



Tubular photobioreactor design for microalgae cultivation: Maximising efficiency for CO₂ fixation

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ABSTRACT

Microalgae, which utilise photosynthesis to convert carbon dioxide (CO₂) into biomass, have gained significant attention as a sustainable source of renewable energy and high-value bioproducts. Among various microalgae cultivation systems, tubular photobioreactors (PBRs) are one of the most established and widely used closed cultivation systems. This review provides an in-depth evaluation of key design properties of tubular PBRs, such as tube geometry, diameter, length, material fabrication, and the selection of appropriate light sources. Critical operational factors, including mass transfer, aeration systems, and mixing strategies, were also covered in detail in this paper. Particular emphasis is given to the novel integration of a helical baffle and membrane sparger into a tubular PBR to improve overall system efficiency compared to conventional systems. Membrane-based CO₂ delivery systems were shown to improve biomass concentration, productivity, CO₂ fixation rate, and CO₂ utilization efficiency by approximately 10–14% compared to conventional sparging methods. Additionally, the integration of a helical baffle into a horizontal tubular PBRs has been shown to significantly enhance the mass transfer coefficient, prolong bubble residence time, reduce mixing time, and promote overall microalgal growth by up to 40%. These improvements are attributed to enhance flow distribution, intensified mixing, and extended bubble residence time. This review concludes by outlining key design recommendations and future research needs to further optimise tubular PBR design for sustainable microalgae cultivation.

1. Introduction

Excessive greenhouse gas (GHG) emissions from anthropogenic activities, including fossil fuel combustion for transportation, industrial processes, electricity generation and other energy-intensive sectors, have significantly contributed to global warming, which has raised global concern. Carbon dioxide (CO₂) remains the dominant anthropogenic GHG, accounting for the largest share of global emissions. Based on the report of “Annual CO₂ emissions worldwide 1940–2020” [1], global CO₂ emissions reached approximately 36 billion metric tons prior to the COVID-19 pandemic, reflecting a persistent upward trend despite

temporary reductions during global lockdowns.

The Paris Agreement [2] and the European Union’s mandate [3] have further intensified the demand for effective strategies capable of achieving long-term net-zero carbon emission (NZCE) targets. A growing focus is being prioritised on the implementation of renewable energy sources and the investigation of novel approaches in an effort to attain the goal of net-zero carbon emissions (NZCE) and mitigate the escalating CO₂ levels.

Among these solutions, the implementation of photobioreactors (PBRs) to cultivate photosynthetic microalgae using industrial flue gas as a sustainable feedstock presents a potential approach in mitigating

Abbreviations: CO₂, Carbon dioxide; PBR, Photobioreactor; COP21, United Nations Climate Change Conference; EU, European Union; NZCE, Net-zero carbon emissions; PVDF, Polyvinylidene fluoride; O₂, Oxygen; S_v/V, Surface to volume ratio; PMMA, Polymethyl methacrylate; LED, Light-emitting diodes; DIC, Dissolved inorganic carbon; NaHCO₃, Sodium bicarbonate; MDRMA, Magnet-driven rotary mixing aerator; PVDF-co-PTFE, Polyvinylidene fluoride–polytetrafluoroethylene; FTIR, Fourier transform infrared; XRD, X-ray diffraction.

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greenhouse gas emissions and making a significant contribution towards the NZCE target. Microalgae, the primary source of biomass, exhibit higher photosynthetic efficiencies and specific growth rates than terrestrial plants, offering effective solutions for scalable CO₂ fixation and reutilisation processes [4–6].

Fig. 1 illustrates the life cycle of microalgae-based bioproduct production, including biofuels and food supplements, within a bio-circular economy framework. Microalgae cultivation utilizes CO₂ emissions from industrial sources as carbon feedstock, contributing to carbon capture while generating value-added products. Previous life-cycle assessment (LCA) studies have reported that microalgae-based systems offer potential environmental benefits, including greenhouse gas emission reduction, carbon sequestration, and decreased reliance on fossil-based resources [7], although the economic feasibility remains highly dependent on cultivation and processing efficiencies. These findings highlight the potential of microalgae as a sustainable feedstock for biofuel and nutraceutical production [7]. However, these environmental and economic benefits depend significantly on the efficiency of the cultivation system [7]. Photobioreactor (PBR) design plays a critical role in determining biomass productivity, mass transfer, and CO₂ fixation efficiency. Despite substantial advances in PBR development, identifying an ideal design configuration of PBRs for microalgae cultivation remains challenging, particularly in integrating innovative mixing and aeration methods to enhance biomass productivity and CO₂ utilization efficiency.

Recent theoretical and experimental studies related to the PBR design have extensively examined gas-liquid flow behaviour, CO₂ dissolution, bubble dynamics, and mass transfer enhancement. For instance, Fu et al. [8] reviewed the interaction between fluid dynamic and biochemical reaction rates, which is essential for high-performance PBR design. A report by Legrand et al. [9] assessed several modelling techniques to anticipate light distribution in both open and closed PBR systems. However, in their study, the identification of optimal design configuration PBRs was not explicitly addressed.

Previous studies have explored internal mixing modifications, including horizontal baffles and static mixers within flat-panel, tubular, and bubble column PBRs [10]. However, the strategic implementation of non-static or assisted helical baffle structures to induce controlled swirling flow and reduce hydrodynamic dead zones has received comparatively less attention. Such configurations offer potential

improvements in nutrient homogeneity and overall reactor performance.

Additionally, membrane-based aeration has emerged as a promising approach to improve gas transfer efficiency. Studies by Moraes et al. [11] and Mortezaeikia et al. [12] highlighted the potential of membrane spargers in vertical tubular PBR and membrane contactors in PBR, respectively. Furthermore, Assunção and Malcata [10] outlined the material characteristics of hollow fiber membranes and emphasised the advantages of membrane-integrated PBR systems. However, the application and performance evaluation of PVDF membrane spargers specifically within horizontal tubular PBRs remain inadequately explored.

Therefore, this paper reviews the novel combination of assisted helical baffles for mixing and polyvinylidene fluoride (PVDF) membrane spargers for aeration inside the tubular PBR design for microalgae cultivation. This novel approach addresses key limitations in nutrient distribution, gas exchange, and growth optimisation, ultimately contributing to the advancement of microalgae-based CO₂ fixation strategies. The interplay between the developments of helical baffles and PVDF membrane spargers reveals the potential for tubular PBRs to play a key role in environmentally friendly biomass production.

2. Photobioreactor

Microalgae can be cultivated in two main types of systems: open and closed cultivation systems. Commercial microalgae cultivation often uses open systems, such as open ponds, tanks, and raceway ponds, due to low capital and operating costs [5]. However, open systems, like raceway ponds, require large land areas, experience significant evaporation rates, and suffer from low productivity due to their dependence on local weather conditions. These weather conditions can rapidly alter operating conditions, affecting variables like pH, temperature, and light intensity [13–17]. Besides, elevated evaporation rates result in significant water loss [18], reducing the volume of the culture medium and modifying the nutrient content. Additionally, the significant sensitivity to contaminants in an open system causes monoalgal culture to be less secure [17]. Furthermore, scaling up open pond culture systems is generally achieved through horizontal expansion of the cultivation area, as increasing pond depth will result in inefficient light consumption and reduces photosynthetic efficiency [13].

The emergence of closed cultivation systems, or photobioreactors (PBRs), offers industrial integration owing to their high biomass productivity and low risk of contamination, as the environment and operating variables of the systems can be tightly regulated. However, PBR construction is more expensive due to the need for transparent, durable materials and is difficult to scale [14]. Despite these limitations, closed systems are widely regarded as essential for high-efficiency CO₂ bio-fixation because they enable precise control of culture conditions such as light intensity, CO₂ concentration, and nutrient availability [18]. Table 1 summarises the advantages and disadvantages of open and closed systems for microalgae cultivation.

An ideal PBR would have no dead space, high gas-liquid mass transfer for CO₂ absorption and oxygen (O₂) removal, and uniform light distribution [19]. Additionally, a PBR should ideally have a minimum hydrodynamic shear stress on the cells and excellent substrate mixing. In practice, several PBR configurations are available to achieve as close to these ideal conditions as possible to guarantee optimal growth and production throughout the process. Tubular, flat plate, and bubble column are the commonly used closed PBR designs for microalgae cultivation [5,17,20]. Consequently, each PBR configuration has unique benefits and drawbacks in terms of operation, biomass output, efficacy in removing pollutants, and level of commercialisation. The designs are upgraded on a regular basis to increase biomass output, enhance the effectiveness of contaminant removal, lower maintenance costs, and minimise land utilisation [17].

Flat-plate PBRs consist of semi-transparent materials like polycarbonate or Plexiglass to allow light penetration [21]. Flat panels are

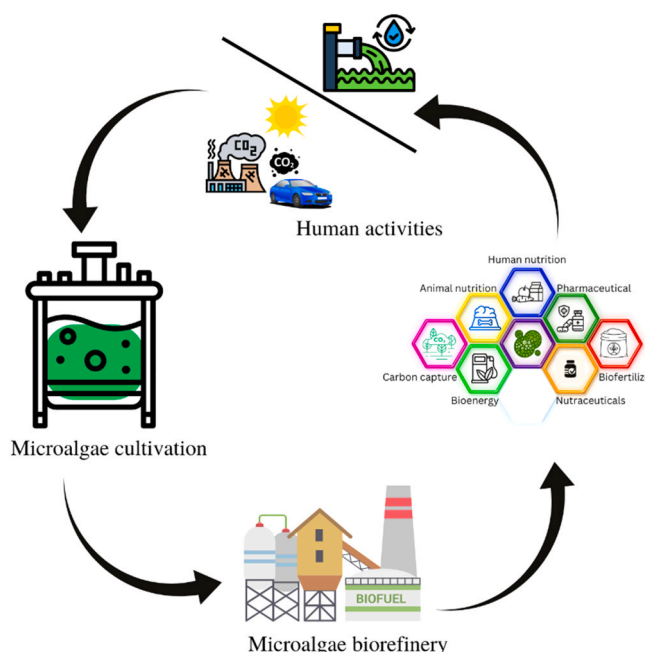


Fig. 1. Life cycle evaluation for bioproduct production from microalgae.

Table 1

The advantages and disadvantages of closed and open systems for microalgae cultivation.

Microalgae cultivation system	Advantages	Disadvantages	References
Open system	• Easy to build • Easy to operate • Economically feasible • Opportunity using large body of water as medium, e.g., seawater	• Large areas of land • High evaporation rate • High risk of contamination • Low productivity • Inefficient light transfers due to high depth • Climate dependence • Low atmospheric CO₂ mass transfer rate due to its ineffective mixing processes • Difficult to maintain monoculture	[13–15, 17]
Closed system	• High rates of CO₂ biofixation • High photosynthetic efficiency • High biomass productivity • Improved culture variables control • Low risk of contamination	• Expensive construction • Operationally complicated • Difficult to scale up	[5,6,13,14, 19]

typically displayed vertically and horizontally, but they can also be arranged inclinedly. A flat-plate PBR offers a broad illumination surface as well as the benefit of a high surface to volume (S_f/V) ratio, making it possible to produce optimal cell illumination and low O₂ concentration [13]. This PBR configuration has one significant drawback in comparison to a tubular PBR, which is channel fouling owing to the short, rectangular-shaped channels that reduce turbulence [21]. A bubble column PBR is a relatively simple system with a single vertical cylindrical vessel aerated at the base, without an internal draft tube. These systems typically exhibit low shear stress and simple hydrodynamic behaviour [21].

Tubular PBRs are more ideal for outdoor microalgae cultivation owing to the broad lighting produced by the arrangement of the tubes, which may be set in horizontal, vertical, or inclined planes. Specifically created to boost the surface-to-volume (S_f/V) ratio of the reactors, illuminated tubular PBRs maximise the amount of light that is available to the cells [19]. A tubular PBR is generally made up of two differentiated components: a gas delivery unit and several parallel tubes that act as solar collectors. The solar collector is made up of a collection of identical-diameter tubes joined together by elbows and sleeves to create a compact shape on a horizontal or vertical plane. This arrangement is intended to maximise photosynthetic efficiency and capture light, optimising the production of microalgae [22]. Table 2 provides an overview of the benefits and drawbacks of three different PBR configurations.

Tubular PBR systems can enhance temperature homogenisation through continuous circulation of culture, which promotes heat dissipation along the tubes. In outdoor cultivation, the integration of Digital Control Units (DCUs) can further support temperature regulation to maintain stable operating conditions. However, CO₂ gradients occur along tube length due to progressive gas consumption, reducing mass-transfer efficiency. Flat-plate PBRs offer very short light paths, enabling uniform light penetration across the culture, but wall growth is common because illuminated flat surfaces promote biofilm deposition [21,24]. Bubble column PBRs achieve effective gas exchange, as rising bubbles continuously renew the gas–liquid interface [25]. However, light availability in these systems may become limited due to factors

Table 2

Summary of the advantages and disadvantages of different PBR configurations.

Closed PBR system	Advantages	Disadvantages	References
Tubular	• High S_f/V ratio • Effective temperature regulation • Suitable for outdoors cultivation • Expandable	• Low gas exchanges • Significant gas gradient throughout the tubes • High energy input • High shear stress • Biofilm formation • Biomass accumulation in the tubes	[23]
Flat plate	• High S_f/V ratio • Extremely short light path • Flexible light capturing angle • High mixing rates • Low shear stress depends on the selection of agitation method used	• Challenging for scaling up • Difficult to regulate temperature • Fouling up of the rectangular shape channel • Possible hydrodynamic stress	[21,24]
Bubble column	• Low oxygen builds up • Effective gas exchanges • Low shear stress • Low cost • Low energy consumption • Good mixing • High mass transfer • Easy to sterilize	• Low S_f/V ratio • Ineffective solar radiation capture during outdoor cultivation	[23]

including low surface-to-volume ratio, longer optical path length, high cell density, and hydrodynamic conditions, especially in outdoor systems [19,26]. Among these designs, tubular PBRs are the most established and well-known technology [22].

Tubular PBRs provide a number of advantages in comparison to other PBR configurations, including higher productivity, scalability, reduced culture contamination, and enhanced light distribution. Tubular horizontal PBRs have a higher S_f/V ratio, which promotes greater biomass productivity [24]. The use of tubular PBRs for large-scale microalgae cultivation and CO₂ fixation is more appealing, as vertical column tubular PBRs can be readily scaled up for commercial production [24]. In addition, the biomass productivity in tubular PBRs is more reliable as cultivated microalgae are less likely to face culture contamination compared to open pond systems [27]. Furthermore, tubular PBRs can be designed to enhance light distribution and increase biomass productivity [28].

Tubular PBRs can be designed and optimised to improve CO₂ utilisation efficiency in microalgae cultivation through factors such as PBR geometry, material selection, operating conditions, and biomass harvesting strategies [13,29]. The geometry of the tubular PBR, including tube diameter, length, and configuration can be optimised to enhance light penetration, mixing efficiency, mass transfer and nutrient distribution [29]. Besides, material selection is also important because highly transparent materials, such as glass can improve light transmission and enhance photosynthetic activity [26,30]. Additionally, materials with good chemical resistance and smooth surface properties facilitate reactor maintenance, supporting effective sterilisation and reducing the risk of contamination when combined with appropriate operational practices [26]. Furthermore, key operating parameters, such as pH, temperature, light intensity, and CO₂ supply rate can be controlled to optimise photosynthetic efficiency and carbon fixation by microalgae. Biomass harvesting is also an important consideration, as it represents one of the most energy-intensive stages of microalgal production [31].

The concentration of nutrients in the medium, the availability and distribution of light, the concentration of CO₂ in the intake gas and its speciation in water, pH, and temperature are the most crucial parameters that must be considered in evaluating the growth of microalgae in

novel PBRs [32]. Therefore, this study aims to focus more on the design of tubular PBRs, as this configuration was reported to sustain high CO₂ biofixation rates and high photosynthetic efficiency while maintaining technical process control throughout cultivation [6].

3. Design properties

3.1. Geometry of the tube

Depending on the design objectives, tubular PBRs may adopt straight, helical, or coiled configurations to optimise light exposure and hydrodynamic performance. Straight tubular systems offer simple construction, low pressure drop, and ease of cleaning but may experience suboptimal mixing in long runs. Helical and coiled configurations enhance mixing and light–dark cycling due to secondary flow formation; however, these configurations typically impose higher pressure drop and increased energy demand for circulation. Several studies have explored these configurations, such as helical tubular PBRs with integrated membrane spargers [33], horizontally oriented systems with helical baffles to improve gas–liquid mass transfer [6] and hybrid indoor helical tubular systems [15].

3.2. Diameter and length of the tube

Torzillo and Chini Zittelli [34] reported that the selection of the tube diameter is crucial for the optimal PBR design, as it influences the following factors: (1) the S_p/V ratio, and consequently the ability of the culture to absorb light; (2) the biomass concentration; (3) the volumetric productivity; (4) the temperature profile of the culture; (5) the O₂ concentration in the culture; (6) the capacity of the PBR to store CO₂; (7) the head loss for culture recycling; and (8) the length of the tube. Microalgae could receive sufficient light for photosynthesis in the depth range of 20–50 mm [35].

A longer tubular PBR allows for a longer residence period for the culture medium, which can improve nutrient utilisation and CO₂ uptake by microalgae. However, light attenuation within the culture is primarily influenced by the optical path length, biomass concentration, and light scattering effects rather than the overall reactor length alone [36]. Larger tube diameters increase the light path through the culture, which may reduce light penetration due to absorption and scattering by microalgal cells [26]. Therefore, maintaining an appropriate tube diameter is important to ensure sufficient light availability for photosynthesis. According to Cuello et al. [37], the optimal light path thickness for microalgae cultivation is typically between 2 and 4 cm.

3.3. PBR material fabrication

Several factors must be considered when selecting materials for a PBR design, including the specific requirements of the microorganisms being cultivated, the operating conditions of the PBR, and the risks of material degradation or contamination. The principal factors to consider are optical properties, biocompatibility, cleanability, durability, and economic viability [38].

Several materials are commonly used for PBR fabrication, including polymethyl methacrylate (PMMA or acrylic) [38], glass [39], polyvinyl

chloride [40], polyurethane [15], and polyethylene [41]. Table 3 shows a list of studies with different materials used in PBR fabrication. Thermal sterilisation is generally unsuitable for most polymeric materials except glass, and chemical cleaning agents may compromise long-term stability [30]. Besides, chemical cleaning can be considered with caution as it may damage the stability of the material. For instance, prolonged exposure to ethanol can reduce the durability of PMMA-based systems due to partial solubility [42,43].

PMMA offers high light transmittance, low light absorption, favourable mechanical strength, and ease of fabrication [38]. Due to its attractive characteristics for developing efficient and long-lasting PBR applications, PMMA is an appealing material among researchers and industry professionals.

3.4. Source of light

The availability and characteristics of light are critical factors influencing microalgal culture performance, as light serves as the fundamental energy source for photosynthesis. Therefore, the light source in a closed cultivation system should provide adequate intensity, spectral quality, and distribution to maximise photosynthetic efficiency and biomass productivity. Light intensity directly affects the rate of photosynthesis and CO₂ fixation. Insufficient illumination can limit photosynthetic activity, carbon assimilation, and microalgal growth. While excessive illumination may induce photoinhibition, reducing photosynthetic efficiency and overall culture performance.

Reported light sources for microalgal cultivation include natural sunlight, fluorescent lamps, light-emitting diodes (LEDs), high-intensity discharge lamps, fibre optics, and hybrid systems that combine natural and artificial illumination [38]. The suitability of each light source depends on installation cost, spectral control, energy efficiency, and system geometry.

Artificial illumination is commonly employed in indoor closed cultivation systems and as supplemental lighting when natural sunlight is insufficient. Among the available technologies, LEDs have gained increasing attention due to their high energy efficiency, long operational lifespan, low heat generation, and ability to provide specific wavelengths that closely match the photosynthetic requirements of microalgae [36]. These characteristics enable improved light utilisation and enhanced photosynthetic performance compared with conventional lighting systems [49]. In outdoor tubular PBRs, natural sunlight remains the primary light source; however, reactor geometry should be designed to ensure adequate light penetration and minimise self-shading effects within dense cultures.

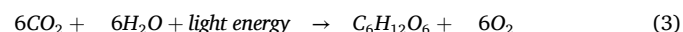
4. Factors critical to PBR operations for microalgae cultivation

4.1. Mass transfer

One of the important parameters of mass transfer is CO₂, the most crucial element involved in photosynthesis. The following chemical equilibria are generated when CO₂ dissolves in water:



The process of converting CO₂ into organic compounds through the action of photosynthetic organisms such as algae, bacteria, and plants via photosynthesis is known as CO₂ fixation. However, in order for microalgae to absorb and subsequently biofix the gaseous CO₂, it must first be transported into the liquid phase as dissolved inorganic carbon (DIC) [50].



Eq. 3 shows the equation for photosynthesis that occurs in a PBR to

Table 3

Various materials used in design and fabrication of PBR.

Material fabrication	Type of PBR	Reference
Glass	Tubular PBR	[9]
Plexiglass	Flat panel PBR	[44]
PMMA	Raceway pond	[45]
PMMA	Hollow tubes embedded into a flat-plate PBR	[46]
PMMA	Horizontal tubular PBR	[6,47]
PMMA	Bubble column	[48]

produce biomass and O₂, which involves the fixation of CO₂ into organic compounds using energy from light. According to Wang et al. [51], the carbon fixation rate assessed during culture can be determined as Eq. 4 where R_{CO_2} is the carbon fixation rate (g/L/d); D_1 and D_2 are the algal dry weights (g/L) at time t_1 and t_2 (d), respectively, η is the carbon fraction in algal cells; and M_{CO_2} and M_C are the molecular weights of CO₂ and carbon, respectively.

$$R_{CO_2} = \frac{D_2 - D_1}{t_2 - t_1} \cdot \eta \cdot \frac{M_{CO_2}}{M_C} \quad (4)$$

Carbon dioxide may be delivered to the algae in a PBR using different gas delivery systems, such as spargers or diffusers, where CO₂ or CO₂-enriched air is bubbled through the growth medium to enhance gas-liquid mass transfer [18]. When exposed to light, algae convert CO₂ into lipids, proteins, and carbohydrates that may be used for a variety of purposes, such as the production of biofuel and food supplements. The rate of CO₂ fixation in a PBR is influenced by several variables, such as temperature, light intensity, and nutrition supply [28]. Different conditions may be optimum for microalgae cultivation only, but not CO₂ fixation, depending on the type of algae being utilised and the intended application of the organic compounds generated.

A CO₂ microbubble dissolver was developed by Cheng et al. [4] to improve inorganic carbon dissolution and maximise mass transfer in a horizontal tubular PBR. The study found that using ceramic shell aerators increased the biomass production of the microalgae *Chlorella* PY-ZU1 due to the lower bubble formation time and higher mass transfer coefficient. In addition, Li et al. [52] used a column PBR integrated with a novel magnet-driven rotary mixing aerator (MDRMA) to reduce bubble diameter and rising rate while strengthening the impact of CO₂ mass transfer during microalgae cultivation. The study found that the aerator significantly affected the bubble diameter and bubble rising rate as the rotation rate increased. Additionally, the use of rotation helps to distribute the flow field, improve mass transfer, and accomplish effective CO₂ fixation by microalgae. Overall, these studies suggest that PBR technology may be essential for decreasing GHG emissions and producing sustainable bio-based products as it can sequester CO₂.

The mass transfer of CO₂ from gas bubbles to microalgae cultures is one of the significant limiting variables to improve microalgae productivity and carbon capture rates [53]. Theoretically, smaller-diameter bubbles tend to have a higher S_f/V ratio, which increases mass transfer rates in accordance with Fick's law of diffusion [53]. Consequently, the mass transfer rates of CO₂ are significantly influenced by the design of the gas sparger for bubble generation and mixing mechanisms [54]. Therefore, to evaluate the effectiveness of a PBR, it is necessary to consider the overall CO₂ volumetric mass transfer ($k_L a_{CO_2}$). In practical tubular PBR systems, reported $k_L a_{CO_2}$ values typically range between 0.003 s⁻¹ and 0.01 s⁻¹, depending on reactor configuration, superficial gas velocity, tube diameter, and sparger design [55]. Enhanced $k_L a$ values are generally correlated with improved dissolved inorganic carbon availability and higher CO₂ utilisation efficiency.

Controlling O₂ inhibition and optimising microalgae growth both depend on increasing O₂ and CO₂ mass transfer. The saturated dissolved O₂ concentration (as determined by Henry's Law) and the overall mass transfer coefficient ($k_L a$) serve as the upper limits on the O₂ stripping rate [56]. While the dissolved CO₂ concentration can be substantially increased by enriching the sparging gas with CO₂. However, CO₂ dissolution and transfer are still governed by gas-liquid equilibrium, hydrodynamic conditions, and operational parameters [57]. Eq. 5, where C is the dissolved O₂ (DO) (mg L⁻¹) at time (t) (h), C^* is the saturated concentration of DO (mg L⁻¹), C_0 is the DO at time 0, and $k_L a_{O_2}$ is the overall volumetric O₂ mass transfer coefficient (h⁻¹), can be used to determine the dynamic O₂ transfer behaviour in a PBR. The slope of the graph represents the volumetric O₂ mass transfer coefficient. The entire CO₂ volumetric mass transfer coefficient can then be calculated using Eq. 6, where $k_L a_{CO_2}$ is the overall volumetric CO₂ mass transfer coefficient (h⁻¹), DCO_2 is the diffusivity coefficient of CO₂, and DO_2 is

the diffusivity coefficient of O₂.

$$k_L a_{O_2} = \frac{-1}{t \cdot \ln \left(\frac{C^* - C}{C^* - C_0} \right)} \quad (5)$$

$$k_L a_{CO_2} = k_L a_{O_2} \left(\left(\frac{DCO_2}{DO_2} \right)^{0.5} \right) \quad (6)$$

4.2. Aeration and gas-liquid mass transfer systems for CO₂ fixation

Degasser units are commonly integrated into tubular PBRs to remove excess dissolved oxygen and prevent photosynthetic inhibition [58]. However, a tubular PBR design with a degasser unit alone is insufficient to accommodate CO₂ mitigation and optimising microalgal cultivation performance. Effective microalgal growth also requires efficient CO₂ delivery, gas-liquid mass transfer, culture circulation, and mixing to maintain homogeneous nutrient and light distribution throughout the PBR [58]. Consequently, aeration is essential in most microalgal cultures to supply CO₂ for photosynthesis, serve as the sweeping gas to eliminate O₂ generated, and also providing the hydrodynamic forces necessary for mixing and biomass suspension, thereby enhancing both biomass productivity and CO₂ utilization efficiency [59]. Several gas aeration techniques are used to aerate the microalgal solution by introducing gas in the form of bubbles. Babcock et al. [57] installed a sparging system at the end of the bubble column in a near-horizontal tubular PBR, together with a large degasser, to increase the dissolution and deoxygenation efficiency. However, the drawbacks of this technique include the possibility of contamination caused by the large contact area between the solution and the air, as well as a loss in mixing effect due to the liquid flow rate in the tubes.

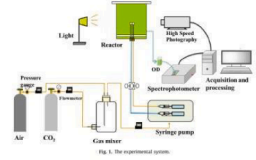
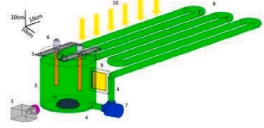
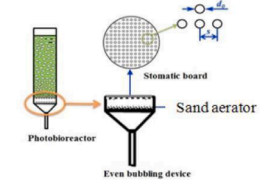
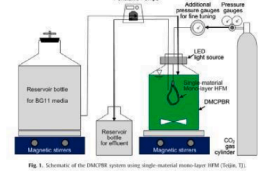
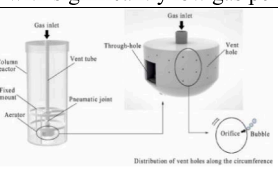
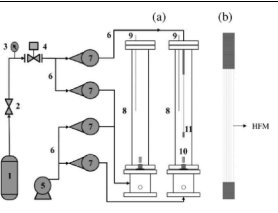
Gases delivered as small bubbles can enhance gas dissolution into the liquid phase due to the enormous gas-liquid interfacial area generated per unit volume, thereby improving mass transfer efficiency [4]. Consequently, there is widespread use of microbubble generation technologies in aquaculture, sewage treatment, and fixation by microalgae. The various state-of-the-art aeration system designs employed in PBRs are shown in Table 4. In order to boost CO₂ fixation in microalgal culture by increasing the concentrations of DIC in the liquid medium, Moraes et al. [11] developed a membrane sparger incorporated into a vertical tubular PBR. By directly submerging a hollow fibre membrane carbonation module within the PBR, Kim et al. [60] developed a direct membrane carbonation PBR. In the comparison of the effectiveness of using a ceramic shell aerator and a rubber strip aerator built into the microbubble dissolver, Cheng et al. [4] discovered that the rubber strip aerator caused a lower bubble formation frequency and diameter. However, it was reported that the ceramic shell aerator had higher hydrophobicity than the rubber strip aerator, suggesting that the bubble on the ceramic shell aerator experienced less surface tension. As a result, when a bubble was created using different aeration techniques, the internal pressure of the bubble changed.

Fig. 2 shows various designs of perforated porous spargers that are commonly used to supply carbon dioxide in the form of gas bubbles within both open and closed microalgae cultivation systems. While the primary function of all gas spargers is to introduce gas into the liquid medium, the different designs do not fundamentally change this essential operation. The variations in the sparger design are strategically developed to optimize critical parameters such as bubble size, bubble distribution, and gas retention time [62], which directly influence the efficiency of CO₂ dissolution and absorption by microalgae.

However, the supply of CO₂ through these conventional systems (shown in Fig. 2) is limited by a number of drawbacks, including the loss of exhaust gases to the environment, a poor mass transfer efficiency caused by a small interfacial exchange area, and a short residence time of the gas in the culture medium [64]. Several methods, including bubbling, surface aeration, and membrane sparging have been utilised

Table 4

Different designs of aerators utilised in PBRs [4,11,20,52,60,61].

Design of aerator	Aim	Pore diameter (mm)	Pore spacing (mm)	Bubble diameter (mm)	Mixing time (s)	References
 PBR -Capillary orifice	Analyse the impact of the gas flow rate and the centre distance of the capillary orifice on the dynamic behaviour of the bubbles in the suspension of microalgae.	0.5	1.5	2.65	1.9	(Zhao et al., 2015)
 Ceramic shell aerator	Study the appropriate base area ratio of the aerator to the dissolver and the effect of aerator surface curvature on the mass transfer coefficient and mixing time.	0.028	NA	0.91	19	(Cheng et al., 2019)
 Airlift PBR -Sand microbubble aerator	Investigate the effects of orifice size, arrangement type, and spacing during microalgae growth.	0.5	1.5	1.25	31	(Y. Huang et al., 2017)
 Tubular reactor - Polyethylene-based hollow fibre membrane with significantly low gas permeability.	Analyse the effect of directly immersing a membrane carbonation unit with a range of surface areas on biomass production.	NA	NA	NA	1.02	(Kim et al., 2016)
 A novel rotational mixing aerator powered by magnets	Construct a novel MDRMA based on the secondary compression by centrifugal force and shear stress principle for microalgae production.	0.6	NA	0.7	NA	(Li et al., 2022)
 A vertical tubular PBR with a membrane and conventional sparger	Study the impact of supplying CO ₂ using a membrane sparger on biomass production, CO ₂ usage effectiveness, and the biochemical composition of <i>Spirulina</i> .	0.4	NA	NA	NA	(Moraes et al., 2020)

for gas sparging. Bubbles are created by injecting gas directly into the culture medium using a porous diffuser or sparger at the base of the PBR [64]. Surface aeration is the process of introducing air or O₂ into a culture medium at the liquid's surface, typically via a rotating impeller

[65]. Membrane sparging involves the introduction of gas through a microporous membrane, which offers a large surface area for gas transfer and can increase O₂ transfer efficiency.

Conventional CO₂ supply technologies in PBRs, such as direct

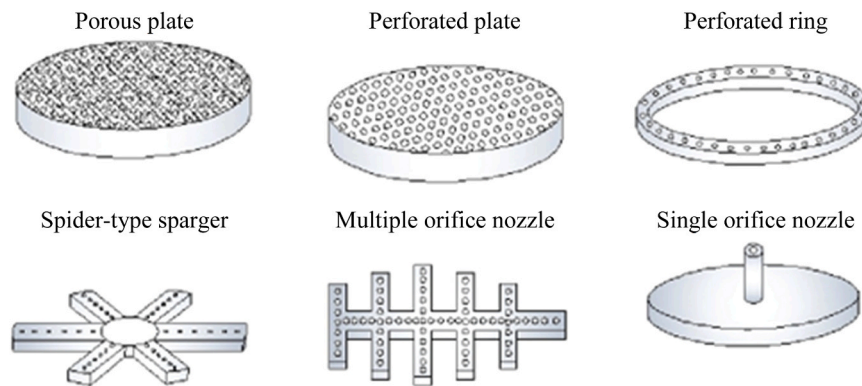


Fig. 2. Different designs of gas spargers integrated into bubble column reactors [63].

bubbling through diffusers or gas injection systems, often exhibit several limitations, including significant exhaust gas loss and low mass transfer efficiency, limiting the effectiveness of CO_2 dissolution in the culture medium. Therefore, integrating a membrane sparger in a PBR as gas sparging technology could effectively tackle these challenges by facilitating precise gas delivery through its microporous design, which guarantees consistent CO_2 gas distribution and improved gas-liquid mass transfer [11]. This method reduces gas loss, enhances CO_2 availability for microalgae, and promotes efficient CO_2 fixation, presenting a sustainable solution to optimize the performance of PBR system. Additionally, the incorporation of conventional mixing technologies in PBRs, such as static mixers, typically exhibits high energy consumption and less reliable on larger scale [66]. The integrated use of a helical baffle within a PBR tackles these challenges by inducing a spiral-ascending flow pattern for CO_2 bubbles that enhances gas-liquid mass transfer. This baffle configuration extending the bubble flow trajectory, which increases gas-liquid contact time and enhances the overall mass transfer coefficient. Furthermore, the baffle promotes the formation of smaller bubbles with shorter generation times, facilitating efficient CO_2 dissolution and reducing liquid phase mixing time, which ensures uniform nutrient distribution and enhances microalgal biomass accumulation in horizontal tubular PBRs [6]. Consequently, the integration of a membrane sparger and a helical baffle in a tubular PBR could result in increased biomass productivity and optimized system efficiency by leveraging both complementary advantages.

Several studies on the membrane integrated into the PBR have shown the potential for the fixation process in microalgae cultivation. Fig. 3 shows various membrane-assisted microalgae cultivation systems, categorized into two groups based on the primary function: carbonation membranes (C-MPBR) and biomass retention membranes (BR-MPBR). In C-MPBR systems, the main function of the membrane is to facilitate efficient CO_2 transfer to the microalgae culture, which is essential for photosynthesis [11]. These systems can utilize membrane contactors to separate gas and liquid phases, facilitating controlled CO_2 dissolution, or membrane spargers to enhance gas transfer through the generation of fine bubbles [67]. BR-MPBR systems utilize membranes for the

separation and concentration of microalgae biomass, facilitating efficient harvesting and allowing for potential continuous operation [67]. These systems may incorporate submerged membranes within the PBR or use external membrane filtration units for the circulation of the culture broth [67].

This study focuses on the membrane sparger configuration of the C-MPBR for microalgae cultivation, highlighting the potential to enhance CO_2 mass transfer efficiency significantly. Membrane spargers increase the gas-liquid interfacial area and residence time through the generation of fine bubbles, which facilitated more effective CO_2 dissolution [68]. This process is essential for maximizing photosynthetic activity and CO_2 fixation in microalgae. This configuration offers promising advantages for improving the overall productivity and sustainability of cultivation systems.

Moraes et al. [11] reported that the carbon feed through the membrane sparger integrated into the vertical tubular PBR improved the growth parameters and fixation in the microalgae culture while increasing the buildup of DIC in the liquid medium. In addition, the study by Mortezaeikia et al. [12] compared the performances of a hollow fibre membrane sparger and a membrane contactor PBR on *Synechococcus elongatus* growth and fixation for a variety of contents in batch and semi-continuous cultivation. According to the authors, the presence of 10% input feed gas inhibited the growth of high cell densities [12]. Additionally, the microalgae in the membrane carbonation PBR grew more effectively at 10% CO_2 concentration than the membrane sparger PBR did at 5% CO_2 concentration.

Membrane spargers operate via bubble-mediated mass transfer, where gas is dispersed into the liquid phase as fine bubbles through a microporous membrane [68]. The overall mass transfer performance therefore depends strongly on bubble size distribution, gas flow rate, hydrodynamic conditions, and residence time within the PBR. In contrast, membrane contactors operate based on diffusion-controlled mass transfer across a non-dispersive gas-liquid interface, where gas and liquid phases are separated by a microporous hydrophobic membrane [67]. The interfacial area is structurally defined by the membrane surface area, and mass transfer is governed by diffusion resistance in the gas phase, membrane pores, and liquid boundary layer [67]. However, performance may be influenced by membrane wetting, pressure differentials, and operating conditions [67]. Table 5 presents a mechanism-based comparison between membrane spargers and membrane contactors for CO_2 delivery in PBR systems, with performance criteria interpreted in relation to their underlying mass transfer mechanisms.

The utilisation of a membrane sparger within a PBR as a CO_2 sparger has numerous advantages, including a large interfacial area for CO_2 transfer, which facilitates the rapid dissolution of the gas into the liquid medium. In addition, the design of the membrane sparger promotes homogeneous growth conditions for microalgae by distributing CO_2 bubbles evenly throughout the PBR [68]. In addition, the gas-permeable

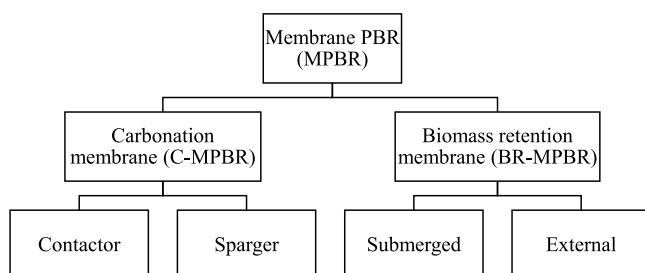


Fig. 3. Microalgae cultivation systems with membrane technology.

Table 5

Mechanism-based comparison between membrane spargers and membrane contactors for CO₂ delivery in PBR systems [69].

Description	Membrane sparger	Membrane contactor
Mass transfer mechanism	Bubble-mediated gas–liquid mass transfer via dispersed microbubbles	Diffusion-controlled gas transfer across a non-dispersive gas–liquid interface
Principle of operation	Gas diffusion through microporous membrane and forms bubbles in the liquid phase	CO ₂ diffuses across hydrophobic membrane pores
Interfacial area	Dynamic interfacial area generated by bubbles; depends on bubble size, gas flow rate, and hydrodynamics	Structurally defined membrane surface area
Gas transfer efficiency	High under optimized bubble size and sufficient residence time	Very high under stable non-wetting conditions and controlled pressure gradients
Gas distribution	Bubble distribution depends on membrane design and reactor hydrodynamics	Gas transfer uniformity depends on flow distribution across membrane surface
Liquid contamination risk	Lower risk of liquid intrusion into gas line due to outward gas pressure	Risk of membrane wetting or liquid penetration under high transmembrane pressure
Mass transfer limitations	Limited by bubble coalescence, short residence time, and hydrodynamic conditions	Limited by diffusion resistance in membrane pores and liquid boundary layer
Maintenance requirements	Relatively easy maintenance; cleaning frequency depends on biomass concentration and operating regime	Periodic cleaning required; performance sensitive to fouling and pore wetting
Scalability	Suitable for small- to medium-scale systems	Suitable for large-scale systems
Cost considerations	Generally lower capital cost	Higher capital cost due to membrane module complexity and pressure control requirements
Advantages	- Enhanced gas dispersion under proper hydrodynamics - Increased bubble interfacial area	- Controlled and bubble-free gas transfer - High CO₂ utilization efficiency under non-wetting conditions
Limitations	- Reduced exhaust gas loss when optimized - Performance sensitive to bubble size and flow regime - Possible gas loss if residence time is insufficient	- Suitable for precise CO₂ dosing - Membrane wetting risk - Higher operational and maintenance complexity

membrane serves as a barrier, preventing contaminants, microorganisms, and solid particles from entering the PBR. Due to the much greater interfacial surface area generated by the small bubbles compared to the membrane contactor, Zhang et al. discovered that the integration of the membrane sparger was preferable for high cell density development under low CO₂ concentrations [69].

Polyvinylidene fluoride (PVDF) has gained significant attention in various applications due to its exceptional piezoelectric properties, thermal stability, and mechanical strength. PVDF is highly processable, has chemical resistance to a variety of substances, and has a high porosity [70]. The semi-crystalline polymer PVDF is well known for its high thermal stability and strong intermolecular forces [70]. Moreover, PVDF membranes possess a unique combination of hydrophobicity and microporosity, characteristics that are highly advantageous for gas–liquid mass transfer applications in PBRs [70,71].

In the context of CO₂ sparging, the morphology of the membrane, including pore size, porosity, and surface hydrophobicity, has directly influences bubble formation, gas dispersion, and CO₂ transfer efficiency [71,72]. Membranes with controlled microporous structures can

generate finer bubbles, thereby increasing the effective interfacial area and gas residence time, which enhances CO₂ dissolution and microalgal carbon fixation [71].

The morphology and performance of PVDF membranes are significantly influenced by the fabrication methods used to develop the membranes. Various fabrication techniques such as electrospinning, stretch etching and phase inversion are used to produce PVDF membranes [73]. Among these, phase inversion is commonly employed due to its ability to tailor membrane porosity and pore structure, which are critical parameters governing gas permeability and bubble characteristics [74,75]. The selection of PVDF membrane fabrication method and operating parameters must be optimized to balance structural stability and CO₂ mass transfer performance, as membrane morphology ultimately determines gas dispersion behavior, interfacial area generation, and overall microalgal productivity in the PBR [69].

4.3. Mixing

One of the important variables that limit the growth of microalgae is the lack of nutrient distribution in the medium, which is indicated by the limited mass transfer from gaseous to liquid phases owing to the poor solubility of gas in the medium [76]. In addition, as cells need to be able to capture enough light in the light zones, the coexistence of dark and light zone frequencies within a PBR should also be considered to ensure effective development [18]. The cells must not stay in the dark zones for too long to experience photoinhibition, making adequate lighting essential to avoid extreme photosaturation [14,77]. As a result, optimal mixing and effective mixing times are developed to optimise the distribution and frequency of contact in the light and dark cycles while simultaneously eliminating O₂ inhibition of photosynthetic processes [59]. Furthermore, mixing prevents cell sedimentation and cell growth on the reactor walls [66], which may result in biofilm formation.

Xu et al. [6] proposed the integration of a helical baffle and central hollow tube located in the gassing unit of a horizontal tubular PBR as a simple strategy to improve bubble behaviour and mixing performance. This design has been proven to increase the mass transfer coefficient while reducing the mixing time, shortening the bubble generation time, decreasing the bubble generation diameter, and enhancing the overall microalgal growth by 40.8% [6]. Similarly, Xia et al. [78] developed a flat-plate PBR with an inner perforated arc baffle, which promoted periodic CO₂ storage and release by extending bubble retention duration. Meanwhile, Zhang et al. [79] used a static mixer in the horizontal tubes to increase mixing performance in the tubular PBR by greatly increasing the inner swirl intensity. However, the use of static mixers resulted in high energy consumption and increased fabrication costs due to mixer installation throughout the entire tube length [66], limiting its suitability for large-scale commercial applications.

Although it is critical to optimise culture mixing, it is also necessary to consider shear stress, which is caused by excessive mixing and reduces PBR productivity [32]. Additionally, reduced mixing intensity on the upper surface of the baffle may facilitate cell sedimentation and biofilm formation, which potentially compromise PBR performance. This observation highlights the importance of evaluating flow uniformity and hydrodynamic distribution in the implementation of baffle-assisted mixing strategies in PBR systems. Incorporating computational fluid dynamics (CFD) analysis in future studies is recommended to identify and mitigate such limitations in flow distribution throughout PBRs [54].

A novel gas exchange method, such as membrane spargers, in combination with enhanced mixing mechanisms like helical baffles, can boost CO₂ utilization and mass transfer efficiency [6]. Membrane spargers provide precise CO₂ delivery, minimizing gas loss and enhancing mass transfer efficiency [80]. Alternatively, the integration of helical baffles generates a spiral-ascending flow pattern that extends gas–liquid contact, increases mixing intensity, and guarantees uniform nutrient distribution [6]. The combination of both of these innovations could overcome significant challenges in tubular PBRs by enhancing CO₂

dissolution, promoting efficient photosynthesis, and increasing biomass productivity.

5. Research needs and perspectives

The fixation of CO₂ through microalgae cultivation in PBRs is a crucial aspect of sustainable development, especially in response to climate change. However, several critical research gaps must be addressed before tubular PBRs can be deployed at industrial scale. While tubular PBRs offer favourable surface-to-volume ratios, reduced contamination risk, and high productivity, future research must move beyond these well-established advantages toward quantitative performance assessment, system integration, and economic feasibility under large-scale operating conditions.

Optimizing the efficiency and sustainability of microalgae cultivation in large-scale production remains challenging due to the necessity for innovative technologies to address limitations in gas exchange, nutrient delivery, and environmental control [18]. Furthermore, the limited number of reported long-term industrial-scale studies make it difficult to comprehensively evaluate system reliability, fouling behaviour, material degradation, and maintenance requirements [29]. The scalability of novel gas-exchange approaches such as membrane spargers also requires validation beyond pilot scale [81]. While membrane-based sparging can improve mass transfer efficiency and reduce CO₂ losses, challenges such as membrane fouling, transmembrane pressure stability, and long-term durability remain insufficiently characterized [81]. Similarly, the hydrodynamic benefits of helical baffles must be evaluated under industrial flow rates, including their energy demand and impact on shear-sensitive strains [41,82,83].

Future research should also incorporate techno-economic analysis (TEA) and life-cycle assessment (LCA) to evaluate the feasibility of tubular PBR deployment. The high capital cost of transparent reactor materials, circulation pumps, and instrumentation represents a major component of system economics, while operational expenditures are strongly influenced by energy consumption and CO₂ supply [84,85]. Integrating improved mixing mechanisms, adaptive lighting, or in-situ harvesting must therefore be evaluated, not only for technical performance but also for economic return and environmental impact [85]. Standardized TEA and LCA frameworks would enable consistent comparison across different PBR designs and cultivation strategies.

Key strategies for an ideal microalgae cultivation system include the adjustment of pH, temperature, light intensity, and effective nutrient transfer through gas-liquid interactions, specifically tailored to the needs of targeted strains. Additionally, research should focus on adaptive light sources, straightforward operational procedures, and the economic aspects of manufacturing and production costs. Furthermore, the integration of real-time monitoring systems with sensors and automated control units to track and adjust key parameters ensures optimal cultivation conditions, facilitating the development of scalable, efficient, and sustainable PBR systems.

6. Conclusion

This study emphasizes the importance of optimizing the design and operation of tubular PBRs for microalgae cultivation, which offer an appealing approach for CO₂ fixation. The design characteristics of tubular PBRs, including tube geometry, diameter, length, and material fabrication, significantly influence productivity and scalability. The selection of optimal light source is crucial for enhancing photosynthetic activity and biomass production. Effective mass transfer, facilitated by well-designed aeration and mixing systems, ensures an adequate supply of nutrients and the removal of metabolic by-products. Efficient mixing techniques prevent sedimentation and ensure consistent nutrient distribution throughout the PBR. Reactor geometry, flow regime, and medium characteristics must be carefully considered to maximize carbon fixation and microalgal biomass production while minimizing

energy consumption and expenses. Overall, a well-designed tubular PBR with optimised hydrodynamics has the potential to significantly contribute to the sustainable production of biomass and other valuable bioproducts using microalgae. This review provides valuable insights into the factors to be considered in the design process of tubular PBRs for CO₂ fixation through microalgae cultivation without extensively discussing hydrodynamics. Future research in this area should focus on the development of advanced computational models for simulating hydrodynamic behaviour in PBRs and experimentally validating these models to improve the design and operation of these systems.

CRediT authorship contribution statement

Nadia Syauqi Syahid Mohammed: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Farah B. Ahmad:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization, Formal analysis. **Azlin Suhaida Azmi:** Validation, Supervision, Funding acquisition. **Noor Illi Mohamad Puad:** Validation, Supervision, Writing – review & editing. **Maziati Akmal Mohd Hatta:** Writing – review & editing, Validation, Supervision. **Syarifah Nor Faizah Syed Abdul Rahman:** Resources, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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