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Establishment of an effective photobioreactor for growing microalgae: A review

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ABSTRACT

The premise that microalgae could be used to produce landscapes of biofuel, nutrition, and bioremediation is gaining popularity. The four main factors influential to microalgae growth are light, CO_2, nutrients, and process conditions-including temperature and pH. Compared to other open systems such as ponds, control and efficiency in flat plate and tubular type photobioreactors are much higher. A photobioreactor needs to be developed to enhance the mass transport, and light penetration, and to reduce contamination. Every kind of photobioreactor has its advantages and limitations in using the airlift, bubble column, and stirred tank. Thus, the use of hybrid bioreactors makes it possible to eliminate individual limitations. This review discusses and analyzes the features of photobioreactor systems, their drawbacks, and the progress achieved in the field of microalgae production.

Keywords: Biofuels, Open systems, Cultivation systems, Algal biomass production, Bioreactor technology

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Introduction

Microalgae have been regarded as a vital source of biofuels like biodiesel, bioethanol and biohydrogen (Islam and Dixit, 2024; Torres *et al.*, 2023). In addition to energy generation microalgae have many uses as a nutrient source, biofertilizer and a tool to combat environmental pollution (Chowdury *et al.*, 2020). The rapid depletion of fossil fuels, as well as other challenges like as the environmental effects of carbon, has widened the hunt for renewable energy supplies such as microalgae (REDEC, 2020; Egbo *et al.*, 2018). One disadvantage of first-generation biofuels they compete for food resources unlike third-generation biofuels hailing from microalgae, which is regarded as more sustainable and hence more efficient as they use lesser resources and they yield more energy (Abdur Razzak *et al.*, 2024; Abo *et al.*, 2019; Arabian, 2024).

Photobioreactors, or PBRs, have already been established as the best method of microalgal growth in a closed environment for maximum biomass production for purposes of biofuel and other commercial uses (Singh and Sharma, 2012; Santek and Rezic, 2017). This makes PBRs superior to open systems such as ponds because they provide improved control of growth conditions, contamination, as well as productivity (Al-Dailami *et al.*, 2022; Erbland *et al.*, 2020). Nonetheless, different PBR designs which exist as mentioned in this paper are not without shortcomings such as; they are expensive, complicated to maintain and do not always distribute light effectively (Benner *et al.*, 2022). It is for this reason that there is a need to design and construct efficient and economical photobioreactors to support algae production within these constraints (Chanquia *et al.*, 2022a).

Though PBRs are among the best-suited designs for large microalgae production, they are plagued with some technical issues such as light penetration, mixing as well as energy utilization (Al-Dailami *et al.*, 2022). These obstacles can be overcome by properly designing and optimizing the photobioreactor system, making microalgal biomass production for biofuel and other applications more sustainable. Moreover, there is a disagreement on the practical photobioreactor design, which created problems of bio-reactor performance variability across the systems and applications (Khoo *et al.*, 2016).

This paper aims to present the current state of photobioreactor technology, compare the efficiency of the chosen designs for microalgae cultivation and reveal its further development perspectives. The work will review the numerous photobioreactors that are currently in use in terms of relative features as well as their strengths and weaknesses to guide the development of PBR that will boost algal biomass production.

The findings of this research are significant since they respond to the rising interest in using microalgae in the production of efficient green energy. The contribution of this study to enhance the design of photobioreactors leads to efficient biofuel production and minimization of environmental destruction caused by the use of fossil fuels. Furthermore, the discoveries will aid in the creation of novel photobioreactors that will benefit sectors that significantly depend on microalgae for the production of biofuel, food, and waste treatment.

In this research, features of diverse photobioreactor configurations, such as tubular, vertical, airlift, bubble column and hybrid bioreactors, are characterized. It assesses their effectiveness in growing microalgae for biofuel and other related industries' use. The areas of advantages and disadvantages of each design will be analyzed as well as touch on recent technological developments intended to mitigate the current drawbacks of PBR systems.

Integrated photobioreactors that incorporate features of several basic designs (such as tubular and airlift designs) yield greater biomass production than reactors based on a single design. Advanced technologies, for example, nanobubble systems enhancing the delivery of CO_2 with unique bioreactors and light conditions in photobioreactors, have created new photo-bioreactor designs that substantially enhance the effectiveness of photobioreactors (Hossain *et al.*, 2018).

This study shall test these hypotheses through a survey of new developments in PBR technology, and from experiments done on different reactor models.

General characteristics of algae

One of the largest classes of organisms capable of photosynthesis is made up of green microalgae, which were once known as blue-green algae (Abdur Razzak *et al.*, 2024; Abo *et al.*, 2019). As one of the most adaptable groups of organisms on the planet, algae can thrive in a diverse range of environmental settings. Because algae thrive in moist habitats or sources of water, they can be found in various locations, including terrestrial and aqueous. It can be found all over the biosphere and adapted to various environments, including aquatic (freshwater to high salt) and terrestrial settings. Its diversity of growth circumstances is unparalleled. The different features found in terrestrial plants, such as phyllids (stems) and rhizoids in nonvascular plants, as well as the need to leave, branches, or other tissues found in tracheophytes, are absent in algae. Algae are classified as single-celled organisms (vascular plants) (Singh and Sharma, 2012). Because they contain chlorophyll and are capable of photosynthetic activity within a single algal cell, they are distinguished from other types of microorganisms under their uniqueness. This enables simple operations for the production of biomass as well as efficiency caused by genetic research in a significantly more expedient manner than is possible with conventional plants. The major structural elements of green algae include a nucleus that is well defined, a cell wall, chloroplasts that absorb sunlight and other colors, pyrenoids, which are dense regions that contain starch granules on their surfaces, stigmas, and flagella. Cyanobacterial filamentous colonies can develop into various microbes, including microbial cells, akinetes, and heterocysts. Vegetative cells, kinetes, and heterocysts each have a general purpose that includes the potential to execute in entire photosynthetic organisms, endurance to climate, and the capability to process nitrogen.

Algae cultivation methods

Microalgae can indeed be produced in outdoor culture conditions such as ponds and lakes, which is a low-cost and straightforward method (Kumar *et al.*, 2021). In addition, they can be grown in isolated culturing, such as photobioreactors, which allow for a greater yield of biomass and improved control. This scenario has attracted the interest of numerous experts in recent years and may be the best one.

Aquatic algae culture in ponds

Constructing an outdoor pond system is more cost-effective, as it requires no more than a canal or lake at the very least. The production capacity of huge ponds is significantly higher than that of other methods with costs that are equivalent (Assunção and Malcata, 2020; Sutor *et al.*, 2014). Additionally, open pond farming can take advantage of peculiar conditions that only some algae require to thrive. For example, the microorganism *Spirulina* sp. flourishes in water with a large volume of sodium bicarbonate, and *Dunaliella salina* flourishes in water with exceptionally high salt content. Open culture has the potential to be successful as well provided that there must be a method for removing the required algae and inoculating fresh ponds with the adequate beginning quantity of the algae that is intended (White and Ryan, 2015). The open ponds' simplicity results in cheap production rates and reduced operational expenses, which is by far the most significant benefit offered by these facilities (Ugwu *et al.*, 2008). Ponds that are open to the sky can be separated into two categories: instinctual waters (lagoons, ponds, and lakes) and man-made ponds. Commonly referred to as "raceway ponds," these bodies of water are utilized to cultivate algae (Fig. 1).

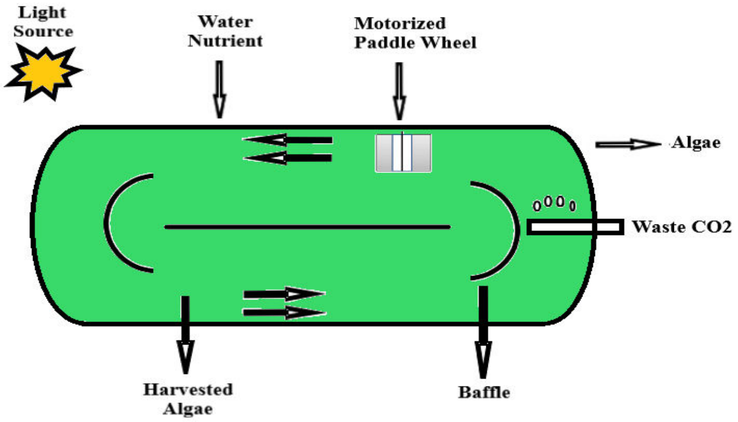

Fig. 1. A schematic diagram of a raceway pond.

In such pools of water, microorganisms, water, as well as essential minerals move underneath a drag strip with the help of paddlewheels. This keeps the algae inside the water and brings them up to the surface daily. Because sunlight can only penetrate to a particular depth into the water of a pond, the vast majority of ponds have been maintained to have a shallow water level. This is because algae require sunshine to survive. In most cases, these raceways are constructed out of cementitious materials or are excavated into the surface and coated with plastics so that the earth does not become saturated with extra water (Legrand *et al.*, 2021). Befuddles inside the stream help water flow around curves so that as little space as possible is used. The process is almost run in a continuous conduction mode, where fresh feed (with nutrients such as nitrogen, phosphorus, and inorganic salts) has been placed next to the hydraulic piston and algal broth is collected beside the hydraulic piston after it has gone around the circle. Different kinds of contaminated water could be used to grow algae depending on what children need to be given each type of algae. Certain varieties of marine algae can be cultivated using saltwater or groundwater with a saline condition (Pires *et al.*, 2017).

Although this is the least complicated of all the methods for cultivating plants, it has a few limitations because conditions within and surrounding a pond may not be completely manageable. Outdoor ponds have a very high risk of being polluted by various types of microorganisms, including different kinds of bacteria and algae (Vijayaram *et al.*, 2024). As a result, farmers almost always select closed systems for monocultures. In addition, open systems do not provide any control over the environment, including the temperature and the illumination (REDEC, 2020). The length of the growing cycle is mostly determined by latitude and, except in tropical regions, is confined to such summer time of the year. The effects of bad weather can frequently inhibit the growth of algae. However, outdoor ponds have several significant drawbacks, the most significant of which are the fluctuating radiant energy, the evaporative losses, the CO_2 penetration into the atmosphere, and the demand for enormous farmland (Hossain *et al.*, 2018).

Furthermore, only those bacteria that could thrive in hard settings were able to produce algae in open systems of cultivation due to pollution from scavengers and other fast-growing heterotrophs. This has led to a restriction on the types of algae that can be used in large-scale production. Additionally, because open culture methods have agitating mechanisms that aren't particularly effective, their mass transfer rates are quite low, and result in a minimal level of biomass production (Egbo *et al.*, 2018). Investigators have looked into the possibility of using closed ponds to circumvent the problems caused by the use of open systems.

Compared to the open ponds, the level of environmental control present here is significantly higher. The cost of operating a closed pond process is significantly below that of a photobioreactor in an area of activity that is comparable to that of an open pond (Chanquia *et al.*, 2022b). The closed pond is a system that is an alteration of an outdoor pond. The difference between the two is that the closed pond is covered with a transparent barrier to visible light, turning this into a greenhouse. Plexiglass is utilized in the construction of these enclosed systems.

In addition, it stretches out the growth cycle, if the ponds are heated, they can generate food throughout the year. It not only makes it possible to cultivate additional species but also allows organisms being farmed to preserve their prevailing status; it permits the species currently being cultivated to remain dominant. It's also very likely to advance the concentration of carbon dioxide in these semi-closed systems and accelerate the rate at which algae reproduce.

Photobioreactor

A photobioreactor is a type of bioreactor lit from within and designed for biomass production in a regulated environment (Ratomski and Hawrot-Paw, 2021). A photobioreactor is any closed system that is sealed off from the surrounding environment and does not have any specific exchange of oxygen, carbon, or contaminants with the surrounding environment (Chanquia *et al.*, 2022b). Even though they are more expensive, photobioreactors have many valuable features over open systems (Gupta *et al.*, 2015). Table 1 highlights the advantages and limitations of various photobioreactors.

Table 1. Advantages and limitations of photobioreactor.

Production system	Advantage	Limitation
Raceway Pond	Quite affordable	Poorly productive biomass
	Easily cleanable	Requires a huge amount of land
	Makes use of non-agricultural land	Restricted to a few types of algae
	Minimal energy required	Inadequate mixing, use of light, and CO_2
	Simple to maintain	Cultures are prone to contamination
Tubular Photobioreactor	Large region of illumination	Wall growth to some extent
	Suitable for tribes that live outside	Fouling
	Quite affordable	Demands a lot of space
	Effectively productive biomass	pH, dissolved oxygen, and CO_2 gradients along the length of the tubes
Airlift photobioreactor	Effective blending and uniformity	Limited oxygen transfer rates
	Easy to scale-up	Foaming issues
	Reduced shear stress	Bubbles forming
	Minimal energy usage	Scale-up challenges
	Ease of operation	Require specific design
Column photobioreactor	Superior mass transfer	
	Minimal energy required	Costly in comparison to open ponds
	Optimal mixing and little shear stress	Sophisticated design
	Simply sterilizable	Small illumination area
	Reduced photoinhibition and photo-oxidation	

Many researchers suggested that when designing the photobioreactor, these things be taken into account:

- The reactor ought to be able to uniformly support the cultivation of a wide variety of algal species.
- The design of the reactor needs to allow for consistent illumination of the culture area as well as a rapid exchange of Carbon dioxide and oxygen in the reactor's interior.
- Because the cells of microalgae are very sticky, fast fouling of the light-transmitting surfaces of reactors can occur when they are exposed to microalgal growth. This results in the reactors having to be shut down frequently to undergo mechanical cleaning and sterilizing. The design of the reactor needs to prevent or reduce the amount of fouling that occurs in the reactor, particularly on the surfaces that allow light through.
- To attain maximum levels of mass transfer, a method must be utilized that does not harm cell cultures nor inhibit the proliferation of the cells.

Vertical tubular photobioreactor

It is constructed from tubing that runs vertically and is composed of a translucent material so light can pass through it (Ramanathan *et al.*, 2011). The gas being sparged is turned into very small bubbles by a sparger connected to the base of the reactor (Hossain *et al.*, 2018). The removal of oxygen from the air by the use of a gas mixture in sparging achieves general mixing, and the mass transfer of carbon dioxide, and also eliminates the oxygen that is created during photosynthesis (Acieh *et al.*, 2001). According to how liquid is moved through the device, upright tube photobioreactors can be categorized as either bubble columns or airlift reactors (Hawrot-Paw and Sąsiadek, 2023).

Bubble column photobioreactor

Reactors in the form of bubble columns are vessels that are cylindrical in shape and have heights that are larger than double the diameters (Fig. 2).

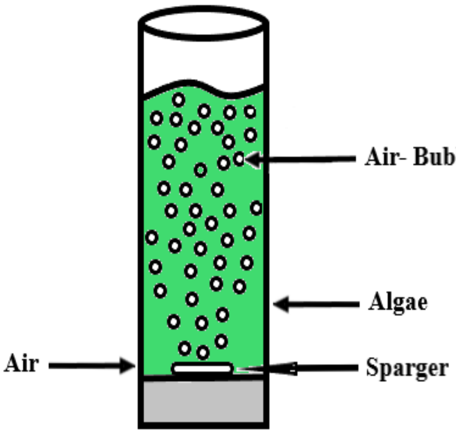

Fig. 2. A schematic diagram of Bubble column photoreactor.

It features a low initial cost, an adequate surface-to-volume ratio, without moving components, acceptable heat and mass transmission, a relatively homogeneous growing environment, and appropriate discharge of oxygen gas and the remaining gas combination (Penloglou *et al.*, 2024). These are its advantages. The bubbling of the gas mixture coming from the sparger accomplishes the mixing and the transfer of the carbon dioxide mass (Hossain *et al.*, 2018). When the process is scaled up, perforation plates are utilized in long bubble columns to break up consolidated bubbles and disperse them (Kubar *et al.*, 2022). The source of the light comes from the outdoors (Mubarak *et al.*, 2023). To a large extent, the efficiency of photosynthesis is determined by the gas flow rate, which in turn is determined by the darkness and light cycle (Hosseini *et al.*, 2016). This is because the liquid is circulated regularly from the internal dark zone to the external photic zone when the gasification rate is higher. Because there is no opportunity for back mixing when the gas flow rate is less than 60.01 ms^{-1}, a dispersion diffusion trend was observed (Uyar *et al.*, 2024). The gas flow rate can be increased, resulting in a shorter period of darkness and light, which will substantially enhance photosynthetic activity (Putra *et al.*, 2021; Sánchez Mirón *et al.*, 2004).

Airlift Photoreactor

Airlift reactors are containers that have two different zones that are connected. One of the tubes is referred to as a riser, which is the location where the gas combination is sparged (Li *et al.*, 2014). The other area, which is referred to as a downcomer, would not collect the gas. In most cases, it may be found in two different forms: an internal loop and an exterior loop (Hincapie and Stuart, 2015). The sections of the inner loop reactor are partitioned using either a split cylinder or a draft tube, depending on the configuration of the reactor (Dunford, 2006). The internal loop reactors are being improved by the development of the inner loop divided airlift reactor and the internal loop circumferential tube reactor (Acieh *et al.*, 2001). The riser and down comer are physically separated from one another in an external loop consisting of two independent tubes (Fig. 3).

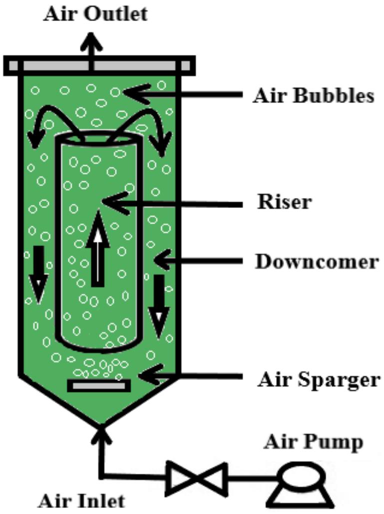

Fig. 3. A schematic diagram of the airlift photoreactor.

The gas is mixed by flowing it via a sparger that is located in the riser tube. There is no other form of physical agitation involved. A riser functions in a manner analogous to that of a bubble column, in which sparged gas flows upward unpredictably and haphazardly. This results in the riser having a lower density, which causes the liquid to travel upward. The gas held up by the riser is assisting this upward movement. In the disengagement zone, the liquid and the gas separate, and the performance of this part is dependent on the design of this section as well as the operating circumstances (Paladino and Neviani, 2021). The quantity of gas that doesn't even disengage in the disengaged zone is the quantity that is engulfed by the liquid that is going downhill in the down comer. The amount of gas that is allowed to accumulate in the down comer has a sizeable impact on the hydrodynamics of the airlift reactor (Degen *et al.*, 2001). The degassed liquid travels in a laminar form downstream in the circumferential region, with a motion that is defined and directed (Huang *et al.*, 2016). When building an airlift reactor, one essential factor to take into consideration is how to maximize the differential in the amount of gas held up by the riser and the down comer. The airlift reactor has the benefit of establishing a circular mixing pattern, in which the liquid culture goes between lighter and darker phases continually, giving off flashes of light and impacting micro-organism cell's effect on algal cells (Uyar *et al.*, 2024). The amount of time that a gas spends in each zone determines how well it performs in terms of factors such as mass transfer between gas and liquid, heat transfer, mixing, and turbulence (Madhubalaji *et al.*, 2020). It has been refashioned into a variety of forms, such as by inserting a sparger into an annular tube. It has been suggested that a rectangular airlift photobioreactor may be used since it possesses improved mixing qualities and also high photosynthetic efficiency; however, the drawbacks of this design include its complexity and the difficulty of scaling it up (Putra *et al.*, 2021).

Horizontal tubular photobioreactor

Horizontal tubular reactors are capable of being designed with a parallel arrangement of tubes, loop shape, α shape, inclined tubular shape, or horizontal reactor (Fig. 4).

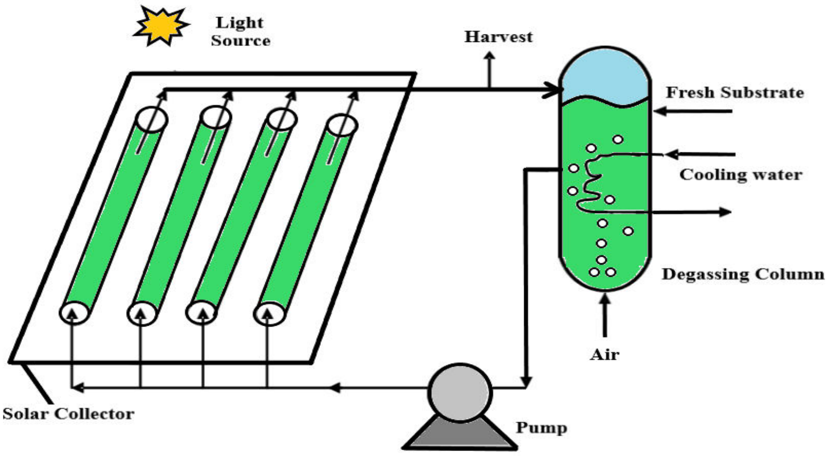

Fig. 4. A schematic diagram of a horizontal tubular photobioreactor.

Because of their orientation toward the sun, results in great light energy conversion, the design of these plants gives an edge in outside culture. A carbon dioxide gas combination is delivered into tubular connections using a gas swap that is specifically designed on the basis (García-Galán *et al.*, 2018). The accumulation of oxygen during the process of photosynthesis generates photobleaching and lowers the efficiency of the process (Madhubalaji *et al.*, 2020). The temperature of the feed or vortex stream can be regulated, as well as the temperature of the system by splashing the surface water of the tubes, bordering the tubes, and putting the luminescence unit on the inside of a pond of thermal management water, and so on (Zhao *et al.*, 2023). These methods have been adapted to cool the system. Another significant drawback is the high amount of energy that is required, which is approximately 2000 Wm^{-3}, whereas vapor column and corrugated photobioreactors only require 50 Wm^{-3}. This greater energy contribution is needed to accomplish tumultuous situations of adequate short light/dark cycles in a way to reach large axial liquid velocities of approximately 20–50 ms^{-1} (Legrand *et al.*, 2021). The inclined tubular reactor is comparable to a flat reactor vessel. The primary difference is that it is tilted at an angle of a few degrees toward the sun. This slant contributes to the increased efficiency with which sunlight can be captured. Manifolds made of tubular plexiglass were used to link the tubes' top and bottom terminals respectively. It was positioned such that it faced south atop a wooden structure at a horizontal angle of five degrees (Hossain *et al.*, 2018). The ratio of surface area to volume was maintained at 70 m^{-1}; however, the gas holdup was maintained at 10.3 percent of the total volume that was possessed by the gas bubbles (Egbo *et al.*, 2018). To keep the temperature under control, an automated evaporation system was utilized. Compared to the flat reactor, the volumetric productivity and photosynthesis significantly improved.

Stirred tank photobioreactor

Stirred tank reactors are particularly widely used kinds of reactors. In this type of reactor, agitation is created mechanically with impellers that come in various sizes and forms. Baffles are utilized in order to accomplish the reduction of vortex (Dai, 2023). The bottom of the tank is bubbled with air that has been enhanced with carbon dioxide to offer a source of carbon for such algae growth (Uyar *et al.*, 2024).

This kind of bioreactor can be converted into a photobioreactor by lighting it outside using fluorescent lights or fiber optics, but this system's main flaw is its low surface area to volume ratio, which reduces the effectiveness of light gathering (Singh *et al.*, 2021). There have also been experiments conducted using optical fibers; however, the utilization of fiber optics for illumination is not without its drawbacks due to the obstruction that it causes inside the blending pattern (Fig. 5).

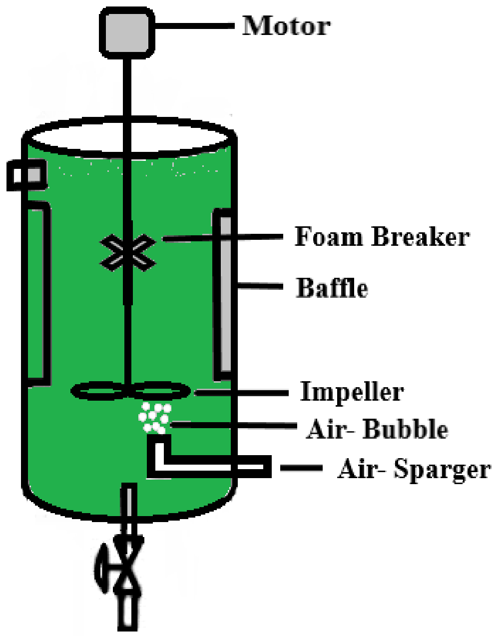

Fig. 5. A schematic diagram of the Stirred Tank Photobioreactor.

The fermenters manufactured by "New Brunswick Bioflo115" and Bioengineering are examples of photobioreactors that are available on the commercial market and have external light systems (Uyar *et al.*, 2024). During photosynthesis, a sizable disengages zone separates the gassed liquid phase from the gaseous phase, preventing the unneeded sparged gas and the oxygen created from mixing (Torres *et al.*, 2023).

Hybrid type photobioreactor

The hybrid form of photobioreactor is becoming increasingly popular. This type of photobioreactor takes advantage of the benefits offered by two distinct types of reactor, with each type overcoming the shortcomings of the others have made use of a separate tubular loop and a consolidated airlift system positioned horizontally in a thermostatically controlled water pond (Patil *et al.*, 2021). The overall volume of the reactor was 200 liters. On the one hand, the external loop performs the function of a light collecting unit due to the high surface area to volume ratio it provides and the fact that it regulates the temperature of the culture (Narala *et al.*, 2016). On the contrary, the airlift system serves as a releasing apparatus and can integrate probes to control the other variables in the culture. One of its benefits is improved control over the variables that affect the culture, which in turn enables higher productivity and lower overall power usage (Egbo *et al.*, 2018). However, the outside luminosity collecting unit of the former was the horizontal parallel combination of tubes, whilst the structure built by the latter was a loop-like configuration (Khoo *et al.*, 2016). Spraying liquid from an additional light collecting unit was the former used to maintain temperature control. The horizontal tubes offered a cost-effective solution in addition to their high photosynthetic efficiency (Al-Dailami *et al.*, 2022). The most significant drawback was the substantial amount of land utilized and the relatively small collecting unit for light (Chanquia *et al.*, 2022a). Due to the high costs involved with acquiring the necessary land area and the bundle of tubes, it would not be financially viable. The α-shaped reactor is also a sort of hybrid system that was established. It was planned and constructed based on the physiology of algae and the amount of sunlight they receive. Under these reactors, the culture is hoisted 5 meters by air to a transceiver tank, and then the cultures flow an angled PVC tube (2.5 cm ID 25 m), making 25 degrees with the horizontal, to hit other pair of air riser tubes, and then the procedure is repeated for the following set of tubes (Deprá *et al.*, 2019). Despite the considerably lower airflow rates, it is possible to accomplish both the bidirectional and higher liquid flow rates. The ratio of surface area to volume is also quite considerable, contributing to the high photosynthetic efficiency.

Results and Discussion

Recent Results of Algal Growth in Various Types of Photobioreactors are Summarized Below (Table 2). In particular, the algal species used and their relative biomass productivity are identified along with important recent developments that have helped achieve these results. These data capture a recent research direction towards the optimization of algal cultivation processes under different photobioreactor designs.

Table 2. Recent algal growth results for various types of photobioreactors with key advancements.

Photobioreactor Type	Algal Species	Biomass Productivity	Key Advancements	Citation
Raceway Pond	*Chlorella vulgaris*	25-30 g/m²/day	CO_2 delivery systems, hybrid systems for improved light and nutrient management	(Kubar *et al.*, 2022)
Tubular Photobioreactor	*Nannochloropsis oculata*	1.5 g/L/day	Transparent UV-resistant materials, optimized tube diameters	(Hossain *et al.*, 2018)
Air Lift Photobioreactor	*Spirulina platensis*	0.8 g/L/day	Enhanced gas sparging, reduced shear stress	(Uyar *et al.*, 2024)
Bubble Column Photobioreactor	*Dunaliella salina*	1.2 g/L/day	Nanobubble technology for improved gas-liquid mass transfer	(Patil *et al.*, 2021)
Stirred Tank Photobioreactor	*Scenedesmus obliquus*	1.0 g/L/day	Advanced mixing techniques, magnetic stirring, modified impellers	(Kubar *et al.*, 2022)

Data indicates that photobioreactors have strongly impacted algae growth rates, thanks to recent advancements in technology. Improved CO2 delivery systems and advanced nutrient management methods have taken raceway pond biomass productivity to an all-time high of 25–30 g/m²/day, an achievement to be commended not only for its economy of operation and scalability but also for the enhanced biomass productivity. The use of transparent, UV-resistant materials and the design optimization of tubes for maximizing light distribution has resulted in biomass productivities of 1.5 g/L/day in tubular photobioreactors, which lend themselves to continuous culture. *Spirulina platensis* has shown promising operation in airlift photobioreactors with a biomass productivity of 0.8 g/L/day, mostly attributable to the improved gas sparging methods that enhance oxygen transfer with minimal shear stress. Bubble column photobioreactors integrated with nanobubble technology have attained a 1.2 g/L/day biomass yield with *Dunaliella salina* through the enhancement of gas–liquid mass transfer efficiency, thereby enhancing CO2 utilisation and lipid accumulation. New mixing techniques like magnetic stirring and altered impellers, as well as stirred tank photobioreactors, which are very mixed, have yielded algae biomass productivities of up to 1.0 g/L/day with *Scenedesmus obliquus*.

Conclusion

This research emphasizes the significance of photobioreactors (PBRs) in the effective development of microalgae, specifically in the context of biofuel production. Important results show that compared to single-design reactors, hybrid PBR systems which integrate elements of tube and airlift designs achieve higher biomass productivity. Technological innovations that have demonstrated promise in optimizing light dispersion and gas exchange as well as overall efficiency include nanobubble systems. Nonetheless, issues including biofouling, unequal lighting distribution, and excessive energy usage are still unaddressed. Subsequent investigations ought to concentrate on enhancing the scalability of these systems, optimizing energy consumption, and tackling the performance variability among various PBR designs. This will increase the feasibility of growing microalgae for large-scale biofuel generation and other industrial uses.

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