 day−1. However, biomass productivity dropped significantly when the culture temperature exceeded 45 °C due to the photoinhibition effect. The lipid composition of the microalgae showed that the majority of fatty acids were saturated and monounsaturated (>80%) across all PBRs, with a Cetane number higher than 51. The fed-batch approach proved more effective in achieving higher biomass and lipid production under challenging outdoor conditions. Additionally, the microalgae accumulated omega-3 fatty acid (C18:3) up to 14% (w/w) of total fatty acids under these outdoor conditions [13]. Temperature is a key factor affecting microalgae growth rates and influencing the biochemical processes within cells. The maximum specific growth rate (µˆ), as described in the Monod model, is influenced by temperature and light intensity, not the availability of limiting nutrients. Since light levels were consistent, the maximal specific growth rate is primarily a function of temperature, and the Arrhenius equation can effectively describe this relationship. [14].

$(\boldsymbol{\mu}\hat{}) = Ae^{-E/RT}$

Where,

A = constant, day^{-1};

E = Activation energy, cal mol^{-1};

R = Universal gas constant, cal K^{-1} mol^{-1};

T = Temperature, K.

➢ *Nutrient supply*

In the examined stoichiometry range of cellular constituents, carbon partitioning is significantly influenced by the kinetics of food intake. A maximum value that can be understood as the minimum principle of growth is required by successive metabolic stages that conceal one another. These basic modules must be well defined, but they may be expanded or changed in response to process circumstances and scientific advancements. First, understanding the physiological situation—for which ranges of parameter values are provided—is aided by an explanation of kinetics. Second, kinetics should be applied not only to the construction of photobioreactors but also to the optimisation of gases and nutrients. [15]

In this study, the impact of monochromatic light (blue, yellow, and red) and mixed wavelengths on the nutrient absorption and growth patterns of four benthic microalgae species—*Achnanthes sp., Amphora sp., Navicula sp.,* and *Nitzschia sp.*—was examined. The highest uptake rates (ρmax) for nitrate and phosphate, as determined through short-term experiments, were observed in the order of blue, mixed, red, and yellow light. Among the four species, *Nitzschia sp.* exhibited the highest ρmax. The half-saturation constant (Ks) was found to be higher in *Nitzschia sp.* compared to the other species. Under nitrogen and phosphorus-limited conditions, *Nitzschia sp.* also displayed the highest specific maximum growth rate (µmax') and minimum cell quota (q0) values among the four microalgae. These findings indicate that the benthic microalgae are well-suited for environments with high nutrient levels. Specifically, *Nitzschia sp.*, which has a greater ability to store and absorb nutrients, could be a valuable candidate for phytoremediation purposes. [16].

➢ *CO_2 Supplementation and O_2 Removal*

As a response to the issue of global warming, people around the world are looking for effective solutions. Individuals are trying to capture carbon dioxide from major sources to stop more emissions of large amounts of CO_2. These large sources of CO_2 can include the burning of fossil fuels, natural gas, other synthetic fuel plants, and facilities that produce hydrogen using fossil fuels. One method that has become increasingly popular is the use of photosynthetic CO_2 bio-fixation, which is viewed as both eco-friendly and energy-efficient. Although traditional land plants can absorb CO_2, their slow growth limits them to capturing only 3% to 6% of the emissions from fossil fuels. In contrast, microalgae grow much faster and can be used for on-site CO_2 removal, making them a promising approach for capturing and storing carbon dioxide. In fact, microalgae have been found to be able to capture up to 1.83 kilograms of CO_2 per kilogram, making them a useful tool in the battle against global warming. Microalgae are small, photosynthetic organisms that live in water and absorb CO_2 via photosynthesis. This process transforms CO_2 and sunlight into carbohydrates and produces oxygen (Fig. 5). Microalgae are particularly efficient at this process, which is referred to as "oxygenic photosynthesis". CO_2 is turned into lipids and hydrocarbons, which is a type of "CO_2 fixation". Water acts as the electron donor and releases oxygen. The general equation for photosynthesis is:

$$H_2O + CO_2 + PHOTON \rightarrow [CH_2O]_n + O_2\uparrow$$

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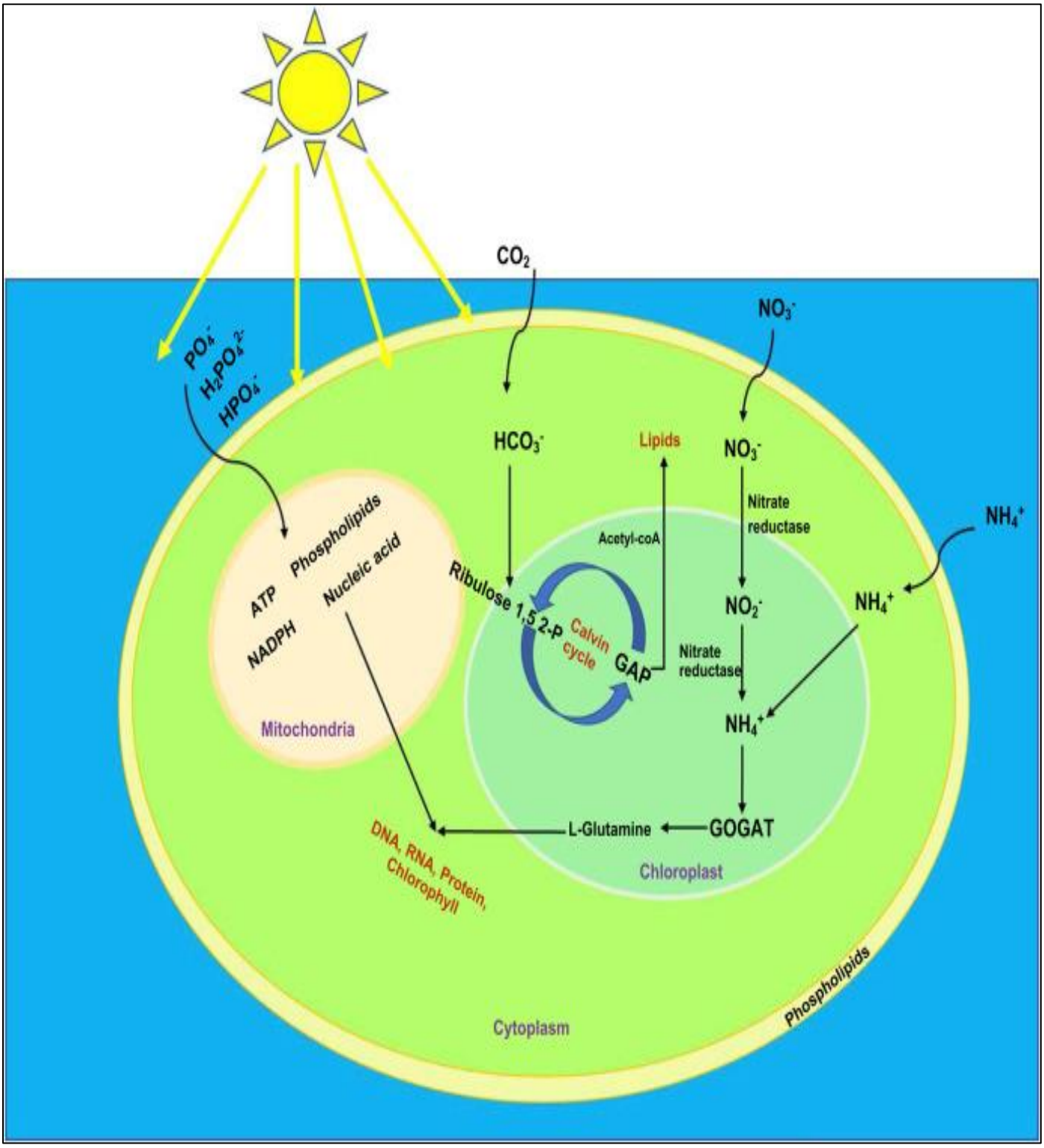

Fig 5 Diagrammatic Representation of the Photosynthesis Process for the Cultivation of Microalgae.

This reaction converts the energy of light to chemical energy (ATP, NADPH). Then, by using this chemical energy, organic carbon is synthesized from inorganic carbon [17].

➢ *Contamination Control*

The goal of researching the various forms of biological contamination and the associated infecting patterns, infecting sources, and bio-contaminant detection techniques is to suggest or create dependable ways to significantly reduce the level of biological contamination while preventing transmission, thereby repairing the entire production of photosynthetic biofuel during the mass cultivation of *microalgae* and *cyanobacteria.*

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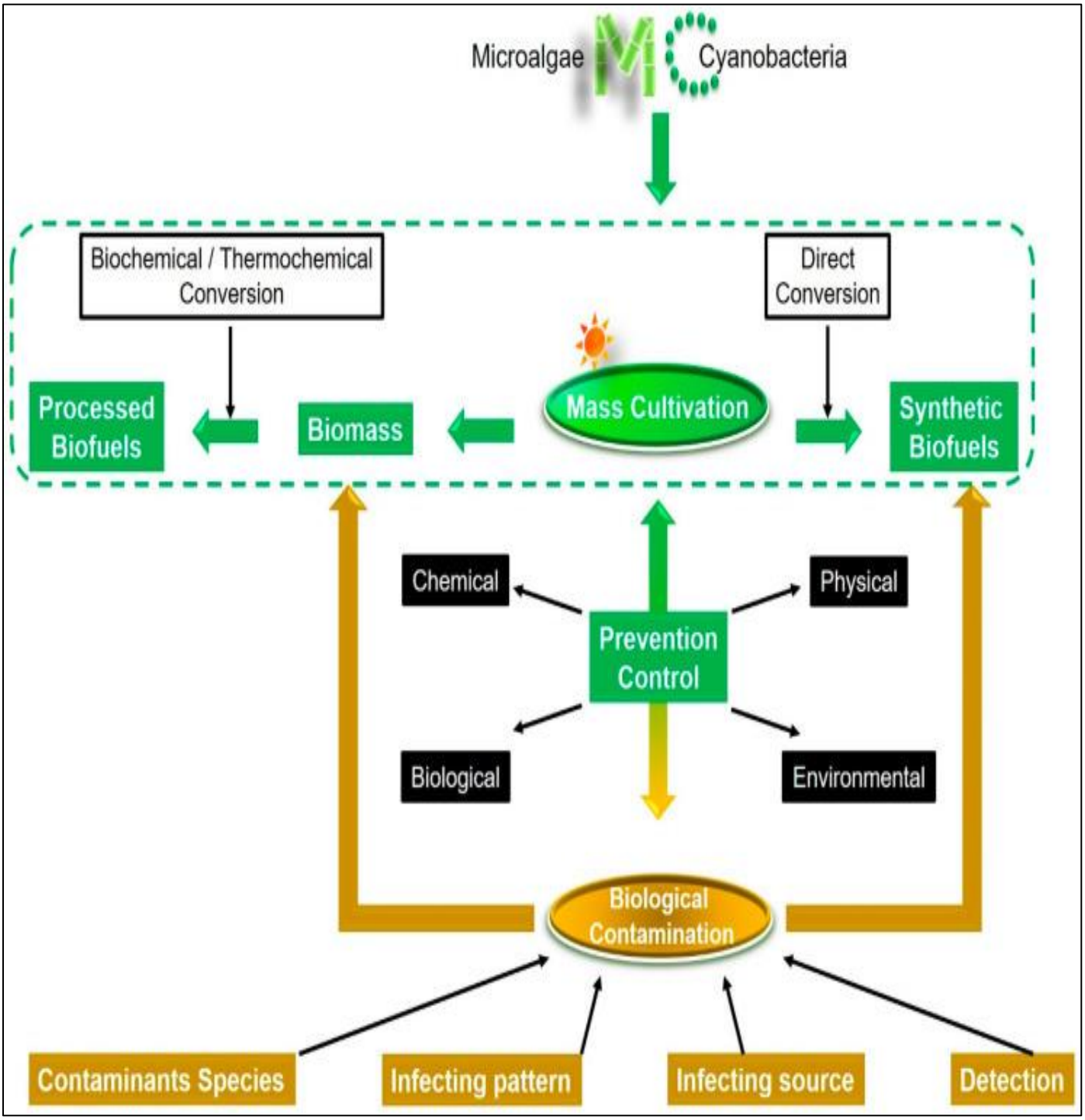

Fig 6 Flow Diagram of Bio-Fuel Production

- *Chemical Control*

Chemical methods are commonly used to manage microalgae and cyanobacteria in civilization systems, often serving as a practical solution for controlling natural pollutants. As previously mentioned, due to the large volume of water involved in biofuel production, substances like hypochlorite or bleach are widely used to eliminate the culture medium before or during the cultivation of *microalgae* and *cyanobacteria*. Park's research showed that a concentration of sodium hypochlorite ranging from 0.45 to 0.6 mg Cl/L was effective in inhibiting the grazing activity of rotifers while still supporting the growth of *Chlorella kessleri*. Traditional chemical fungicides are also frequently used to protect microalgae and cyanobacteria from natural contaminants. Organophosphorus and organonitrogen germicides, such as trichlorphon, dimehypo, methyl parathion, and diazinon, can effectively eliminate rotifers and ciliates. Surfactant Triton-N is used to maintain the health of the inoculum, as it can quickly inhibit the growth of Scenedesmus. Chemical agents like bobby mariners have been reported to act as germicides against chytrids, and their addition can boost algae productivity because they serve as a necessary trace element for algal growth during cultivation. While chemical control appears to be industrially viable, it is

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important to note that many chemical agents may also hinder the growth of other aquatic organisms and lower the concentration of phycocyanin. Furthermore, the excessive use of these synthetic chemicals poses potential risks to the environment and human health. Therefore, there is a need for further research into environmentally friendly natural agents that can suppress the presence of natural pollutants without harming the cells of *microalgae* and *cyanobacteria.*

- *Biological Control*

Using certain pathogens to manage natural pollutants, which overcome the limitations of traditional chemical methods and reduce the harmful effects on the cells of microalgae or cyanobacteria, could be an ideal approach for controlling impurities in large-scale cultivation. However, the successful application of such natural control methods still depends on the careful selection of suitable pathogens for each type of pollutant. This process requires detailed knowledge about the relationship between the pollutants and the specific strains of microalgae or cyanobacteria, which needs further study. According to Huang's acute and long-term experiments, celangulin, matrine, and toosendanin are regarded as effective botanical fungicides for controlling rotifers in microalgal cultures. Additionally, the combined use of celangulin and toosendanin for controlling rotifers in *Spirulina platensis* cultures was further investigated. The results showed that applying a combination of 0.003–0.006 mg/L of these botanical fungicides at a ratio of 19 could suppress rotifer reproduction within three days, without affecting *Spirulina biomass* or phycocyanin levels. Zhang also found that the same combination at a 19 ratio could eliminate *Brachionusplicatilis*, thereby restoring the photosynthetic efficiency of *nannochloropsis cells* damaged by rotifers. Thus, factory-derived fungicides show great potential and practicality for managing natural impurities in large-scale microalgal and cyanobacterial cultures used for biofuel production.

- *Physical Control*

On the one hand, physical filtration and UV sterilisation have been regarded as popular and successful techniques for eliminating biological pollutants, but only prior to the start of the culture. However, the effectiveness of filtration depends on the size of the cells, which also restricts its use in the treatment of biological pollutants like copepod and rotifer eggs. The impact of ultrasound treatment on the survival of phytoplankton, zooplankton, and bacteria has also been studied. Once more, the pollutants' cell size determines the effective dosage. Because it may selectively affect the rotifer but not the microalgae in cell concentration, the new use of pulsed electric fields to control contaminating rotifer in microalgae production is highly suited for implementation on an industrial scale.Additionally, neither a chemical agent nor a major alteration to the current culture facilities are required.

- *Environmental Control*

Microalgae and cyanobacteria are some of the earliest living organisms on Earth, and they have the ability to adapt to almost any of the most extreme environments on the planet. Therefore, many strains of microalgae and cyanobacteria are tolerant to harsh environmental conditions such as extreme pH levels, temperature variations, and intense light exposure. Adjusting these environmental factors to a specific stress level that allows microalgal or cyanobacterial cells to survive, while making it difficult for natural pollutants to thrive, could be an effective and environmentally friendly method for managing impurities. A notable example of successful algal cultivation is *Spirulina*, which thrives in highly alkaline conditions, and *Dunaliella*, which is tolerant to very high salinity. Research by Touloupakis demonstrated that the cyanobacterial strain *Synechocystis* is resistant to alkaline stress, whereas the golden alga *Poterioochromonas* is sensitive to high pH levels, such as pH 11. Based on this, a high pH culture strategy was developed and implemented to effectively suppress or eliminate the golden alga. In our process of scaling up the production of ethanol through photosynthesis using a modified *Synechocystis* strain, we observed that an ethanol-consuming contaminant gradually stopped infecting the culture and began depleting ethanol accumulations. We determined that maintaining a high pH environment, specifically between pH 10 and 11, could successfully prevent impurity growth and help restore ethanol production. Factors such as light shocks (unexpected increases in light intensity to 30,000 Lux), salt shocks (exceeding 15% NaCl), and temperature shocks (which can account for 90% of the variation in copepod growth rates) can also affect the grazing interactions between microalgae or cyanobacteria and protozoa. Biological contaminants can occur at any stage of the mass production process for biofuel-derived photosynthetic products, either as a constant or sudden presence. Four key approaches for managing impurities are outlined in the table and play a crucial role in controlling contamination. Effective impurity control, reducing substrate consumption or product loss, and minimizing the impact of human intervention should be important goals for any culture system used in producing biofuel from microalgae and cyanobacteria. [18].

Table 2 Four categories of solutions to control the biological contaminations.

Solution Type	**Controlling Treatment**
Chemical Control	Copper Salts Surfactant Triton-N Trichlorphon
Biological Control	Specific pathogen
	Celangulin/toosendanin(1:9)
Physical Control	Filtration Pulsed Electric Fields Sonication

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Environmental Control	High pH High salinity Light shock High temperature

V. RECENT TECHNOLOGICAL ADVANCEMENTS IN PHOTOBIOREACTORS

➢ *Smart Materials and Light Distribution Systems*

Currently, microalgae grown in traditional plants show low photosynthetic efficiency even when optimal conditions are met. In fact, studies show that photosynthetic efficiency in outdoor photobioreactors is often below 1%, which is a major obstacle to the industrial use of microalgae. Moreover, the design of photobioreactors (PBRs) has a direct effect on the productivity of the process, and scaling up is usually done by maintaining geometric similarity with lab-scale PBRs, keeping the surface to volume ratio consistent.

At the moment, artificial lighting is mainly used for producing high-value compounds because the current electricity costs make it economically unfeasible for low-value products.

If the best efficiency of white LED lights is about 65%, monochromatic LEDs can reach up to 80% efficiency, and red LEDs, in particular, have a high photoconversion efficiency, which reduces energy loss. Because of this, many internally illuminated photobioreactors have been developed in recent years, driven by growing interest in high-value compounds and improvements in LED technology.

The light spectrum was adjusted for the cultivation of **Acutodesmus obliquus**, as red-blue LEDs in continuous photobioreactors were found to be energy-efficient. These LEDs achieved a photoconversion efficiency above 80%, and photosynthetic efficiency exceeded 15.9% when the light spectrum was limited to the minimal band-gap needed by photosystem II. Initially, the system was tested for mass transfer and reactor mixing to determine if it was suitable for growing microalgae in suspension. [19].

➢ *Automation and Sensors (IoT, Based Control)*

Although research has been done to successfully establish remote environmental monitoring or, in certain situations, remote environmental control, a combination of these systems that provide live stream photos or video has not yet been developed. Therefore, the goal of this research was to design and develop an Internet of Things (IoT)-based environmental control and monitoring system for mushroom cultivation. This system would use a mobile and web application to remotely monitor and control the mushrooms' growth conditions, including temperature, humidity, light intensity, and soil moisture level. Through video and photos on the Internet, users would be able to see the mushroom's growth from a distance. Based on data from the sensors, the control algorithm autonomously adjusts the cultivational chamber's equipment to maintain the ideal conditions for mushroom cultivation. To verify the accuracy of the sensors, they were tested and compared to manual readings. [20]

➢ *3D Printing and Modular Designs*

Recently, the development of 3D-printing technology has sparked more interest in research regarding its use in biotechnology. The latest uses have even expanded to include 3D-printed food items and artificial organs for clinical testing. However, there are not many studies that focus on 3D-printed bioreactors for growing bacteria. Most of these studies either concentrate on microbioreactors or use standard glass containers combined with 3D-printed parts, which restricts the ability to design freely.The main flow of liquid through the system is created by two syringe pumps (CetonineMESYS 290N, Cetoni GmbH, Corbussen, Germany) with 10 mL disposable syringes (Omnifix 10 mL with Luer Lock, B.Braun AG, Melsungen, Germany). A 1-to-10 valve module (CetoniQmix V Ex, Cetoni GmbH, Corbussen, Germany) is used to switch between different feeding or sterilizing solutions (Figure 7A). In front of the main entrance to the bioreactor, a pressure sensor and a 3-2-way valve are placed to monitor the system pressure, followed by the main bioreactor module (Figure 7B), which includes ports for various sensors, a sampling port, and a cell retention membrane, as described in detail in Section 2.1.1. This membrane allows the permeate to exit the bioreactor and be collected in a bottle.

Stirring is used to mix the contents of the reactor (Figure 7C). In addition to the main flow, a six-channel peristaltic pump (Peristaltic Pump peRISYS-S, Cetoni GmbH, Corbussen, Germany) along with two 2-stopper flexible tubes (2.7 mm inner diameter) is used to create a circulation flow. This circulation flow provides oxygen through a membrane diffusion module (Figure 7D) and helps regulate temperature using a heat exchanger module (Figure 7E). Most of the system's modules are connected using PTFE tubing with an inner diameter of 1.6 mm and an outer diameter of 3.3 mm, along with matching ¼″−28 flat bottom fittings and ferrules. To connect the PTFE tubing to the flexible tubing, female Luer to ¼″−28 male adapters are used. All pumps, valves, and pressure sensors are controlled and monitored using the Qmix elements software (Cetoni GmbH, Korbussen, Germany). The related 3D models are included in the supplementary information as .stl files. A flow diagram and images showing the individual modules are displayed in Figure 9.

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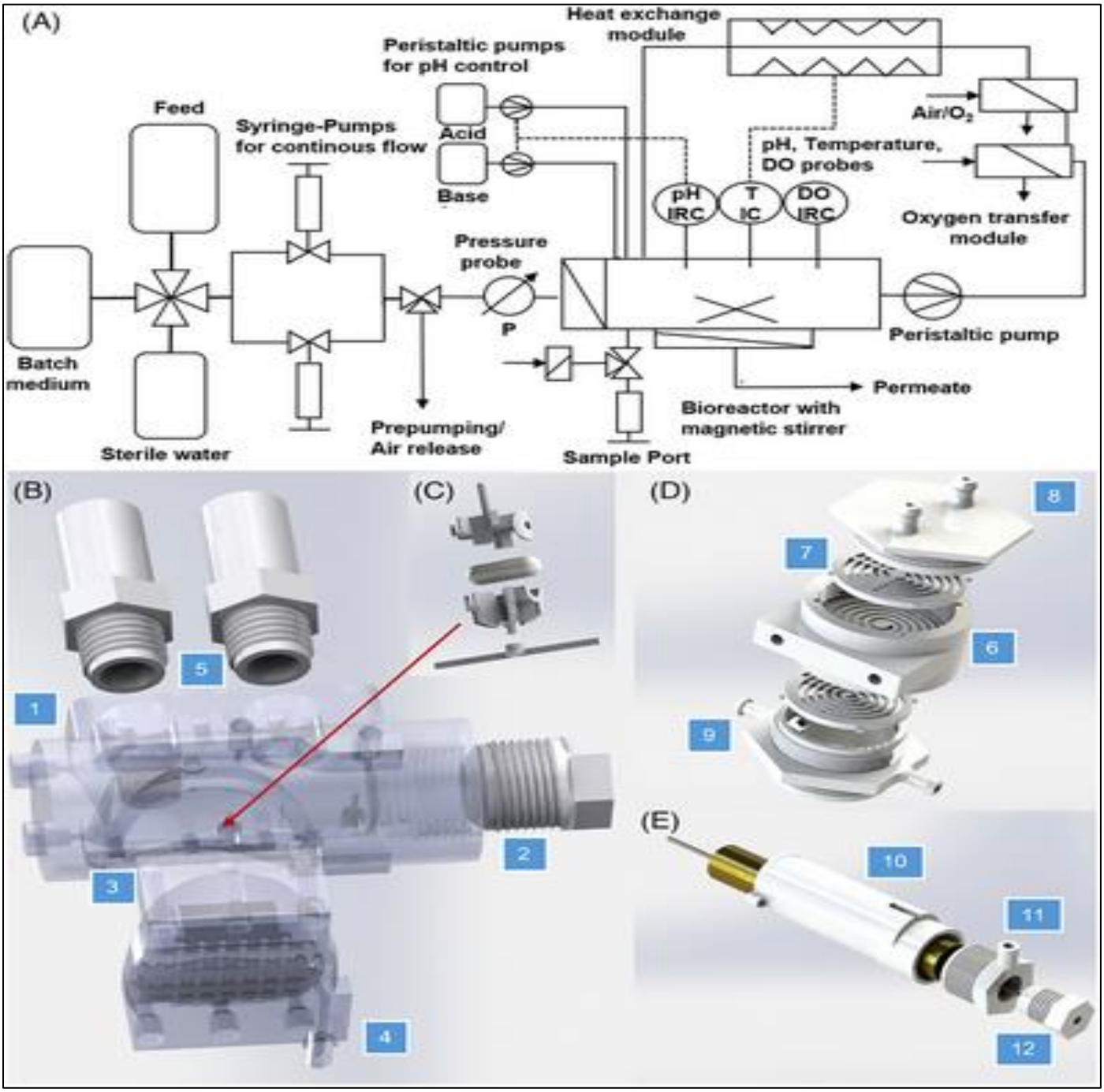

Fig 7 The Perfusion Bioreactor System's Layout and Rendering.

(A) Flow chart of the bioreactor system. (B) Rendered image of the bioreactor main body (1), the cap (2), cell retention membrane support (3 and 4), and probe connectors (5). (C) Rendered image of the 3D-printed stirrer frame. (D) Rendered image of half of the oxygen transfer module, which includes connectors for gas tubing (8), a stabilizer (7), the liquid compartment with spiral flow channels on both sides that are covered by circular membranes (6), and a middle compartment with connectors for gas tubing (9). (E) Rendered image of half of the heat exchange module, which consists of an encasing (10), a fitting with connections to fill the outer tube (11), and a cap for connecting to the flow system of the culture broth (12). The brass tubing and the thin capillary in the middle are not 3D-printed. [21]

➢ *Biofilm and Immobilized System*

Nannochloropsis sp., an oleaginous microalga, was immobilised in alginate gel beads and grown under ideal circumstances so that its growth and lipid synthesis were similar to those of free cells. The immobilised cells were readily collected using a straightforward sifting technique after being utilised in the phytoremediation of secondary wastewater from a palm oil mill. More than 90% of nitrogen and phosphorus were removed, and more than 99% of CO2 was mitigated thanks to the immobilised cells. Additionally, they reported lipid production of 0.356±0.097g/L and biomass of 1.300±0.050g/L.The biomass and lipid production increased by 2.66 and 1.41 times, respectively, as a result of the repeated-batch cultivation. The maximal

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biomass of 3.280±0.049g/L and lipid production of 0.362±0.010g/L were obtained by scaling up in a 3L fluidised bed photobioreactor. [22].

➢ *Integration with Industrial Processes (Flue Gas, Wastewater)*

We are at a critical stage in the history of climate change, which is a major issue caused by an increase in greenhouse gases in the atmosphere. Microalgae have the potential to both purify wastewater and generate renewable energy. For algae to grow, they require nutrients such as carbon, phosphorus, nitrogen, and sunlight. Suitable wastewater can provide the necessary nutrients for algal growth, while industrial exhaust gases can serve as a source of carbon. In laboratory experiments, significant biomass was produced using industrial effluent as the growth medium for algae. This chapter thoroughly examines topics such as membrane synthesis, the development of membrane photobioreactors, future possibilities, and challenges faced. Wastewater from various industrial sectors contains a range of pollutants, including micropollutants, nutrients like nitrogen, sulfur, copper, and phosphorus, carbon-based contaminants such as antibiotics, aromatic hydrocarbons, biocides, phenolic compounds, and surfactants, as well as heavy metals like cadmium, chromium, copper, mercury, nickel, lead, and zinc.[23]

VI. APPLICATIONS OF ALGAE PHOTOBIOREACTORS

➢ *Bio-Fuels Production*

Algae-derived bio-fuels are progressed sustainable fuels obtained from algal feedstock utilizing different conversion systems. This is because of the oil-rich arrangement of this feedstock that can be related to its capacity to plentifully photosynthesize. Lipids, polysaccharides, unsaturated fats, pigmentary compounds, cancer prevention agents, and minerals are among the naturally dynamic mixtures found in algal concentrates (Fig. 10). For the manufacture of bio-fuels, it is essential to produce lipids at high growth rates since high biomass productivity increases yield per harvest volume and high lipid content lowers the cost of extraction per unit product. Therefore, metabolic engineering of microalgae is required to enable the constitutive production of large amounts of lipids without compromising growth. Moreover, lipids encompass the fatty acids which are essential for certain bio-fuels production. Table 1 represents the lipid content of different algae species not withstanding bio-fuels, algae have been viewed as expected makers of synthetics that protect against viral, bacterial, and fungal infections and are also used for the production of antioxidants. In a few viewpoints, microalgae feedstock is desirable to produce biofuels as microalgae does not need cultivable land and new water for development, they are not eatable hence no impact on food chain, can be developed to a few overlays regardless of occasional circumstances, alleviation of barometrical CO_2 and waste water treatment.

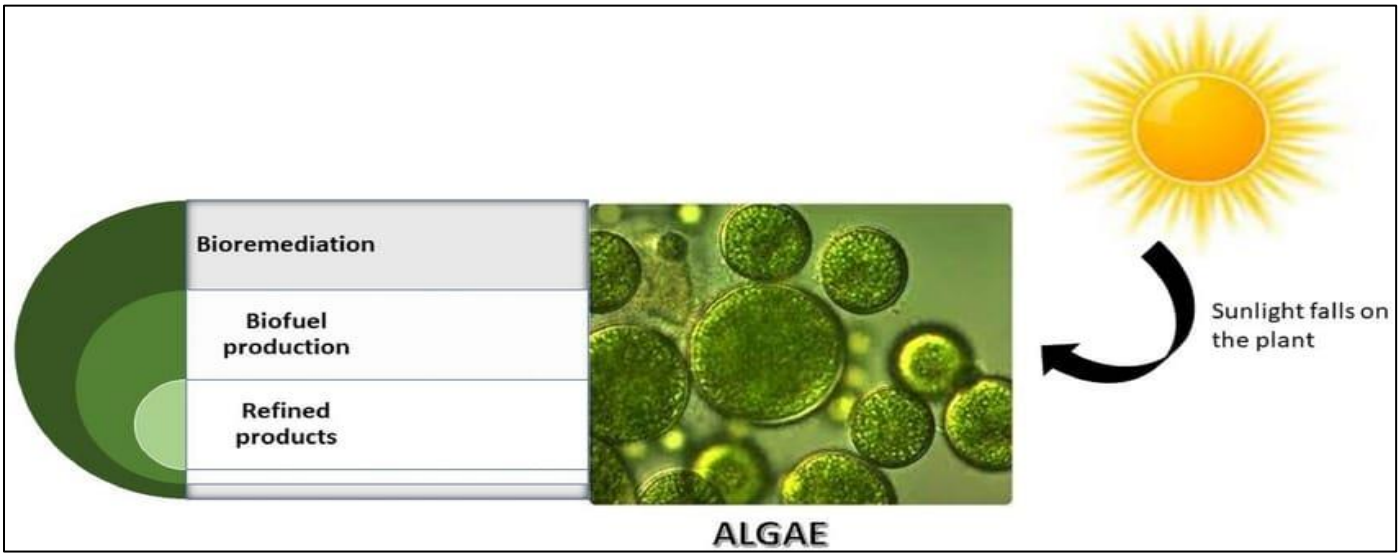

Fig 8 Algae Cultivation for the Production of Biofuel

- *Biobutanol*

Biologically produced butanol is referred to as bio-butanol, which is similar to gasoline and has several beneficial uses. The most effective method previously used for making bio-butanol is called acetone–butanol ethanol (ABE) fermentation. Due to its effectiveness and advantages, this sustainable biofuel can be used together with the fuels currently in use. Microalgae are considered the most promising source for biofuel production because of their high productivity and the presence of carbohydrates. A large amount of algal carbohydrates can be broken down into simpler substances called monosaccharides, which are then used in the fuel production process. Today, biobutanol is produced by several well-known companies such as Gevo, Butamax, Green Biologics, and US Technology Corporation. The production of butanol through biological methods takes place in an anaerobic environment and is part of the ABE fermentation process. In 1862, Louis Pasteur was the first scientist to report the microbial production of biobutanol. Acetone–butanol–ethanol fermentation is a two-phase

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process. During the acidogenesis phase, butyric acid and acetic acid are formed. After these acids are produced, they are re-assimilated to create solvents like ethanol, butanol, and acetone. However, this process also produces other solvents at the same time, which lowers the selectivity of the desired product. It has been noted that the use of enzymes such as cellulases and xylanases allows scientists to use algal biomass obtained from wastewater for biobutanol production. Green seaweed has also been used in biobutanol production with strains of *C. acetobutylicum* and *C. beijerinckii*, along with the metabolism of xylose and glucose. Macroalgae from a marine environment have also been found to be a good candidate for butanol production, with examples such as Ceylon moss, a marine macroalgae feedstock, which was used with Clostridial strains to extract biobutanol.

- *Biodiesel*

Biodiesel is a type of biofuel made from mono-alkyl esters. These esters are created by processing organic oils, such as those from algae, plants, or animals, through a chemical process called transesterification. This process is a kind of chemical reaction that uses a catalyst, typically an alkali like potassium hydroxide, to convert algae oil into biodiesel. To create biodiesel from algae, a large quantity of algal biomass is needed. Algae commonly used for biodiesel production are single-celled organisms that live in water. These algae are usually eukaryotic, meaning they have a nucleus, and they have a strong ability to perform photosynthesis. They also grow quickly and can reach high population densities. Under ideal conditions, some green algae can double their biomass in less than a day. The main methods used to collect microalgae include sedimentation, flocculation, filtration, electrophoresis, and centrifugation. After collection, the biomass is often dried, but if the goal is to produce biodiesel or biogas, this drying step can be skipped because these fuels can handle a high level of moisture, allowing the process to continue directly after extracting the lipids from wet algae. The US Department of Energy's Aquatic Species Program focused on making biodiesel from microalgae and concluded in its final report that biodiesel could be the most viable option to replace the current global use of diesel fuel. It was estimated that if algae-based biodiesel replaced 1.1 billion tons of conventional diesel used annually worldwide, it would only require about 57.3 million hectares of land, which is much more efficient compared to other biofuels. However, despite its potential, biodiesel still faces challenges in competing with traditional petroleum fuels. High production costs and the need for large amounts of organic oils are major obstacles. It is expected that as petroleum fuel prices rise and supplies decrease, alternative biofuels like biodiesel will become more attractive to investors and consumers.

- *Biohydrogen*

Biohydrogen has a consistent but short lifespan. It is produced through two methods: thermochemical processes or biological approaches. Macroalgae is the most important source of biomass used in the production of biohydrogen. Indirect photolysis is a two-step process. In the first stage, highly photosynthetic biomass is created, and in the second stage, anaerobic dark fermentation is used to generate hydrogen. Several models have been developed to implement the indirect photolysis process. Most of these systems use algae, as they can produce a large amount of biomass over a given surface area. Since monomers are widely used in biohydrogen production, converting polymeric carbohydrates into monomers is a key challenge in the production process. To improve hydrogen production from algae, various pretreatment methods are used to break down polymeric sugars into simpler forms. The future role of biohydrogen as a clean energy source for fuel cell production, which emits almost no pollutants, and as a transitional energy carrier for storing and transporting sustainable energy, is becoming increasingly recognized worldwide.

- *Bioethanol*

In today's world, there is significant focus on bioethanol because of its environmental benefits. Bioethanol can be produced from three types of feedstocks: plants, lignocellulosic materials, and algae. When using algae as a feedstock, the cultivated algae are first collected and then dried to remove about 50% of the moisture, resulting in a solid material that is easier to handle. To achieve this, the harvested algae biomass goes through a proper dehydration process to reduce the water content before oil extraction. The removal of moisture is typically done using an effective drying method. Algal biomass can be dried through various methods such as freeze drying, sun drying, or spring drying. The standard method for producing bioethanol from algal biomass is fermentation. This process converts the starch, sugars, or cellulose present in the algal biomass into bioethanol. The process begins with crushing the biomass and then converting the starch into sugars. Water and yeast are then added to this mixture in specialized tanks known as fermenters. Yeast is used because it helps break down the sugar and convert it into bioethanol. After fermentation, distillation is used as a purification step to remove water and other impurities from the diluted alcohol, resulting in concentrated ethanol. The concentrated bioethanol is then separated and transformed into liquid form. This bioethanol can be used as a supplement or replacement for fuel in vehicles. [24].

➢ *Agricultural Applications*

- *Bio-Fertilizers and Soil Conditioners*

Microalgae bio-fertilizers and bio-stimulants are presently proposed as a sustainable strategy for ultramodern husbandry, which seeks to increase the productivity of crops and reduce the environmental impact due to the excess of nutrients in the soil as a result of the magpie operation of synthetic diseases. The development of these bio-products enables the effective and innovative use of natural coffers from a indirect frugality approach, thus allowing us to address the growing extremity regarding energy, water, and food consumption. Accordingly, it was material to dissect the technological trends related to the development of bio-fertilizers and bio-stimulants from microalgae. For this reason, a methodical hunt was carried out in the Scopus database under the hunt criteria established by the coming query string TITLE- ABS- KEY (“bio-fertilizer” OR “bio-stimulant” AND “micro-algae”)AND(LIMIT-TO(

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DOCTYPE, "ar") OR LIMIT- TO (DOCTYPE, "re")). It should be noted that papers published up to 2023 were considered. The information collected was purified to avoid the reiteration of terms with bowdlerizations and hyphens. The VOSviewer interpretation 1.6 software was used alongside CorTextManager to develop the co-occurrence network, Sankey illustration, and literal chart.

The co-occurrence chart allowed us to determine the keywords most constantly cited in scientific publications on bio-fertilizers and bio-stimulants grounded on microalgae. The chart also showed terms related to bioactive composites that are of interest to promote agrarian productivity similar as phytohormones, protein hydrolysates, and phycocyanin (unheroic, blue, and orange bumps). On the other hand, keywords linked to the indirect frugality were linked similar as biorefinery, sustainability, resource recovery, life cycle analysis, and nutrient recovery (unheroic and green bumps). The terms abiotic stress, factory growth, nitrogen, humic substances, nutrients, and *Solanum lycopersicum* were related to agrarian crops (red, blue, and light-blue bumps).

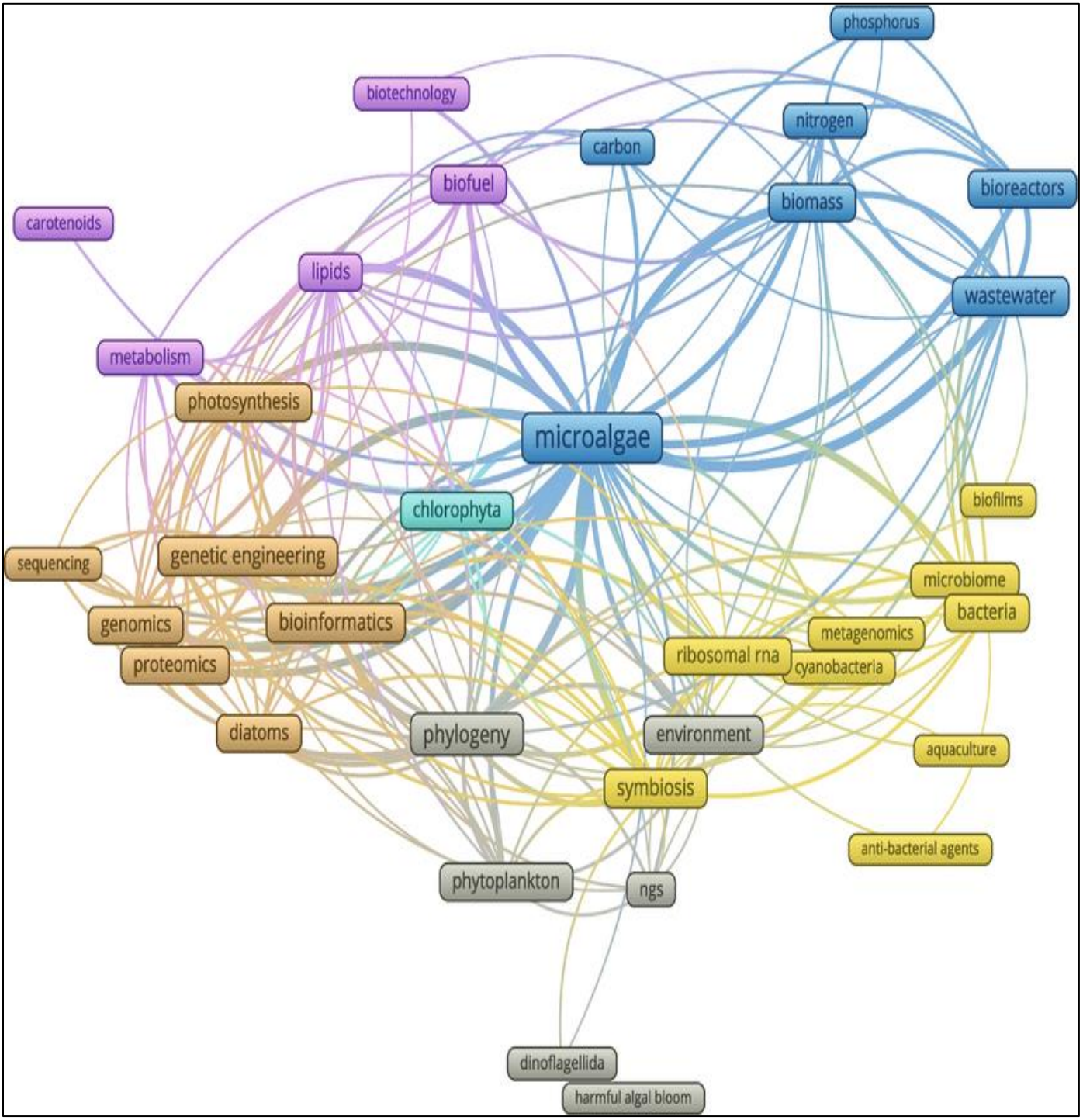

Fig 9 Co-Occurrence Network of Keywords in Publications on Bio-Fertilizers and Bio-Stimulants from Microalgae. Eight Theme Groups: Yellow, Blue, Green, Purple, Light Purple, Red, Dark Red, Orange, and Sky Blue.

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Figure 10. shows the interconnections between the different attributes of the exploration database. This illustration allows us to efficiently represent the elaboration and connection of different motifs over a time scale. Accordingly, metamorphoses in keyword combinations over time were linked and interrelated using argentine overflows. Between 2006 and 2020, the combination of keywords "*bio-stimulant & Solanum lycopersicum*" was linked, which was divided into "*bio-stimulant & Chlorella* " and " protein hydrolysates & abiotic stresses ". latterly, in the period 2020 – 2022, a coincident inflow constituting the combinations "*bio-stimulant & Chlorella*", "*bio-stimulant & bioactive composites*", and "*sustainability & Chlorella*" was set up. This indicates that, in recent times, the *Chlorella rubric* has been distributed as seductive microalgal raw material for the development of sustainablebio-stimulants. It's important to punctuate that the bio-stimulant exertion of microalgae and microalgae excerpts is substantially due to their primary metabolites similar as lipids; proteins and carbohydrates; amino acids similar as arginine, tryptophan, and proline; and vitamins and polysaccharides (β- glucans). Also, small proportions of colorful hormones similar as cytokinins, gibberellins, and auxins were set up that induce agronomic benefits. Another convergent inflow determined in the period 2020 – 2022 showed from the combinations "biodiesel & nutrients junking", "CO_2 prisoner &bio-fuels product", and "bio-products & agrarian development" that, presently, microalgae are n't only delved for operations in the energy sector, but they've gained strength in the agrarian sector due to the benefits they've for crops.

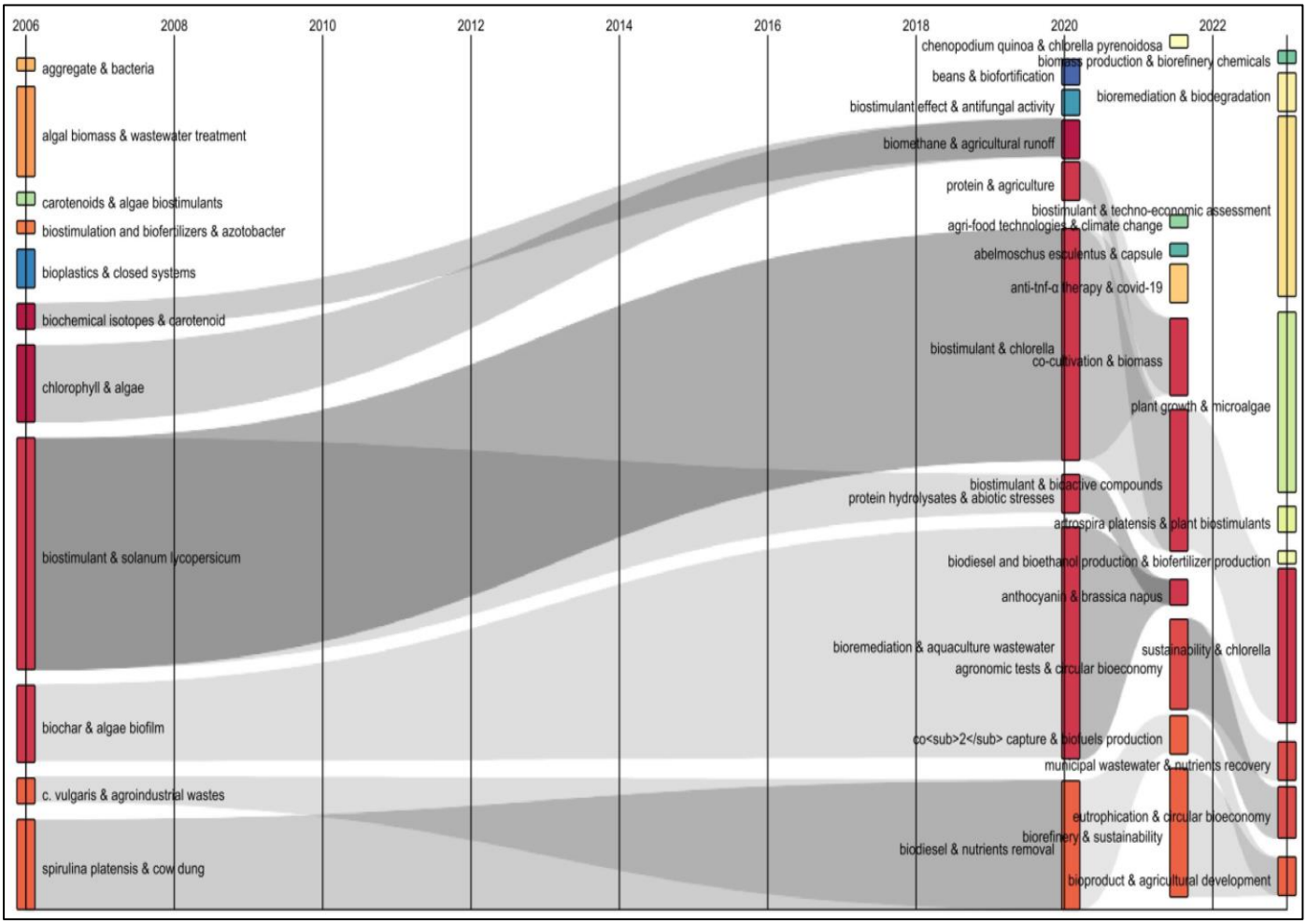

Fig 10 Sankey Diagram of Author Keywords in Publications on Bio-Fertilizers and Bio-Stimulants from Microalgae.

Also, the literal chart was created between the years 2020 and 2023, showing the relationships among the most significant keywords based on the co-occurrence analysis of scientific publications on bio-fertilizers and bio-stimulants that use microalgae (Figure 11). This analysis confirmed the trends seen in the co-occurrence chart and the Sankey diagram. For example, in 2021, keywords such as sustainable agriculture, bio-fertilizer, cyanobacteria, and indirect frugality, among others, were interconnected. In 2022 and 2023, the keywords included algae bio-stimulants, sustainability, Spirulina, Chlorella, bio-refinery, wastewater, and microalgae biomass, among others. From the trends in the keywords, it was possible to see that within the context of indirect frugality, products derived from microalgae can contribute in various ways, such as being used as bio-fertilizers or bio-stimulants, and helping recover nutrients through more cost-effective and sustainable methods like wastewater or chemical waste treatment. Therefore, using sustainable nutrient sources in agriculture, such as microalgae biomass, enhances sustainability and supports the concept of indirect frugality.

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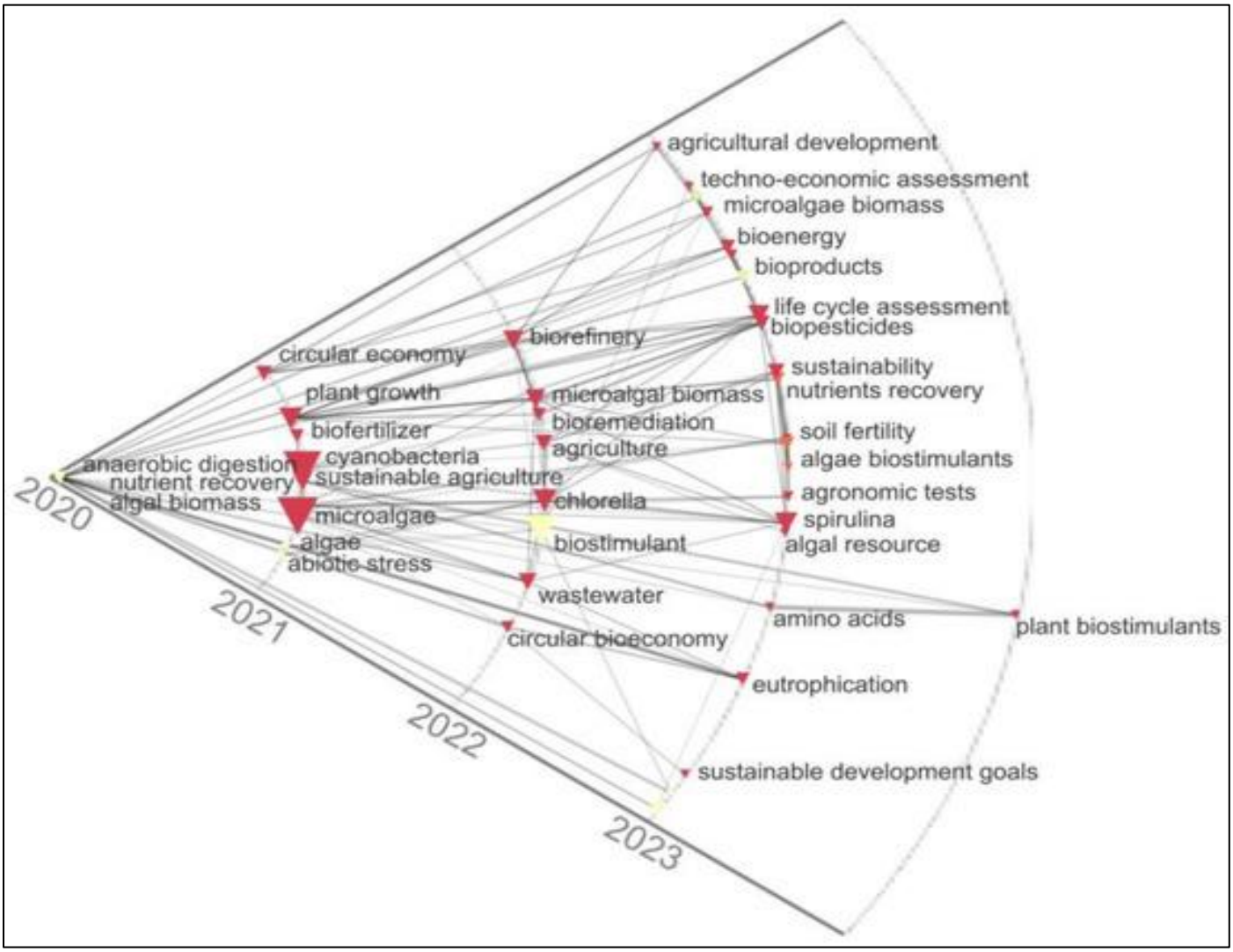

Fig 11 A Historical Keyword Map of Publications About Microalgae-Based Bio-Fertilizers and Bio-Stimulants [25].

VII. ENVIRONMENTAL BENEFITS

➢ *Reduced Greenhouse Gas Emissions*

Industrial flue gas bio-fixation, which uses microalgae, has gained significant attention as a clean alternative for reducing greenhouse gas emissions. Within a circular economy, microalgae can be utilized to create valuable products while capturing carbon dioxide (CO_2) and other gases through photosynthesis. The rate at which microalgae fix these gases from flue gases ranges from 72 mg L^{-1} d^{-1} to more than 435 mg L^{-1} d^{-1}. These rates are mainly influenced by factors such as the type of microalgae and the design of the photobioreactor. [26].

Photobioreactors, closed systems designed to cultivate microalgae, offer a compelling path toward mitigating greenhouse gas emissions. These systems channel carbon dioxide—whether sourced from the atmosphere, industrial flue gases, or concentrated CO_2 streams—into the growth of fast-proliferating microalgae. The result is both immediate carbon removal and the potential for long-term sequestration, as harvested biomass becomes raw material for biofuels, fertilizers, animal feed, bio-plastics, or soil conditioners—products whose lifecycle can lock in or displace carbon-intensive alternatives.In industrial settings, integration of photobioreactors with CO_2-emitting facilities such as power plants or factories shows substantial promise. For instance, pilot systems using flue gas with 3–5 % CO_2 have demonstrated net greenhouse gas emissions as low as –4 g CO_2e per MJ when using biogenic CO_2 sources, underscoring the potential for truly carbon-negative operation. In addition, one demonstration pilot using flue gas-fed photobioreactors reported capturing approximately 2 234 kg of CO_2 per year on just 100 m^3 land area—equating to a large-scale sequester rate of around 74 t/ha annually. Photobioreactors also diverge from conventional cultivation in their relatively minimal land and water footprints[27].

➢ *Low Land and Water Requirements*

By using less water and area than open-pond systems or conventional agriculture, photobioreactors provide a revolutionary method of sustainable algae farming. By repurposing marginal spaces for productive biomass growth, these closed systems can be erected on non-arable land, such as industrial zones, roofs, or wastelands, reducing competition with food crops and biodiversity hotspots. PBRs use vertical or tubular structures that enable microalgae to flourish in stacked or compressed configurations, in contrast

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to conventional agriculture, which requires rich soil and large acreage. The biomass production per unit area is significantly increased by this compact shape, potentially yielding up to 300 times more oil than crops like cotton and 10 to 20 times more productivity than terrestrial plants. Using vertical surfaces instead of horizontal fields, flat-panel or tubular reactors can be incorporated into industrial walls, greenhouses, or façades. Algae may use the nutrients they retain to make fertilisers or bio-fuels, and they can also discharge or reuse clean water, which lessens the demand on freshwater sources and treatment facilities. Hybrid tubular systems can treat runoff on-site in agricultural areas, lowering the amount of land required for traditional treatment lagoons while also growing algae on a little footprint.Life cycle assessments that contrast PBRs with conventional open-pond systems may provide the strongest proof of decreased land use. [28].

➢ *Potential for Bioremediation*

One of the most compelling benefits of PBR-based bioremediation is their remarkable efficiency in removing heavy metals. Microalgae and cyanobacteria possess a porous cell wall and abundant binding sites, enabling biosorption of toxic metals like cadmium, lead, mercury, arsenic, chromium, and zinc even at low concentrations. In both living and dead biomass forms, these organisms actively bind metals, with living cells also capable of bioaccumulation through metabolism. In one study, microalgae grown with coal power plant flue gas effectively sequestered aluminium, manganese, and zinc internally, with uptake rates reaching nearly half a gram per liter of biomass, illustrating PBRs' dual role in mitigating both carbon and metal emissions. Semi-closed tubular PBRs have successfully removed nitrogen and phosphorus from municipal and agricultural wastewater, achieving over 90% removal of phosphorus and 55–65% nitrogen under real-world conditions. In one demonstration treating irrigation water, algal PBRs achieved 60–100% reductions in most pharmaceuticals and variable but meaningful pesticide removals (up to 88%). A pilot study filtering tannery wastewater with Chlorella sp. achieved 90% heavy-metal removal alongside CO_2 sequestration.Mechanistically, bioremediation in PBRs involves several synergistic processes. Biosorption relies on cell wall functional groups that trap metal ions through ion exchange, chelation, adsorption, and diffusion. Living algal cells also metabolize or transform organic pollutants, breaking down pesticides or pharmaceuticals via enzymatic pathways[29].

➢ *Algae as Sustainable Feedstock*

Algae cultivated in photobioreactors represent a remarkably sustainable feedstock option, offering multiple environmental advantages that support circular economies and decouple biomass production from food systems. Firstly, microalgae grow incredibly fast and can accumulate very high lipid and protein content, making them an exceptional raw material for biofuels, animal feed, nutraceuticals, and bioplastics. Species like *Chlorella*, *Botryococcusbraunii*, and *Nannochloropsis* can produce lipids constituting 50–70% of their dry mass, with some even reaching 80% under optimal conditions—yielding far more oil per hectare than oilseed crops. This efficiency translates to dramatically reduced land use and diminished pressure on agricultural resources.Beyond lipids, microalgal biomass is rich in proteins, polysaccharides, antioxidants, vitamins and pigments—compounds with nutritional and industrial value. High-value omega-3 fatty acids like DHA and EPA can be generated through cultivation in wastewater-fed PBRs, providing an eco-friendly alternative to fish oil and supporting aquaculture and health industries. Proteins and other bioactive compounds further enhance the utility of algae as feedstock for animal feed, human supplements, or functional food ingredients.A critical benefit is that PBR-grown algae don't compete with food crops for arable land, avoiding the food-versus-fuel dilemma that plagues first- and second-generation biofuels. This flexibility helps conserve valuable agricultural land and freshwater, and aligns with sustainable resource use goals.Closed photobioreactors also enable precise environmental control: light, temperature, nutrients, and CO_2 are optimized to maximize biomass productivity year-round. Photosynthetic efficiency of microalgae can be 10–50 times greater than that of terrestrial plants, and growth rates can be 20–30 times faster—allowing multiple biomass harvests and consistent output in compact systems[30].

VIII. ECONOMIC ANALYSIS AND FEASIBILITY

➢ *Cost of Construction and Operation*

The cost analysis of a real facility used to produce high-value microalgae biomass is presented. The facility consists of ten 3 m^3 tubular photobioreactors operated continuously for two years, and data on *Scenedesmus almeriensis* productivity, along with nutrient and power consumption data from this facility, are used. The facility's yield was nearly at the maximum expected for the location of Almería, with an annual production capacity of 3.8 tonnes per year (90 tonnes per hectare per year) and a photosynthetic efficiency of 3.6%. The production cost was 69 euros per kilogram. The economic analysis shows that labor and depreciation are the main factors contributing to this cost. Simplifying the technology and scaling up production to a capacity of 200 tonnes per year can reduce the production cost to 12.6 euros per kilogram. Furthermore, to bring the microalgae production cost closer to that of energy or commodity markets, it is necessary to lower the photobioreactor cost by simplifying the design or using less expensive materials, utilize wastewater and flue gases, and reduce power consumption and labor required for the production process. It can be concluded that although it has been reported that producing biofuels from microalgae is relatively close to being economically feasible, the data presented here show that achieving this with current production technologies requires significantly lowering their costs and operating them near their optimal levels. [31].

Based on estimates of material and manufacturing labor costs, the capital cost for a wall photobioreactor (PBR) at full production is approximately $25,000 per hectare. Open ponds, on the other hand, have a cost range of about $10,000 to nearly $79,000 per hectare, which includes the cost of the

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liner and the paddlewheel. Raceway-type open ponds are commonly used in countries such as Israel, the United States of America, China, and others. These systems are reported to maintain a cellular concentration of 0.5 grams per liter and a productivity of 25 grams per square meter per day. Although they have low construction and operational costs, the average cost of producing dry biomass using these systems is between $8 and $15 per kilogram. In large-scale facilities, near 1000 liters, the most commonly used systems are sterile plastic bags with a diameter of about 0.5 meters, equipped with an aeration system. These systems require a significant amount of labor and generally have poor mixing performance, making the production of microalgae biomass quite expensive. The cost of producing microalgae biomass can be nearly $50 per kilogram, and for smaller cultures, the costs can increase to as high as $300 or even $600 per kilogram. These costs are significantly higher compared to the production of *Chlorella, Spirulina,* and *Dunaliella,* which range between $9 and $25 per kilogram. [32].

➢ *Life –Cycle Assessment (LCA)*

The ability of microalgae biomass to be used for various products and environmental cleanup purposes is motivating. The life cycle assessment (LCA) was conducted following the main principles of ISO 14040:2006 and ISO 14044:2006. All process parameters were selected to enable a comparison of the different technological setups of microalgae systems. The scope of the LCA study was limited to the functional phase of the evaluated microalgae systems. It did not include resource inputs, construction activities, or the structure of the product units, as well as their disposal and transportation to the product location. On the other hand, processes related to supplying raw materials such as water, chemicals like nutrients, and energy such as electricity and heat, as well as processes related to managing waste such as wastewater and waste biomass, were included in this study. Since all evaluated systems are located in the Czech Republic and all additional materials come from the same country, the geographical scope of the study was limited to the Czech Republic. The environmental scope of this study is defined by emissions from the functional phase into soil, water, and air. The material use of the assessed systems was considered by including all raw material flows involved in producing the necessary operating substances and energy. Cut-off criteria were not applied in this study. [33].

The distribution of processes was purely physical; whether they were profitable or unproductive was not considered. As part of this life cycle assessment study, it was necessary to apply the following assumptions and simplifications.

The algae biomass was treated as a uniform material throughout the study.

- The presence of active substances in the algal biomass and the specific type of microalgae used were not considered.
- The sources of nutrients for algae cultivation were represented by their main factors—two factors for the phototrophic cascade and the heterotrophic fermenter, and three factors for the flat panel photobioreactor.
- The wastewater generated was considered waste, and no treatment or use of this wastewater was assumed.
- The waste sludge from the algae product was treated as waste, with no further recovery or processing considered. [34].

➢ *Functional Unit and Performance Parameters*

A functional unit (FU) is a quantitative description of the system being studied. It plays an important role in life cycle assessment (LCA) and can influence how different systems are compared, as the FU serves as a common basis for evaluating various technologies or system configurations. Therefore, the functional parameters of the three assessed technological setups for microalgae cultivation were adjusted to the defined FU, allowing for a direct comparison between them. The final product considered in this LCA was process-dried biomass, with one functional unit set as 1 kg of dried biomass. Based on the study, the operational processes of the different microalgae cultivation systems were recalculated to this standard FU, which is 1 kg of dry algae biomass. There is growing interest in the design and development of new microalgae bioreactors. Traditional open reactors depend heavily on sunlight and require significant space, and their productivity is often limited by outdoor environmental conditions. [35].

➢ *Scale-Up Potential and Commercial Viability*

Numerous highly valuable products, such as astaxanthin, polyunsaturated fatty acids, and bioactive compounds, are present in microalgae. However, the challenges in achieving high cell densities and productivity in traditional photoautotrophic systems have limited the large-scale production of these compounds. An alternative approach for producing high-value algal products on a large scale could involve high cell density processes suitable for heterotrophic microalgae cultures. This study aimed to evaluate the three most commonly used scaling parameters for growing *Haematococcus pluvialis* from small growth bottles to 2 and 10 litre stirred tank photobioreactors. The most effective criterion for producing *H. pluvialis* was found to be maintaining a constant volumetric power input (P/V). In the 2 litre and 10 litre stirred tank photobioreactors, the total carotenoid content per unit biomass concentration was measured at 4.57 mg/g and 4.77 mg/g respectively. The antioxidant activity of the total carotenoids extracted from *H. pluvialis* was also found to be higher under the constant P/V condition, with a total phenolic content of 11.76 mg gallic acid per litre and an inhibition rate of 46.91%. These findings could help improve the commercial production of *H. pluvialis* and its extracts. [36].

➢ *Comparison with Traditional Cultivation System*

Microalgae are highly valued for their rich content of protein, lipids, carbohydrates, phycocyanin, and carotenoids, making them a focus of industrial interest in third-generation (3G) biorefineries. These biorefineries aim to replace non-renewable resources with sustainable alternatives[37]. Two main methods for cultivating microalgae are open ponds and closed photobioreactors. The study was conducted using a 5-litre aerated bottle with a tubular shape and a fabricated vessel with an oval shape, both filled with MLA medium, which is

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a modified algae growth medium. The initial seed culture was 10% (v/v) with an optical density (OD) at 680 nm of 1.00. The total volume used was 0.4 litres of microalgae and 3.6 litres of growth medium, while other conditions were kept constant at a temperature of 25 ± 3 °C and a pH of 10.5 unless otherwise stated. The cultivation period was set to 12 days, with a light-dark cycle of 12:12 hours. A comparison of the pros and cons of open versus closed systems is presented in Table 3.

Table 3 Advantages and Challenges of Microalgae Cultivation Systems: Open vs. Closed.

Cultivation Systems	Advantages	Challenges
Open Systems	Lower capital costs Simplicity in design, operation and maintenance	Susceptible to contamination Limited control over environmental factors Seasonal variations in productivity
Closed PBRs	Precise control of conditions Protection against contamination High productivity potential	Higher capital and operational costs Energy requirements for artificial lighting when operating indoors

The growing attention towards photobioreactors (PBRs) in microalgae cultivation, particularly at the pilot and large-scale levels, is reflected in the increasing number of related publications in recent years. As shown in Figure 12a, there is a clear trend of designing, developing, applying, enhancing, and optimizing various PBR setups for different purposes. In the past four to five years, starting from 2020, most research studies have concentrated on tubular, flat-panel, bubble-column, and membrane PBRs, as illustrated in Figure 12b.

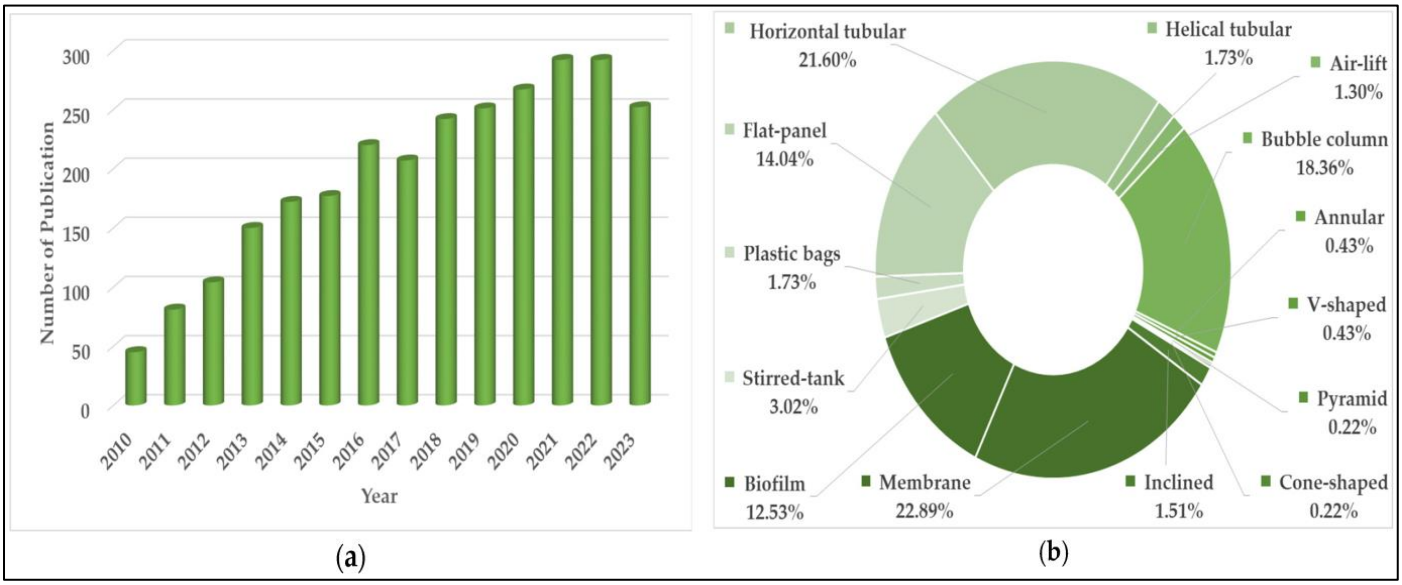

Fig 12(a) The total number of yearly publications focused on the growth of microalgae in photo-bioreactors (PBRs); and the spread of published articles based on the type and setup of PBRs used. (Data retrieved from Scopus, accessed on 5th May 2024. For the first part, the search was conducted across 'Article title, Abstract, Keywords' using the terms: microalgae AND photobioreactors OR photo-bioreactors; covering the period from 2010 to 2023. For the second part, the search was also done across 'Article title, Abstract, Keywords' using the terms: microalgae AND photobioreactors OR photo-bioreactors AND each specific PBR type; covering the period from 2020 to 2023.)

- *Stirred-Tank PBRs*

Chlorella sorokiniana was cultivated in a 2.4-liter standard stirred-tank photobioreactor (PBR), and the results for biomass production were compared with those obtained from other systems, such as air-lift and bubble column PBRs. Due to the relatively low volumetric mass transfer under the selected conditions, the growth rate of microalgae in the stirred-tank PBR was limited to 0.064 grams per liter per day. Similarly, a special strain named *Coelastrella terrestris* was developed using a similar 2-liter stirred-tank PBR, with the aim of producing high amounts of unsaturated fatty acids (85% by weight) and the rare keto-carotenoid adonixanthin (0.13 milligrams per liter per day). In addition to phototrophic cultivation, stirred-tank PBRs can also be used for mixotrophic and heterotrophic modes.They also incorporate sparging system to effectively deliver CO_2, which is essential for enhancing photosynthetic activity.

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- *Tubular PBRs*

One of the most popular configurations, a 119 L horizontal tube PBR, was created and tested while submerged in open seas to efficiently regulate the temperature during outside operation. The authors determined a sufficient yield of CO2 to microalgal biomass bioconversion on a mass basis (13.5%) by tracking multiple consecutive batch trials over a total of two years of cultivation. This resulted in biomass productivity equal to 0.2 g•L−1•day−1. The dried biomass's protein content—specifically, its total essential amino acid content—was increased to 52.4% w/w. Produced β-carotene using Dunaliella salina in a 20-liter indoor helical tubular PBR.in an other application. installed a cutting-edge 145 L helical tubular PBR in animal housing to treat exhaust gases, such as CO2 and NH3, on-site.

- *Air-Driven PBRs*

Estimated the product and composition of biomass from *Chlorella minutissima* in asemi-continuous 3.8 L air- lift PBR. They employed a statistical Design of trials (DoE) approach to optimize the functional profile during civilization in a tip leachate. Under these conditions, the named microalgal species produced high situations of protein (69.6% w/ w). Using a analogous PBR configuration, equipped with an external sparger, Azhand et al. delved the effect of the input gas haste on Chlorella vulgaris growth and CO_2 obsession. The authors reported acceptable growth and CO_2 junking (94% effectiveness), attributed to the optimized conditions for gas transfer within the 20 L PBR.In another study, applied physically dissembled out-of-door conditions during the civilization of *Dunaliella salina* in a 1.8 L air- lift PBR. Their ideal to efficiently produce β- carotene was fulfilled under batch conditions.

- *Simple PBR Configurations*

In a straightforward method, plastic bags can be used for low-value outdoor processes such as the treatment of digestate from an anaerobic plant. A cost-effective 35-liter photobioreactor (PBR) was installed at a biogas plant to grow *Scenedesmus dimorphus*, which helps efficiently remove nitrogen and phosphorus from the culture medium. Similarly, bag-type PBRs can also support higher-value applications. For example, *Nannochloropsis oceanica* was grown in a medium based on deep ocean water to produce autotrophic eicosapentaenoic acid. An outdoor simulated trial was conducted to assess the system's feasibility, using a 5-liter volume. The results showed that productivity increased when a semi-batch strategy was applied, yielding a production rate of 9.9 mg per liter per day. Operating the system with a thin layer of culture medium simplifies both nutrient uptake and gas exchange. Carbon dioxide can be supplied through either a continuous flow or washing system, ensuring an adequate carbon supply for microalgae growth.

- *Membrane PBRs*

The study aimed to take advantage of Chlorella vulgaris's ability to efficiently remove nutrients such as nitrogen and phosphorus. This species was grown in a 10-liter electrokinetic-supported membrane photobioreactor (PBR) for treating wastewater. By using a low-voltage direct current, the researchers successfully cleaned common wastewater channels. Another example of using a membrane PBR for wastewater treatment was presented. They found that applying a two-stage cultivation method for Tetradesmus obliquus increased both biomass production, reaching 0.44 grams per liter per day, and lipid content, reaching 0.1 grams per liter. The use of membrane PBRs allowed microalgae to be separated from the growth medium, forming biofilms that made it easier for the algae to absorb nutrients and carry out metabolic processes.

- *Other PBR Designs*

Beyond the most commonly discussed PBR designs mentioned earlier, biofilm PBRs have been widely used to improve light penetration during microalgae cultivation while reducing the land area required for the system. A new light-conducting porous biofilm PBR was developed using 3D printing, based on a frame that supports the microalgal biofilm and also delivers light for growth. By cultivating *Chlorella sorokiniana*, the researchers demonstrated a strategy that increased biomass production by 82% compared to a flat biofilm PBR. The ability of biofilm PBRs to perform bioremediation was also shown. This was achieved by operating a 7 L open continuous-flow biofilm PBR using *Dunaliella salina*. The study aimed to evaluate the long-term performance of the system in terms of removing organic matter, phosphorus, and nitrogen from saline wastewater, thereby validating the technology under real-world conditions. Following similar cultivation principles, a 30 L short light path annular column PBR was used to compare systems at an industrial scale, and this system was suggested as a source of high-quality feed products. Among other microalgal strains, the study identified *Monodopsis sp.* as a promising candidate for producing lipids (up to 31.9% w/w) suitable for monoculture feeding. This type of annular PBR also allows the cultivation of immobilized microalgae. In their study, they simplified the treatment of real food-based artificial wastewaters in an annular PBR by using alginate beads to immobilize a mixed culture of Scenedesmus obliquus, *Chlorella vulgaris*, and *Chlorella sorokiniana*. As a result, microalgae growth was doubled with improved photosynthesis.[38]

➢ *Market Trends and Industry Investment*

Photobioreactors (PBRs) Are Crucial for Cultivating Photosynthetic Organisms, Such As Algae, Cyanobacteria, And Plants, In Controlled Environments. These Systems Harness Light Energy to drive the biologicalprocesses That Produce biofuels, Pharmaceuticals, andvarious Bioproducts. As The demand for sustainable And Efficient Production Methods Grows, The Photobioreactor Market Is Evolving Rapidly. The Integration of PBRs With Renewable Energy Sources Is Gaining Traction as a Way to Enhance Sustainability. By Coupling PBRs With Solar Panels or Wind Turbines, Operators Can Reduce the Carbon Footprint of Their Operations. This Trend Aligns with The Broader Push Towards Green Energy Solutions and Offers a Dual Benefit: Renewable Energy Production and the Cultivation of Biomass That Can Be Converted into Biofuels, Contributing to Circular Economy. Advancements In Monitoring and Control Systems Are Revolutionizing the Operation of PBRs. Modern PBRs Are Equipped with Sensors and Automation

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Technologies That Provide Real-Time Data on Key Parameters Such as Light Intensity, Temperature, PH, And Nutrient Levels. The Use of Artificial Intelligence (AI) And Machine Learning (ML) Algorithms Further Enhances These Capabilities, Allowing for Predictive Adjustments and Improved Efficiency.

PBRs Are Finding New Applications in The Field of Bioremediation, Where They Are Used to Remove Pollutants from Air, Water, And Soil. Photosynthetic Organisms Can Absorb and Break Down Harmful Substances, Offering A Natural and Sustainable Method for Environmental Cleanup. This Adaptability Makes PBRs More Accessible and Practical for a Wide Range of Applications, From Small-Scale Research to Large-Scale Commercial Production. Reducing Costs and Improving Efficiency Are Ongoing Priorities. In the PBR Market. Researchers And Manufacturers Are Exploring Ways to Lower the Capital and Operational Expenses Associated with PBRs. This Includes Developing More Cost-Effective Materials, Enhancing Energy Efficiency, And Streamlining Maintenance Processes. The Trend Towards Integrating PBRs With Existing Industrial Processes, Such As Wastewater Treatment Plants or Carbon Capture Systems, Also Contributes to Cost Savings and Improved Overall Efficiency[39].

Global Photobioreactors (PBRs) Market Insights and Forecasts up to 2033.

- The global market for Photobioreactors (PBRs) was valued at USD 99.8 million in 2023.
- The market is expected to grow at a compound annual growth rate (CAGR) of 25.75% from 2023 to 2033.
- The global market size for Photobioreactors (PBRs) is projected to reach USD 986.9 million by 2033.
- The Asia Pacific region is anticipated to experience the highest growth during the forecast period.

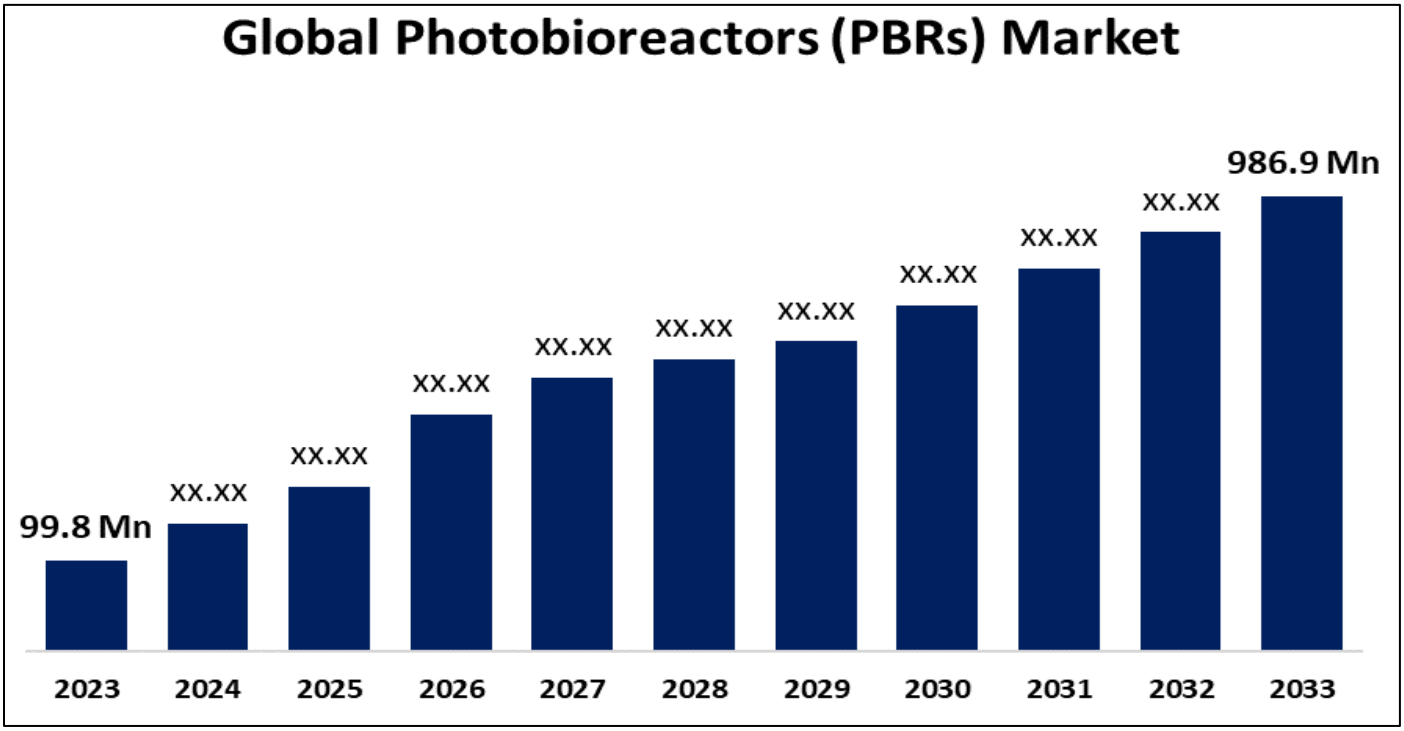

Fig 13 The Global Photobioreactors (PBRs) Market Size is Anticipated to Exceed USD 986.9 Million by 2033, Growing at a CAGR of 25.75% from 2023 to 2033.

There is a growing interest in algae from both the scientific and commercial community due to its ability to create high-value compounds like pigments, medicines, and antioxidants[40].

IX. CHALLENGES AND LIMITATIONS

➢ *High Initial Capital Costs*

The operating cost of the process includes the cost of raw materials (21.8%), labor (0.4%), installation-related costs (20.7%), and service costs (57%), as shown in Figure 14a. The civilization stage accounts for 78% of the total operating costs, and these are distributed as follows: (a) 1.68% is attributed to the consumption of raw materials, with 32.46% of that due to the phosphorus source (K2HPO4 and KH2PO4), 26% to fresh water, 23% to the carbon source (glucose), and 7.8% to the nitrogen source (EDTA), with the remaining nutrients contributing the rest. (b) Labor constitutes 0.23% of the operating cost of the process; for this study, only drivers were considered, with a periodic cost of USD8327. Only drivers were deemed suitable for maintaining the operation of the technologies involved in the process, at a cost of 0.37 USD per hour. (c) The installation-related costs account for 25.14% of the total operating cost, which is calculated by adding the costs of equipment maintenance, depreciation of fixed capital, and other

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expenses such as insurance, property levies, and other similar charges. (d) Finally, 72.94% of the operating cost of the civilization stage is due to the services required for the process, such as standard power and treated water. Closed civilization systems are generally energy-intensive; in this case, the column photobioreactors used in the process design consume 173.21 kWh per kilogram of biomass produced, accounting for 99.95% of the total energy consumption of the process. [41].

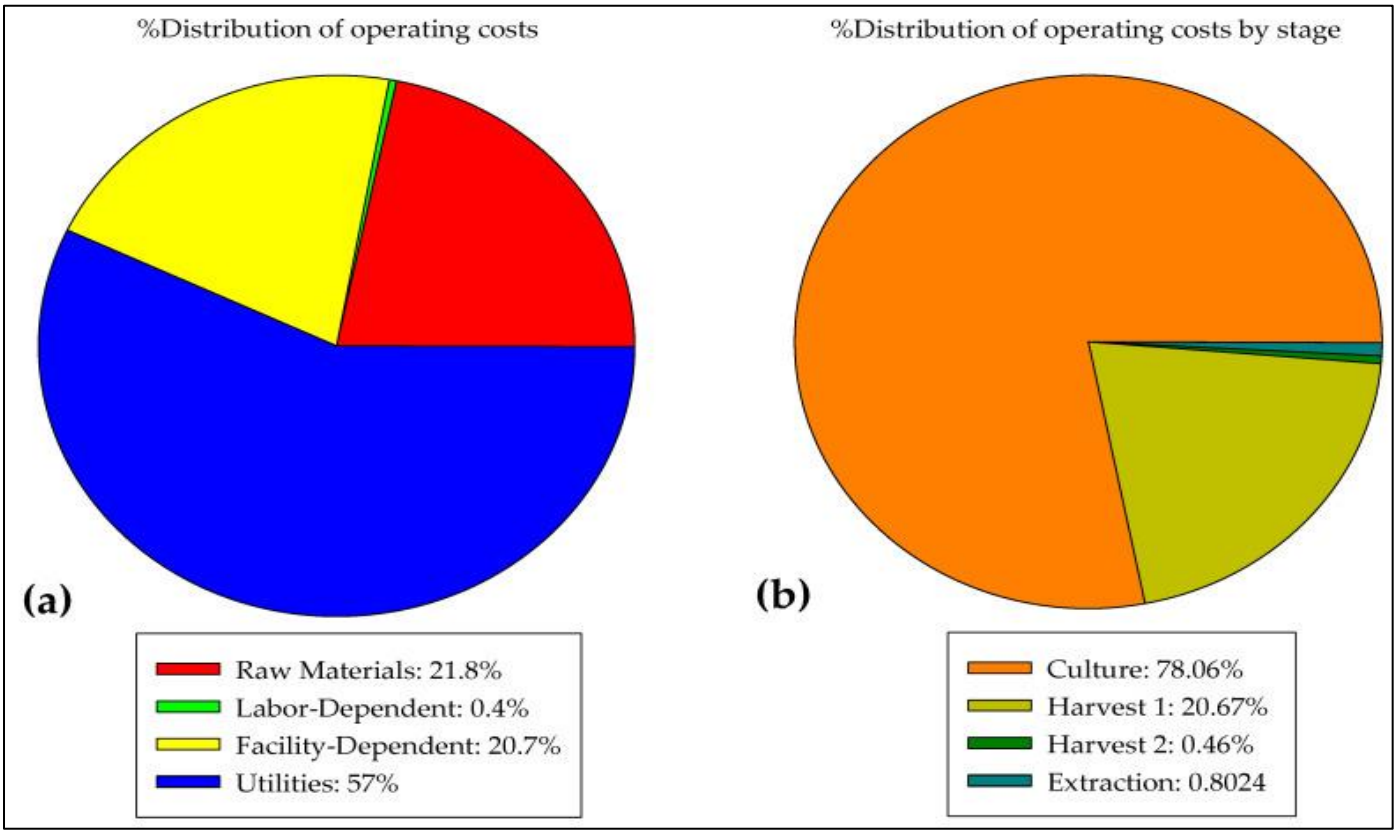

Fig 14 (a) Distribution of Operating Costs of the Chlorophyll Production Process; (b) Distribution of Operating Costs by Stage of the Process.

➢ *Scalability Issues*

It is difficult to evaluate the different parameters that affect the scale-up process during cultivation, which makes scaling up from a laboratory size to a commercial unit problematic. The yield from most large-scale phototrophic cultivations is lower than what is predicted in the lab. Light, inorganic carbon dioxide, water, and inorganic nutrients are essential for the growth of phototrophic microorganisms under ideal pH and temperature conditions. Because of their intimate relationships, the design of a photobioreactor is more difficult. Light intensity, light–dark frequencies, light distribution, hydrodynamics, and environment (nutrients, pH, and temperature) must all be properly balanced for photobioreactors to be scalable. The most crucial element for scaling up in photobioreactors may sometimes be the availability of light for each cell.[42]

Table 4 Challenges During a Scale-up of Photobioreactors

General scale-up problems	Specific microalgae-related challenges
Change in local reaction conditions	Homogeneous light availability
Shear stress vs. mass transfer	Dynamics (light, temperature)
Contamination	Light intensity (photoinhibition/-limitation)
Biofilm formation	Temperature (min./max. extrema)

➢ *Scalability Issues*

As a sustainable way to grow microalgae for a variety of uses, including biofuels, bioplastics, animal feed, and pharmaceuticals, photobioreactors (PBRs) have drawn a lot of interest. Nevertheless, despite their potential, PBRs encounter significant scaling issues that prevent their commercial implementation. Maintaining consistent light dispersion throughout the reactor as its size grows is one of the most important challenges. Microalgae depend on photosynthesis, and light frequently becomes a limiting element in large-scale systems. Light penetration decreases as the reactor's diameter or depth increases, resulting in uneven growth as light and dark zones appear. Gas delivery sparging methods frequently lead to energy-intensive mixing, particularly when system size grows. Furthermore, in industrial-scale systems, it becomes more difficult to maintain the precise balance required to achieve adequate mixing without generating cell shear damage or excessive

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energy consumption. At scale, temperature control also gets more complicated.

Despite ongoing research and pilot projects, scalability remains one of the key bottlenecks in realizing the full potential of photobioreactor systems[43].

➢ *Contamination and Maintenance*

A photobioreactor's productivity, efficiency, and sustainability are all directly impacted by contamination and maintenance. Unwanted microorganisms including bacteria, fungus, protozoa, or other algal species that might outcompete or damage the intended microalgae culture are usually the cause of contamination in photobioreactors. Water sources, air exchange ports, equipment surfaces, and manual handling are some of the ways that these pollutants might get into the system. To prevent biofilm formation and microbial accumulation, photobioreactor components such pipes, valves, filters, and culture vessels must be cleaned and sterilised on a regular basis. In certain systems, steam sterilisation is utilised in addition to chemical disinfectants such hydrogen peroxide or sodium hypochlorite. Since unexpected changes frequently point to microbial involvement, monitoring pH, temperature, and nutrient levels also aids in the early detection of contamination. The risk can be further reduced by putting proper laboratory and operational procedures into place, such as using sterile growing material and a filtered air supply.For photobioreactors to continue operating, mechanical maintenance is just as important as cleaning. Regular wear and functioning checks are necessary for pumps, mixers, and light systems. [44].

X. ENGINEERED AND NATURALLY OPTIMIZED ALGAL STRAINS

Selective breeding, chemical or physical mutagenesis, and adaptable laboratory evolution (ALE) are methods used to create naturally optimised algae strains. ALE was used to produce Chlorella sp. AE10 and AE20 at increased CO2 concentrations of 10% and 20%, respectively. The AE10 strain grew quickly in 30% CO2 after 31 cycles, attaining a biomass content of 3.68 ± 0.08 g/L—nearly three times that of the original strain—showing a markedly improved capability for carbon fixation.Through EMS mutagenesis, a pale-green mutant of *Nannochloropsisgaditana* known as e8 was produced and chosen for its lower chlorophyll concentration.Under nitrogen-replete circumstances, this mutant exhibits a 30% decrease in chlorophyll and an approximate 80% rise in lipid output; important gene changes in DGDG synthases were found.To produce reduced-chlorophyll variations with increased biomass production in photobioreactors, many mutant *Nannochloropsis gaditana* strains were produced using random EMS mutagenesis. Several candidates with reduced pigment content and improved photosynthetic efficiency were identified during screening.Atmospheric and Room Temperature Plasma (ARTP) mutagenesis was used to improve the freshwater alga Ulothrix. The resulting strains, designated A20 and A23, showed remarkable increases in lipid content under high CO2 settings, ranging from 139% to 668%, highlighting the effectiveness of non-GMO methods.Variants with increased biomass and lipid yields were produced by EMS (chemical) mutagenesis of Chlorella pyrenoidosa strains.Selected mutants outperformed wild-type in both productivity and oil content, illustrating successful strain optimization.The heat-tolerant Chlorella sp. GD M4 strain was developed through chemical mutagenesis (e.g., N-methyl-N′-nitro-N-nitrosoguanidine, MNNG) and screening under elevated temperature. M4 achieved 8.22 g/L biomass in hot outdoor photobioreactor conditions and displayed superior photosynthetic CO_2 fixation—even under temperatures exceeding 40 °CAdditional ALE-derived strains include phenol-tolerant Chlorella sp. (31-cycle ALE)**,** which removed 500 mg/L phenol from wastewater within seven days and nearly doubled biomass yield. Flue-gas adapted Chlorella (46-cycle ALE) grew in media containing 10% CO_2, 200ppm NO_x, and 100ppm SO_x.*Picochlorum sp.* BPE23 underwent ALE for thermal stress, achieving a maximal growth temperature of 44.6 °C (compared to 42 °C in wild type), a 70.5% higher growth rate at optimal 38 °C, and a 22.3% greater biomass yield per light compared to the wild strain.Finally, an improved *Chlamydomonas reinhardtii* strain featuring shorter light-harvesting antenna (via mutagenesis) performed better at high cell densities—showing increased productivity and better light distribution[45].

These examples collectively demonstrate the breadth of naturally optimized strains developed through non-GMO methods:

- Chlorella sp. AE10 & AE20 – ALE under CO_2 stress
- N. gaditana e8 – EMS mutant with 80% more lipids
- Multiple N. gaditana mutants – EMS variant selection
- Ulothrix A20/A23 – ARTP mutagenesis with high CO_2 lipid gains
- Chlorella pyrenoidosa EMS mutants – enhanced biomass and lipids
- Chlorella GD M4 – heat-tolerant, high-CO_2 fixation
- Additional ALE strains: phenol- and flue-gas adapted Chlorella, temperature-evolved Picochlorum
- Nannochloropsisgaditana (ExxonMobil/Synthetic Genomics strain) was engineered using CRISPR-Cas9 to knock out a regulatory gene responsible for lipid synthesis suppression under nitrogen deprivation. This modification resulted in a strain with approximately 40% lipid content-double what is seen in the wild-type—while retaining normal growth rates.
- Nannochloropsisoceanica "bkt" strain was developed by integrating a β-carotene ketolase gene from *Chlamydomonas reinhardtii* into the N.oceanica genome via homologous recombination. The engineered strain produced ketocarotenoids such as canthaxanthin and astaxanthin, which comprised about 50% of total carotenoids, significantly improving pigment yield.
- A CRISPR/Cas9-engineered Nannochloropsisoceanica nitrate reductase (NR) knockout was created to serve as a chassis strain, demonstrating precise editing and opening the door for subsequent metabolic engineering, with normal growth on ammonia but not nitrate.

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- CRISPR-based transcription regulator knockdown in N. gaditana (ZnCys regulator) produced mutants that doubled lipid productivity under semi-continuous dense culture conditions while maintaining robust CO_2 fixation and growth characteristics.
- A DNA-free CRISPR-Cas9 RNP approach in *Tetraselmis sp.* targeting AGP (ADP-glucose pyrophosphorylase) resulted in strains that accumulated 2.7–3.1 times more triacylglycerol than wild-type algae under nitrogen starvation.
- Overexpression of key lipid biosynthesis genes in Phaeodactylumtricornutum, such as GPAT and DGAT2, via genetic transformation, led to a 2.6-fold increase in total lipid content, reaching 57.5% of dry cell weight.
- In *Schizochytrium sp.*, overexpression of the enzyme MCAT enhanced total lipid levels and polyunsaturated fatty acid production, contributing to yields over 40% of dry biomass in fed-batch cultures.
- *Synechocystis sp.* PCC 6803 was engineered—for example, through overexpression of acyl-ACP synthetase (aas)—to boost lipid content by approximately 5.4%.
- In Chlamydomonas reinhardtii, TALEN or CRISPR-Cas9 knockouts of lipid-degrading enzymes such as phospholipase A2 (PLA2), malic enzyme isoform ME2, PEPC1, and ZEP/AGP have yielded 23–81% increases in lipid productivity.
- In both nitrogen-rich and nitrogen-depleted environments, strains of Nannochloropsissalina that were modified to overexpress a bHLH transcription factor (NsbHLH2) showed enhanced growth and lipid synthesis.
- These modified strains demonstrate the ability to improve lipid or pigment content, biofuel potential, and photosynthetic performance through **metabolic and genetic engineering,** including gene knockouts, transcription factor manipulation, and heterologous enzyme expression. Increasing fatty acid synthesis, decreasing carbon flux to competing pathways, improving CO2 fixation, and boosting pigment biosynthesis for high-value outputs are important changes. When taken as a whole, these initiatives demonstrate the technical viability and increasing sophistication of strain engineering in microalgae biotechnology[46].

XI. FUTURE PROSPECTS AND RESEARCH DIRECTIONS

➢ *Genetic Engineering of Algae for Enhanced Productivity*

These days, advances in genetic engineering allow scientists to create special algal strains that boost the production of valuable products from microalgae as well as improve biomass output. In microalgae cells, the production of proteins, lipids, carbohydrates, and pigments is controlled by certain limiting steps and is closely connected through the metabolic network. Genetic engineering can be used to modify growing conditions so that the flow of metabolic processes is directed towards specific substances. The main focus is on understanding how microalgae respond metabolically during primary production and developing strains with better photosynthetic efficiency to raise product levels and reduce the cost of producing algal biomass. To enhance the production of byproducts, new gene-editing methods such as RNA interference (RNAi), CRISPR/Cas9, zinc finger nucleases (ZNFs), and transcription activator-like effector nucleases (TALENs) have been applied. However, changing the genome of microalgae is still challenging when compared to simpler organisms like bacteria [47].

- *Chlamydomonas Reinhardtii* as a Long-Standing Model Alga

Since it was first discovered in Amherst, USA, in 1945, *C. reinhardtii* has been the commonly used green alga in laboratory studies and remains the most studied algae species up to now. It can grow using light and carbon dioxide alone, or with light and organic compounds like acetate as a carbon source. Its cells divide every 6 to 8 hours, and it is relatively easy to cultivate in a pure culture. [48].

- *The Non-Nuclear Genomes of* C. Reinhardtii

C. reinhardtii's plastid genome shares evolutionary similarities with those of contemporary plants. The majority of the proteins that operate in plastid compartments are nuclear-encoded, transcribed on cytoplasmic ribosomes, and transported into the organelle. Plastid compartments represent a separate milieu from the cytoplasm. Compared to the mitochondrial genome, the chloroplast is better suited for biotechnological uses like recombinant protein overexpression.After a transformation event, selection pressure is needed to reach homoplasmy, a state in which all genome copies are identical, because the number of copies of the chloroplast genome fluctuates from 40 to 100. [49].

- *Major Milestones in the Development of* C. *Reinhardtii Nuclear Genome Transformation*

One of the first algae to have a high-quality genome sequence made public was *Chlamydomonas.* Research on *C. reinhardtii* first concentrated on forward genetics screening. Cell-wall-deficient strains, starchless mutants, strains used to discover the xanthophyll cycle and its involvement in photoprotection, and mutants involved in lipid biosynthesis were among the many strains produced by early chemical and radiation mutagenesis experiments. The glass-bead-mediated transformation approach, which allowed DNA to be randomly integrated into the nuclear genome of cell-wall-deficient or -removed strains, allowing for some transgenic expression, was a significant advancement in *C. reinhardtii* genetic engineering. Originally, auxotrophs—strains without a native metabolic capacity—were complemented by transformation and insertional mutagenesis utilising endogenous genomic or cDNA sequences. [50]

➢ *Integration with Renewable Energy Systems*

Energy efficiency is a key issue for buildings, and the design of facades greatly influences their appearance. In the past, green facades have mainly used land plants to enhance their visual look. The word "green" is linked to the chlorophyll pigment, which is responsible for the green color in most plants that perform photosynthesis. However, microalgae presents a promising alternative for use in building facades. This approach, which is spread out across different areas, has the potential to make a major positive impact on society. Creating prototype panels to test how well

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they work and function is essential for moving this technology forward. [51].

The integration of photobioreactors (PBRs) with renewable energy systems presents a promising avenue for sustainable bioresource production. Coupling PBRs with solar photovoltaics (PVs) enables dual land use, where light can be shared for both electricity generation and microalgal growth, optimizing energy efficiency and land productivity. Microbial fuel cell–photobioreactor (MFC–PBR) hybrids further extend this synergy by converting organic waste into bioelectricity while utilizing algal biomass for CO_2 capture and oxygenation. Building-integrated photobioreactors (BIPBRs) represent an innovative approach for urban energy systems, where algae panels serve as dynamic facades that produce biomass, reduce heat gain, and support on-site energy generation. These approaches collectively position PBRs as multifunctional components in renewable energy landscapes[52].

- *Development of Cost –Effective Harvesting and Downstream Processing*

The downstream processing of microalgal biomass—especially harvesting and dewatering—represents a significant portion of photobioreactor (PBR) operational costs, often accounting for 20–30% of total costs due to dilute cultures and small cell size. Efficient, cost-effective harvesting strategies are therefore critical to making PBR-based production viable.One of the most widely used approaches is flocculation, which aggregates cells into larger particles, facilitating separation and reducing energy consumption for subsequent steps. Membrane filtration—including microfiltration, ultrafiltration, and vibrating membranes—offers low energy consumption (~0.0044 kWh/m³) and high recovery rates (>97%). Membrane fouling remains a challenge, prompting use of anti-fouling methods such as vibrating panels, hydrophilic coatings, and crossflow operation. Centrifugation provides rapid and high-concentration results (20–30%) but is energy-intensive (0.1–0.7 kWh/kg) and best suited for high-value products.An advanced harvest strategy is the two-stage dewatering process, combining flocculation (bio/flocculation) and low-energy filtration. Sedimentation, optimized with pH adjustment and salinity tweaks, is another low-cost method. A recent study reported an optimized protocol using NaCl and HCl achieved 77–79% cost savings compared to centrifugation ($0.43 vs. ~$1.91 per m³) while maintaining biomass recovery.Cost distribution analyses across PBR-based biomass production show harvesting and drying constitute 10–50% of total costs. Integrating ultrafiltration with spray drying reduced harvesting and drying costs by ~7%. Capital expenditure for PBR structures, drying systems, and construction can contribute 20–30%, 21–24%, and 18–21% respectively—highlighting the importance of streamlining downstream flow[53].

- *Circular Bioeconomy and Biorefinery Approaches*

Certain types of microalgal species can be specifically chosen to efficiently produce specific biofuels because they can generate particular metabolites in higher concentrations. For instance, *Nannochloropsis oceanica* is known for its high lipid productivity, producing 158.76 mg per liter per day. These lipids are mainly neutral in nature, which makes the resulting biodiesel have favorable characteristics. This biodiesel has a high cetane number of 54.61, a low iodine number of 104.85 gI2 per 100 g, and a relatively low cloud point of 3.45 °C. Biodiesel produced from other species like *Chlorella*, *Spirulina*, *Dunaliella*, and *Chlorococcus* also meets the fuel quality standards set by ASTM D6751 and EN 14214. [54].

- *Sequestration of Carbon Dioxide*

With extremely excellent CO_2 collection efficiencies ranging from 40% to 93.7%, microalgae are primarily responsible for global carbon fixation and can tolerate high CO_2 concentrations. Because they can withstand CO_2 concentrations higher than 30% v/v, species including *Chlorella*, *Synechococcus*, *Scenedesmus*, and *Chlorococcum* present a possibility to use industrial gaseous effluents with high CO_2 concentrations (about 6–20% v/v) as a raw material in the culture process. When grown under species-specific pH, illumination, and temperature conditions, microalgae such as *Chlorella*, *Botryococcus*, *Desmodesmus*, and *Spirulina* exhibit significant CO_2 bio-fixation efficiencies. For instance, *Chlorella spp*. grown for 38 days at 30 °C and pH 8 in BG11 medium supplemented with $NaNO_3$ can impact over 85% CO_2 capture efficiency while synthesising 710.6 mg/L, 143.6 mg/L, and 164 mg/L of lipids, polysaccharides, and proteins, respectively. In nitrogen-limited Bold Basal Medium (BBM), *Desmodesmus sp.* produced high cellular levels of lipids (about 41.5%) and carbohydrates (approximately 32.44%) while enacting CO_2 sequestration from undiluted (15% CO_2) simulated cement flue gas. When grown in BBM at room temperature and pH 8.5, *Parachlorella kessleri* produced 44% DW carbohydrates, 17.1% DW lipids, and 20.8% DW proteins while successfully removing 86.4% inorganic carbon. [55].

- *Recovery of Waste Nutrients*

Both solid and liquid waste streams can be used as culture media to enhance the circular bioeconomy approach in microalgal cultivation for biofuel production. Industrial and agricultural activities, including dairy, aquaculture, poultry, tanneries, textiles, pulp and paper, edible oil, tobacco, and livestock maintenance, produce large volumes of waste. Tanneries generate toxic wastewater with high heavy metal content, producing 15–50 tonnes of wastewater and 400–700 kg of solid waste per tonne of leather. Dairy businesses generate 1–3 litres of wastewater for every litre of milk. Animal husbandry alone produces an estimated 3.12 billion tonnes of manure annually, along with other waste streams like wastewater and waste feed.

In this context, many studies have been conducted to explore the potential of different wastewaters for growing a variety of microalgal species. A mixed consortium of microalgae, mainly consisting of *Cyanobacteria, Microcystis aeruginosa*, *Synechocystis sp.*, and *Thermosynechococcus elongatus*, was cultivated in dairy wastewater containing 5.5 mg nitrate/L, 3481 mg COD/L, 9 mg phosphate/L, and 19.6 mg ammonium/L. The cultivation process achieved 100% nitrate, 100% phosphate, approximately 90% ammonium,

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and 93% COD removal within 48 hours. The biomass produced had lipid and carbohydrate contents of 50% and 14% of dry weight, respectively. The relatively high lipid content shows that this mixed consortium of microalgae could be used for biodiesel synthesis. Similarly, biodiesel was produced from *Scenedesmus quadricauda* and *Tetraselmis suecica* grown in dairy wastewater. *S. quadricauda* showed stronger nutrient removal efficiencies, removing 86.21% total nitrogen, 89.83% phosphate, and 64.47% total organic carbon, while *T. suecica* had higher biomass productivity of 0.61 g/L. However, *S. quadricauda* produced more C16 saturated fatty acid, making it more suitable for biodiesel production. *C. vulgaris* grown in wastewater from tilapia culture ponds was fermented by yeast to yield approximately 33 g/L of bioethanol.

Fig 15 A) The nutrient removal efficiencies of microalgae grown in various waste streams, as well as their lipid and carbohydrate compositions, are presented here. Data for the figures are derived from studies on *Nannochloropsis gaditana* cultivated in municipal wastewaters, which produced 93.4 mg/g of bioethanol when fermented with yeast. In another study, Batista et al. (2015) grew **Scenedesmus obliquus**, **Chlorella vulgaris**, and a naturally occurring algal consortium C (comprising **Chlorella**, *Scenedesmus*, *Chaetophora*, and **Navicula**) in urban wastewater. As the nutrients in the culture media were removed due to nutrient recovery, the microalgae were left in the wastewater for an additional two weeks. This allowed them to synthesize high levels of sugars under nutrient-depleted stress conditions. The resulting sugar content was measured as 42%, 21%, and 28% ash-free dry weight for **S. obliquus**, **C. vulgaris**, and *Consortium C*, respectively. When fermented with **Enterobacter aerogenes**, the volumes of biohydrogen produced were 56.8, 40.8, and 46.8 mlbio-H2/g volatile solids for **S. obliquus**, **C. vulgaris**, and *Consortium C*, respectively. **S. obliquus** showed 98% ammonium, 100% phosphate, and 54% COD removal from urban wastewater, while **C. vulgaris** achieved 96% ammonium and 7% phosphate removal but saw an increase in COD by approximately 37%. Consortium C, on the other hand, demonstrated nearly 100% removal of both ammonium and phosphate but did not significantly reduce COD.

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In addition to producing high levels of lipids and carbohydrates suitable for biofuel production, microalgae are highly effective in tolerating and detoxifying heavy metals through biosorption and bioaccumulation.

This capability is very valuable for cost-effective biological treatment of toxic wastewater. Certain microalgal species such as *Chlamydomonas reinhardtii*, *Scenedesmus obliquus*, and *Diogenes palatina* have achieved bioremediation efficiencies of 63.3%, 92.7%, and 87.99%, respectively, against cadmium. Species like *Chlorella sorokiniana* and *Pseudanabaena kessleri* have shown bioremediation efficiencies of 99.67% and 90.54% against chromium. Tannery wastewater, which contains high concentrations of heavy metal pollutants, has been successfully treated using *Chlorella* species. These species achieved removal efficiencies exceeding 90% for all heavy metals present, including chromium, cobalt, nickel, cadmium, lead, zinc, and copper. When cultivated in heavy metal-rich tannery wastewater instead of bold basal media (the control), *Chlorella* species showed a 51% increase in lipid content and a 52% increase in carbohydrate content. [56]

- *Policy Support and Commercialization Strategies*

The advancement of photobioreactor (PBR)-based microalgae systems from experimental stages to industrial deployment is largely dependent on commercialisation strategies and policy assistance. Although microalgae have enormous promise for sustainable biofuels, pharmaceuticals, food, feed, and CO2 reduction, their market acceptance is still restricted because of high operating and capital costs, unpredictable policy environments, and immature supply chains. Despite providing regulated and superior biomass output, photobioreactors demand a large initial investment, especially for materials, automation, and energy inputs. (Processes, MDPI) describes how the majority of algal PBR systems' low Technology Readiness Levels (TRLs) increase investor reluctance and commercial risk. Governments and academic institutions must invest in scaling technology from TRL 3–6 (lab/pilot scale) to TRL 7–9 (pre-commercial/commercial demonstration) in order to address. This include capital equipment subsidies, long-term pilot trial funding, and risk-sharing arrangements like public-private partnerships. Clear commercialisation pathways can also be achieved by harmonising Commercial Readiness Indices (CRIs), which assess elements including market competition, financing readiness, and policy support. Clearer regulatory roadmaps and expedited evaluations should be made possible by governments, particularly for algae grown in controlled PBRs with little contamination risk. The financial and administrative obstacles now impeding industry-wide adoption can be greatly reduced by policy tools including carbon credits, innovation grants, feed-in tariffs for bioenergy, and expedited approval procedures for algae products[57].

XII. CONCLUSION

Algae photobioreactors (PBRs) have emerged as a revolutionary instrument in the quest for sustainable development, with a variety of applications in energy generation, environmental conservation, and the manufacturing of bioproducts. This research has discussed the metabolic potential, biological traits, and essential role of algae in photobioreactor-based growth systems. The separation of PBRs into open, closed, and hybrid systems provides a systematic approach to understanding how various reactor designs satisfy various industrial and environmental requirements. Every system has a unique set of operating advantages and disadvantages, and the purpose of a given application and the availability of resources determine the configuration to be used.Additionally, we have examined the operational and design factors that have a major impact on the productivity and efficiency of algal PBRs. High algal biomass yield requires careful optimization of variables such light intensity and dispersion, CO_2 availability, temperature control, mixing, and nutrition supplementation. Innovations like biofilm reactors, modular designs made with 3D printing, automation through IoT and AI, and smart lighting systems are turning conventional PBR setups into extremely intelligent and efficient systems.The adaptability and ecological significance of algal photobioreactors are highlighted by their wide range of uses, which include the generation of nutraceuticals and biofertilizers, wastewater treatment, carbon capture, and biofuels including biodiesel, bioethanol, and biogas. By trapping CO_2, these systems not only aid in the mitigation of climate change, but they also promote the growth of a circular bioeconomy by turning waste materials into useful goods. Nevertheless, despite all of their advantages, algal PBRs continue to confront significant obstacles to widespread adoption. Obstacles include high initial capital costs, regulatory concerns, scalability issues, pollution dangers, and technological complexity. Strong legislative frameworks that support innovation and commercialization, public-private collaborations, and integrated research activities will be necessary to overcome these constraints.The key to making algal PBRs economically viable in the future lies in developments in algal genetic engineering, affordable harvesting techniques, and integration with renewable energy networks. PBRs can greatly increase their influence when incorporated into models of industrial symbiosis and climate mitigation techniques. Algal photobioreactors ultimately provide a route toward environmentally friendly industrial processes, energy security, and sustainable practices. In order to reach their full potential, multidisciplinary cooperation, sustained investment, and pro-bio-based, greener international policies are required.

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