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Improving biomass yield in bubble column reactors: A review on cultivation, treatment, and applications of microalgae

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ABSTRACT

In the 21st century, the world faces growing environmental and energy challenges, including rising carbon dioxide emissions (exceeding 420 parts per million), water pollution from excess nutrients (nitrogen and phosphorus), causing ecological imbalance, and a 45–50% increase in global energy demand by 2050. Microalgae offer a comprehensive solution thanks to their high photosynthetic efficiency (8–10%), high productivity (50–70 g/m²/day), and ability to produce valuable compounds such as lipids, proteins, and pigments. Bubble column reactors (BCRs) are considered the most attractive option for industrial applications due to their low energy consumption (0.2–2.0 kW/m³ compared to 1–15 kW/m³ for mechanical systems), low shear stress (less than 5 Pa), and a volumetric gas transfer coefficient ranging from 0.01–0.035/s, in addition to absence of mechanical stress, simple design, and high gas transfer efficiency. This research reviews strategies for improving productivity, such as optimizing lighting, gas flow, and the use of wastewater as a nutrient source, as well as incorporating packing media that increase the surface area by up to 56%. It also covers wastewater treatment applications (removal of nitrogen, phosphorus, and heavy metals), carbon dioxide capture from industrial gases, and the production of biofuels, animal feed, fertilizers, and high-value dyes. Despite the progress made, challenges remain regarding harvesting efficiency, light distribution at large scales, and long-term stability. The research concludes that bubble column reactors represent a promising path toward a low-carbon circular bioeconomy, particularly when combined with advanced automation and process control.

Keywords: BCRs, CO_2, treatment applications, optimal growth, nutrient, biomass.

INTRODUCTION

The 21st century presents humanity with unprecedented environmental and energy problems. From a global perspective, these problems threaten the sustainable development of the world as well as ecological balance. Human emission of CO_2 is now at the crisis point and pouring into the atmosphere around 36.4 billion tons every year, as shown in Figure 1, prompting rapid change in climate conditions with its catastrophic consequences, such as global heating up, severe weather patterns, rising sea levels, ecological destruction, and social disintegration (Harris and Roach, 2017) Atmospheric CO_2 concentrations now exceed 420 × 10^{-6} g·cm^{-3} and have risen >50% above preindustrial levels, with climate models projecting further rise annually form 2 × 10^{-6} to 3 × 10^{-6} g·cm^{-3}, wide-ranging mitigation efforts are not undertaken (Chen et al., 2026) At the same time, water pollution by industrial discharges, effluent from agricultural processing, urban storm drains, and inadequately treated municipal wastewater remains a global hazard to aquatic environments as well as to drinking water safety and public health (UNESCO, 2023; Glibert, 2020).

Excessive influx of nutrients, particularly nitrogen and phosphorus compounds, is the key cause of eutrophication in the receiving water bodies, resulting in poisonous algal blooms, acute oxygen depletion or hypoxia dead zones, and extensive loss of biodiversity, causing devastating effects on commercial fisheries (Wurtsbaugh et al., 2019). Modern wastewater treatment works (WwTW) struggle to meet strict discharge criteria, particularly to remove nutrients such as total nitrogen and phosphorus below 3–10 milligrams per litre and 0.1–1.0 milligrams per litre, respectively, or require advanced cost-efficient treatment technologies (Sutherland et al., 2020) Increasing these pressures further, global energy needs surge continuously in response to population expansion, industrialization rates rising swiftly and living standards which are also improving quickly, with demands projected to increase by a value of between 45–50% (from the year 2020 up until the year 2050) (WEO, 2021). This boom is happening when industrial society finds its main energy source, fossil fuels, to be increasingly depleted, and it becomes necessary to resort to more costly methods of extraction, such as environmentally disruptive unconventional sources, and resultant costs in air pollution, habitat degradation, and climate change are all becoming chronic (Khan et al., 2018; Fawzy et al., 2020).

These interrelated challenges, increasing carbon emissions, declining water quality, and security concerns related to energy, cannot be solved in isolation with single-purpose solutions, but instead necessitate creative integrated solutions that can address multiple sustainability objectives at once (Li and Zhang, 2023). Photosynthetic microorganisms, especially microalgae, present a unique opportunity for the development of integrated processes that can simultaneously address atmospheric carbon capture and storage, efficient recovery of waste nutrients from polluted water bodies, biological treatment of wastewater and sustainable production of renewable fuels and chemicals in a circular bioeconomy context (Yu et al., 2024) Microalgae are known to have high photosynthetic conversion efficiency up to 8–10% (i.e., solar energy transfer into biomass) as compared to only 1–2% for common agricultural crops due, among other reasons, to a lack of non-productive tissues, direct access to nutrients and minimal mutual shading and the well-designed light-harvesting complexes acquired during their evolution process (Mao et al., 2024; Miyamoto, 1997). High yields, in the range of 50–70 g m−2 day−1, have enabled theoretical annual yields of 20–100 t h^{-1} to be estimated, significantly greater than greenhouse-grown terrestrial energy crops (Khan et al., 2018). Aside from growing traits, the microalgae have the ability to produce various valuable substances such as lipids for biodiesel of 22–64.9% DW, proteins for feed of 20–70% DW, and high-value pigments with a price ranging from \$100 to \$7000/kg (Babu et al., 2022; Wong et al., 2025).

For practical microalgae cultivation from research laboratories to industrial scale, bubble column photobioreactors are the most attractive species, especially with high operation simplicity and good robustness (Chanquia et al., 2022; Uyar et al., 2024a). These upright cylindrical vessels utilize continual gas sparging from the base of the reactor to achieve liquid recirculation to avoid cell settling, high level gas/liquid mixing for CO_2 delivery in and O_2 removal from solution, and sufficient mixing to ensure the presence of cells across illuminated volumes without mechanical stirring and its inherent capital costs, maintenance requirements, and sterility risks(Banerjee et al., 2020; Uyar et al., 2024a). Bubble columns have attractive features of easy fabrication with few internal parts, low energy consumption (0.2–2.0 kW/m^3 versus 1–15 kW/m^3 for mechanically agitated systems) (Uyar et al., 2024a), mild mixing without harmful cell damage at shear stresses below 5 Pa (Banerjee et al., 2020; Michels et al., 2016), effective gas mass transfer of volumetric coefficients of 0.01–0.035/s for high rates of photosynthesis (Burns, 2014), and robust operation from laboratory vessels to industrial scale up to (80–281 L) (Khan et al., 2018).

This review is designed to systematically present the existing knowledge on microalgae cultivation within bubble column reactors, highlighting practical approaches for biomass productivity enhancement and product yield improvement, noting those that focus on process economy reaching commercial scale by addressing microalgae biological characteristics; reactor design and hydrodynamics; factors that influence productivity such as light distribution, carbon supply, and nutrient management; operational optimization strategies; environmental applications in wastewater treatment and carbon capture; challenges in

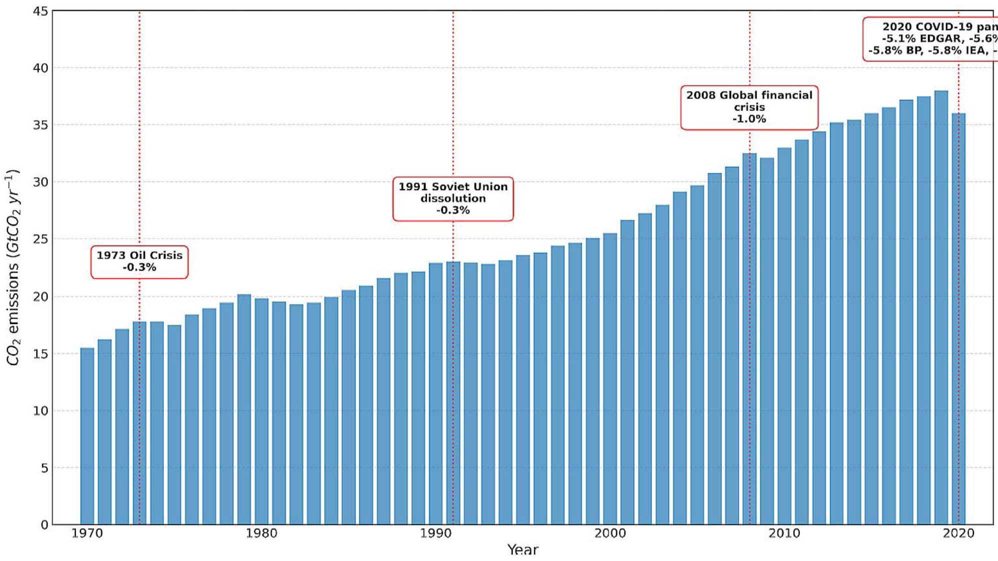

Figure 1. World CO_2 emissions and how they are affected by economic and geopolitical events (1 GtC = 1 billion metric tons of carbon equivalent)

harvesting and downstream processing of microalgal products; diverse product applications and market opportunities toward bio-based industries, as well as identifications of future research directions containing advanced monitoring systems, control methods for implementation in circular bioeconomy concept.

MICROALGAE: CHARACTERISTICS AND BIOMASS POTENTIAL

Classification and frequently-used species

Microalgae are a highly diverse polyphyletic group of photosynthetic microorganisms, belonging to several taxonomic divisions such as Chlorophyta (green algae), Cyanophyta (cyanobacteria), Bacillariophyta (diatoms), and Rhodophyta (red algae), among others, which show marked morphological, physiological, and biochemical differences in terms of biotechnological potential for different uses (Khan et al., 2018). An estimated of nearly 800,000 microalgae species live in a wide variety of aquatic ecosystems around the world, but only a few have been thoroughly described and have met the requirements for international trading under standardized conditions (Fernandes and Cordeiro, 2021). The properties of some commonly-utilized microalgae species based on their division, protein and lipid contents, CO_2 stress response, and major applications are summarized in Table 1.

Growth requirements

Effective cultivation of microalgae requires control of multiple interacting environmental parameters, which all have an influence on photosynthesis, cellular metabolism, and productivity (Aditya et al., 2023). Light is the primary energy source for photosynthetic electron transport and ATP production, and its appropriate intensity varies around 100–400 μmol photons $m^{-2}.s^{-1}$ for most commercially cultivated species in terms of maximum productivity; beyond such optimal ranges, excessive light causes photoinhibition through reactive oxygen species accumulation and photo-oxidative damage to the reaction centers of photosystems (Gao et al., 2024). In dense cultures, light is limiting (severely so in very dense conditions) due to self-shading whereby the cells on the outer layers absorb most photons coming through, creating steep light gradients with exponential attenuation, which snub any volumetric productive zones (Saccardo et al., 2022).

Light-providing technologies

Microalgal cultivation relies on two major light-providing strategies: using natural sunlight and artificial illumination systems. Natural sunlight is the optimum low-cost energy source for open pond and large outdoor photobioreactor systems, but also suffers from inherent diurnal and seasonal variability, geographical latitude limits to growth, weather dependence that controls process

Table 1. The characteristics of prominent microalgae: Taxonomy, nutrition profiling, and industrial use

Microalgae species	Division	Protein content	Lipid content	Characteristics	CO_2 tolerance	Application	Reference
Chlorella vulgaris & *C. sorokiniana*	Chlorophyta	45.4–57.2% of biomass	5-15 %commercial biomass	Wide environmental adaptability	20–30%	Wastewater purification	(Barouh et al., 2024; Bulynina et al., 2023; D. Li et al., 2015; Assim and Buthena, 2025; Talha et al., 2025)
Scenedesmus obliquus & *S. dimorphus*	Chlorophyta	35–58% dry weight	33.1–45.1% (under N-limitation)	High growth rate of all essential amino acids	13.8± 1.5%	Nutrient removal from municipal & agricultural wastewater	(Basu et al., 2013; J. Liu et al., 2021; Silva et al., 2021; Trivedi et al., 2022; Vidyashankar et al., 2013)
Chlamydomonas reinhardtii	Chlorophyta	46.9% dry weight; FAO/WHO score 0.9–1.9	4.9% dry weight; 80% unsaturated; ~48% Omega-3	Complete protein; research model organism	17.4%	Nutraceuticals & food supplements	(Darwish et al., 2020; Mortensen and Gislerød, 2014; Salomé and Merchant, 2019)
Arthrospira platensis & *A.maxima* (Spirulina)	Cyanophyta	60–70%; all essential amino acids	30.23 %dry biomass cultivated	Vitamin B12; bio-available iron; phycocyanin (anti-inflammatory & antioxidant)	1–9%	Commercial food & health products (>10,000 metric tons/ year)	(Chunzhuk et al., 2023; Hena et al., 2018; L. Pereira et al., 2025; Thevarajah et al., 2022)

stability, and year-round productivity (Penloglou et al., 2024a). Artificial light systems circumvent these shortcomings by providing continuous, controllable, and spectrally-definable lighting regardless of outside conditions. Currently, despite the wide range of artificial light sources, the most preferred technology for indoor photobioreactor systems is still light-emitting diodes (LEDs) due to their excellent energy efficiency, long lifetime span, minimal heat emission, and controlled spectral tuning (Wang et al., 2014).

LEDs are programmable, emitting selectively at wavelengths where chlorophyll a (420 nm and 660 nm) and accessory pigments absorb to optimize photosynthesis while reducing the wastage of energy from non-absorbed wavelengths(Maltsev et al., 2021). Red LEDs (630–680 nm) are mainly responsible for photosynthetic carbon fixation, while blue LEDs (420–470 nm) control photomorphogenic responses, along with pigment production and enzyme activity. Single-wavelength illumination had lower biomass productivity and biochemical composition compared with combined red-blue LED regimes, which have consistently outperformed(Marchese et al., 2025; Schulze et al., 2014). An important advancement in the use of LED-based illumination is the integration of flashing or pulsed light regimes, making use of the so-called "flashing light effect." The capacity of the photosynthetic machinery to use accumulated photochemical energy during dark intervals, while at a given frequency, mitigates a decrease in net carbon fixation rates (Wang et al., 2014). Such a decoupling of light absorption from photochemical utilization can significantly increase photosynthetic efficiency over values offered by continuous illumination at similar average intensities. Recently, it has been proven that high-intensity illumination cycling with white light can induce better growth and yield of fatty acid biosynthesis and pigments in more than one microalgal species (Shankar et al., 2025). The development of reflective baffles and top diffusing glass was proposed, and internally illuminated photobioreactor configurations have partly addressed the self-shading restrictions that microbiota in dense microalgal cultures experience, by more uniformly distributing light throughout the reactor volume and minimizing the steep exponential light gradients that generate non-productive dark zones within the culture interior (Liang et al., 2025).

CO_2 and nutrient requirements

CO_2 as a major source of inorganic carbon for photoautotrophic growth, yet air atmosphere being comprised only 0.04% CO_2 is typically not able to support high density intensive cultivation and supplementation with CO_2 enriched gas mixtures (generally 2–15%), We have found that this approach could substantially relieve the inorganic carbon limitation, which has been extensively shown to greatly increase biomass productivity in comparison with cultivation systems when only supplied with atmospheric air (Chiu et al., 2009; Subashchandrabose, 2019). For most microalgae species, optimal growth is observed at 2–10% CO_2, while some robust strains can tolerate 15–40%, which allows them to use undiluted industrial flue gas (from coal, natural gas, or cement plants) (Liu et al., 2013). Nitrogen is a critical macronutrient needed for the synthesis of proteins, nucleic acids, and chlorophyll (from 1 to 14% dry biomass weight), whose availability strongly affects biomass composition (Mujtaba et al., 2012; Maltsev et al., 2023). Phosphorus, necessary for nucleic acid, phospholipid, and ATP production, occurs at a concentration of 0.03 to 3% dry weight as orthophosphate at levels in the range of 1.96–124 milligrams per litre (Bossa et al., 2024).

Biomass composition and value

Compositional plasticity in the microalgae biomass is significantly high, with a relative abundance of major biochemical fractions that varies widely across species and responds strongly to growing conditions (Van Wychen et al., 2021). These lipids include neutral storage triacylglycerols amenable to biodiesel production, and polar structural lipids critical for membrane stability (Mallick et al., 2016; Maltsev et al., 2023; Morales et al., 2021). Apart from biofuels, microalgal lipids are an important source of omega-3 long-chain polyunsaturated fatty acids such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which sell between \$80–160 per kg for human food, infant formulae, and applications in the pharmaceutical industry (Adarme-Vega et al., 2012; Schade and Meier, 2021) Protein contents vary from 6–40% in common species to 50–70% in high-protein species like Spirulina, with amino acid profiles similar to or better than their traditional plant counterparts, used for human nutritional supplements, animal feedstocks for aquaculture and livestock industry, as well as specialised products such as enzymatic proteins and fluorescent phycobiliproteins(Saeed et al., 2025). Varieties of high-value pigments, which command covalent market prices, are produced naturally in microalgae for example B-carotene from *Dunaliella salina* served as natural provitamin A and antioxidant (US\$300–3000/kg), astaxanthin from *Haematococcus pluvialis* showed potent antioxidant property for aquaculture and nutraceuticals (US\$2500/kg) and phycobiliproteins including phycocyanin used as a natural blue food colorant and fluorescent biochemical labels (Matos, 2017).

Photobioreactors with a bubble column have been widely studied for cultivating microalgae in different applications, including high-value bioactive compound production, potential biofuels generation, CO_2 fixation, and wastewater treatment. Summary of significant previous works to highlight the versatile configurations of bubble columns for different microalgal species and cultivation targets in Table 2. Recently, the vast bulk of studies have emphasized whether or not to realize high-high-quality production. Mohamadnia et al. (2022) had a systematic investigation on the production of fucoxanthin from the marine microalga *Tisochrysis lutea* showed biomass productivity of 0.284 $g \cdot L^{-1} \cdot day^{-1}$, highlighting the criticality of further mass transfer coefficient optimization. Like the study of Macías-de la Rosa et al. (2023) obtained secondary metabolites production in *Heterosigma akashiwo* and showed that changing operational strategies can increase their synthesis, nevertheless, at a lower biomass productivity of 0.02 $g \cdot L^{-1} \cdot day^{-1}$. Another major research direction is biofuel applications. Pourbakhtiar et al. (2022) developed a two-step growth system for lipid synthesis from *Chlorella vulgaris* with productivity of 0.143 $g \cdot L^{-1} \cdot day^{-1}$. applicable to biodiesel production.

Bubble column photobioreactors have demonstrated significant potential for enhancing microalgal biomass production and CO_2 fixation through improved gas–liquid mass transfer and light distribution. Several studies have shown that reactor hydrodynamics play a crucial role in determining cultivation performance. Enhanced mixing and light dispersion strategies have resulted in biomass productivities ranging from 0.21 to 0.52 $g \cdot L^{-1} \cdot day^{-1}$, with higher values generally associated with improved circulation patterns and more uniform light availability (Naira et al., 2020; Saxena et al., 2022)

Similarly, optimization of gas–liquid interactions has been widely recognized as a key factor in improving CO_2 utilization efficiency. Modifications in aeration systems, bubble dynamics, and bubble size distribution have been reported to enhance mass transfer rates, leading to increased biomass productivity and carbon fixation performance. In particular, smaller bubble sizes and advanced aeration designs improve the gas–liquid contact area and CO_2 availability for microalgal growth (Barahoei et al., 2020; Zhao et al., 2023) (Zhao et al., 2023;).

Recent developments have further focused on intensifying mixing through innovative flow patterns. For example, the introduction of spiral flow vortices has significantly enhanced gas–liquid contact efficiency, resulting in high biomass accumulation and improved CO_2 fixation performance. These findings collectively indicate that hydrodynamic optimization, including mixing enhancement, bubble management, and aeration design, remains one of the most effective approaches for improving the productivity and environmental performance of bubble column photobioreactors (Kumar et al., 2025).

The application of microalgae-based bioreactors for wastewater treatment has gained increasing attention due to their ability to simultaneously remove pollutants and generate valuable biomass. Early studies demonstrated the effectiveness of microalgal cultivation in bubble-column photobioreactors for industrial effluent treatment, achieving significant nutrient removal together with biomass productivities of up to 0.224 $g \cdot L^{-1} \cdot day^{-1}$ (Marchão et al., 2016).

More recently, research has focused on integrating immobilized microalgal systems and packed bioreactor configurations to enhance pollutant removal efficiency and operational stability. Immobilization techniques have been shown to improve biosorbent mechanical strength, facilitate biomass recovery, prevent washout, and maintain high adsorption capacities. These advantages have enabled efficient removal of a wide range of contaminants, including synthetic dyes and heavy metals from industrial wastewater streams (Alsarji et al., 2024, 2025).

Several studies have reported that microalgal biosorbents exhibit considerable potential as low-cost and environmentally friendly packing materials in airlift and bubble-column bioreactors. Enhanced pollutant removal performance has been attributed to improved mass transfer characteristics and increased contact between contaminants and immobilized biomass. In particular, successful applications have been demonstrated for methylene blue, mercury (Hg^{2+}), and Orange G dye removal, highlighting the versatility of microalgal biosorption systems for treating different classes of industrial pollutants (Aljuboori et al., 2025; Alsarji et al., 2024, 2025).

Furthermore, process optimization approaches such as response surface methodology and central composite design have been employed to identify optimal operating conditions and evaluate interactions among process variables. These studies demonstrated that optimized operating parameters, as well as the use of mixed algal consortia, can significantly improve pollutant removal efficiencies while reducing operational costs. Collectively, these findings indicate that immobilized microalgae integrated with airlift and bubble-column bioreactors represent a promising and sustainable technology for industrial wastewater remediation and resource recovery.

As summarized in Table 2, biomass productivity from all these studies ranges from 0.02 to 0.521 g, in a bubble column photobioreactor. Depending on the species used, cultivation objective and operation strategies followed, this is the value of L^{-1}.day. Such differences highlight the importance of optimizing the reactor design parameters and hydrodynamic conditions and aeration strategies for specific applications. However, there is still a considerable amount of research work to be done in relation to the use of packing media as an internals for enhancing the mass transfer efficiency and biomass production rate in bubble column photobioreactors.

BUBBLE COLUMN REACTORS FOR MICROALGAE CULTIVATION

Reactor design and working principle

Bubble column reactors specifically belong to the multiphase contactor category of equipment, where a gas is bubbled through the use of immersed sparging devices. BCRs constitute a real three-phase system with different gaseous bubbles delimited in space and from each other on a macroscopic scale. The rudimentary system design involves vertical cylinders, which are made of optically transparent material for penetration of the photosynthetic light. In particular, in the core region, rising gas bubbles produce an arranged flow that tends to rise and circulate while producing downwelling right next to the walls of the vessel, making up a self-sustained mixing pattern without mechanical stirring (Haydar et al., 2023; Thobie et al., 2017). BCR hydrodynamic behavior is inherently correlated to superficial gas velocity (UG) and operates within transition regimes from homogeneous bubble to heterogeneous churn-turbulent flow at maximum critical values of UG. Superficial gas velocity is the main hydrodynamic driver, as shown in

Table 2. Previous studies bubble column photobioreactor

Microalgal species	Objective	Biomass	Reference
Tisochrysis lutea	Fucoxathin production	0.284 $g \cdot L^{-1} \cdot day^{-1}$	(Mohamadnia et al., 2022)
Tisochrysis lutea	Lipid production	0.143 $g \cdot L^{-1} \cdot day^{-1}$	(Pourbakhtiar et al., 2022)
Arthrospira platensis	Carbohydrate production	0.21 $g \cdot L^{-1} \cdot day^{-1}$	(Saxena et al., 2022)
Heterosigma akashiwo	Bioactive production	0.02 $g \cdot L^{-1} \cdot day^{-1}$	(Macías-de la Rosa et al., 2023)
Chlorella pyrenoidosa	CO_2 fixation	0.24 $g \cdot L^{-1} \cdot day^{-1}$	(Zhao et al., 2023)
Scenedesmus obliquus	Wastewater treatment	0.224 $g \cdot L^{-1} \cdot day^{-1}$	(Maria et al., 2016)
Chlorella sp.	Biodiesel production	0.521 $g \cdot L^{-1} \cdot day^{-1}$	(Naira et al., 2020)
Chlorella vulgaris	CO_2 fixation	0.337 $g \cdot L^{-1} \cdot day^{-1}$	(Barahoei et al., 2020)
Limnospira fusiformis (*Spirulina platensis*)	CO_2 fixation	2.81 $g \cdot L^{-1}$ (after 120 h)	(Kumar et al., 2025)
Coelastrella sp.	Methylene blue removal	-	(Al-Sarji et al., 2025)
Coelastrella sp.	Hg(II) biosorption	-	(Alsarji et al., 2024)
Mixed algae biomass	Cationic dye decolourization	-	(Alsarji et al., 2025)
Ferric-modified algae	Orange G dye removal	-	(Aljuboori et al., 2025)

Figure 2, combined linearities of shear and the volumetric gas–liquid mass transfer coefficient (kLa) balance each other strongly at the operational line. Mahmood et al. (2023) surveyed the effect of internals on flow regimes transition in both bubble columns and bubble columns with internal structures, concluding that insulating components drastically change transition points between different kinds of flows, plus change interactions between bubbles. Superficial gas velocity significantly influences interfacial mass transfer properties, including the gas holdup (εG), that is, the volume fraction occupied by the dispersed phase of gas (Haydar et al., 2023).

The volumetric gas–liquid mass transfer coefficient (kLa) is strongly dependent on both aeration strategy and gas–liquid hydrodynamics in bubble columns. Thobie et al. (2017) studied the characteristics of hydrodynamics and gas-liquid mass transfer in thin-gap microalgae bubble column systems, indicating that such micro-porous sparging systems promote small gas bubbles generating, which can effectively boost the interfacial area of the mass transfer process, accelerating kLa. Bubble Control, as shown in Figure 2, is the strategy of fine bubble control where design changes the volumetric mass transfer coefficient, kLa, is influenced by gas velocity UG, through power-law correlations (kLa ∝ UGn). Thus, under optimal conditions, bubble column reactors can be realised to have very high gas–liquid mass transfer efficiencies (Uyar et al., 2024a).

Almani et al. (2023) studied global characterization of hydrodynamics and gas-liquid mass transfer in thin-gap bubble columns with Newtonian or non-Newtonian liquid phases. A conceptual model of the mediating biological effects of algae rheology, with altering rheometry while modifying bubble dynamics, is illustrated in Figure 2. Haydar et al. (2023) studied gas holdup in thin-gap bubble columns, showing predictable relations for εG as a function of superficial gas velocity and scaling. Gas holdup (εG) is plotted as volume fraction of gas in the reactor in Figure 2. In contrast, in heterogeneous flow regimes with high gas holdup, bubbles occur coalescing, and the specific interfacial area decreases with increasing volumetric fraction of gas. Flow regime is a qualitative dependent variable and changes its value categorically based on superficial gas velocity.

Mahmood et al. (2023) examined the features of every regime. By looking at the central comparison in Figure 2, while an empty column (the simplified baseline) shows a homogeneous regime already below and may be even at low to moderate gas velocities, advanced columns containing internal packing show flow regime modification. Homogeneous bubble flow, with its nearly uniform size distribution of bubbles, maintains a steady rise velocity and circulates in predictable patterns. The liquid flow field shows well-ordered upward flow in the center of the column, and downward flow at the walls, forming toroidal circulation cells. Such a wind regime with a low energy dissipation rate is favorable for the shear-sensitive microalgae culture. With a wide bubble size distribution composition and strong coalescence, chaotic liquid motion occurs at higher gas velocities. This regime includes distinct bubble populations for particular rise velocities producing rigorous wake regions, interrupting organized circulation. With energy dissipation rates increasing substantially, with potential for shear stresses that exceed the damage threshold of shear-sensitive microalgae.

Mahmood et al. (2023) pointed out that the presence of internal structures, such as packing media, fundamentally alters hydrodynamics, compared to empty columns. Packing impacts in terms of regime transition delay to higher UG, prevention of coalescence by means of bubble breakage, changing features on εG versus UG relationships, localized high-shear zones created and maintained for radial mixing leading to controlled gas-liquid contact are shown in Figure 2. New surfaces, where the large bubbles hit a wall and burst, provide bumps in flow path and take energy away from hemegeneous to heterogenous flow regime transitions at significantly higher gas velocities, and this is what internals do. Such mechanical bubble breakage leads to smaller average bubble sizes for higher gas velocities, and thus prolongs the homogeneous flow regime operating window. The distinction of packed column behaviour from empty column behaviour due to tortuous flow paths through the packing leading to reduced bubble rise velocity, is often addressed by defining modified gas holdup. Packing breaks up the well-organized toroidal circulating cells and leads to convoluted, three-dimensional flow fields with internal recirculation zones, exaggerated radial mixing, and axial dispersion distributions that are distinct from those predicted by an external stirring unit. Packing generates zones of concentrated shear stress in the vicinity of solid surfaces but disperses overall mild shear into the bulk liquid. But the hit depends largely on the internal structure geometry, packing density, and material properties.

Advantages of bubble column reactors

An ideal microalgae culture process for photosynthesis is a bubble column reactor (BCR). End-on, these reactors cover much lower hydrodynamic shear forces than the conventionally mechanically stirred vessels, which is essential to preserve intact (and still functioning) cells. Quantitatively, it was found that energy dissipation rates in BCRs are much lower than in mechanically stirred tanks, which is beneficial for the cultivation of shear-sensitive diatoms and other fragile microalgae (López-Rosales et al., 2019). Preliminary comparative studies have shown that BCR achieves a better volumetric mass transfer coefficient due to optimal geometry and distributor, with homogenization of less than 10 seconds (Uyar et al., 2024b). In addition, BCRs have been shown to be highly efficient for gas-liquid mass transfer via large interfacial surface areas formed by the dispersed bubble cluster. In such systems,

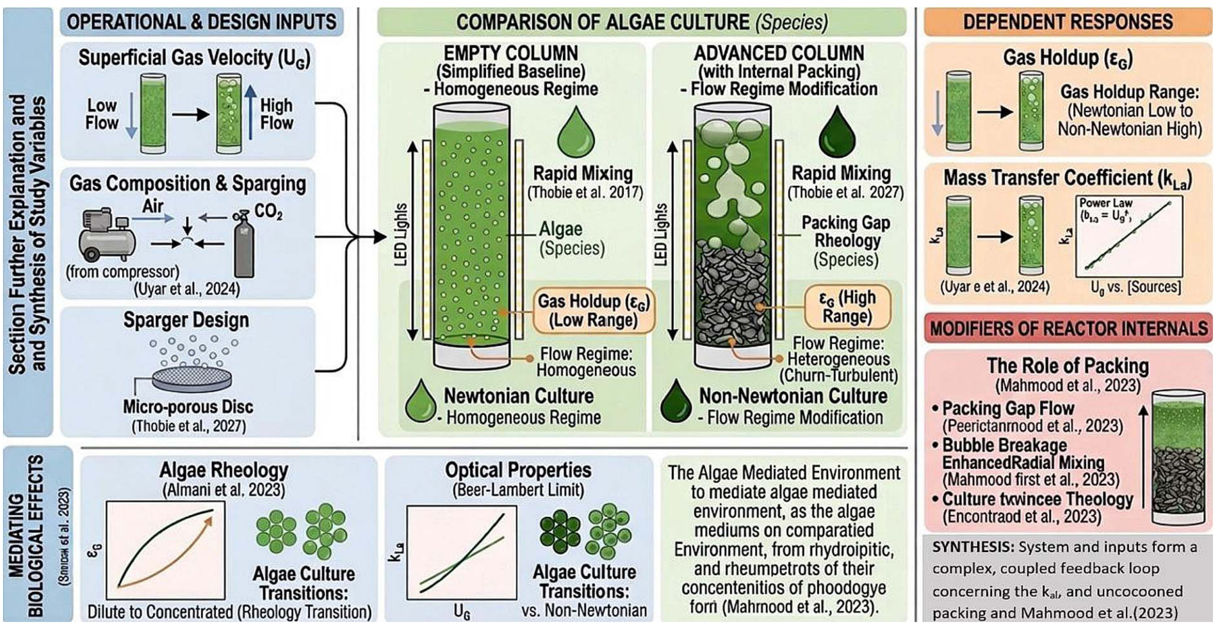

Figure 2. Systematic study of variables in a bubble column photobioreactor system

CO_2 transfer efficiencies rates exceeding 80% in appropriately engineered BCRs with appropriate hydrodynamic conditions, whilst avoiding levels of harmful O_2 that exceed the inhibition threshold of photosynthesis (Manjrekar et al., 2017; Sun et al., 2025a). Experimental correlations indicate that gas holdup and (kLa) rose linearly with superficial gas velocity, thus directly enhancing culture volumetric productivity (Uyar et al., 2024b).

The architectural simplicity of BCRs with the absence of mechanical agitation units also provides a major techno-economic benefit in terms of lowered CAPEX (Capital Expenditure) and minimized maintenance requirements. Net power requirements were limited to gas compression, with volumetric power consumptions of 29.4–49.1 W m^{-3} (0.029–0.049 kW m^{-3}) depending on aeration rate, which still represents substantial energy economy over mechanically agitated options. As far as the mechanical agitation of the impellers is concerned, additional power consumption of 0.65–1.30 W m^{-3} must be spent by the agitated tank reactors (Uyar et al., 2024b).

Comparison between types of photobioreactors

Airlift photobioreactor has an internal draft tube which divides into an explicit riser and downcomer compartments, thus promoting more predictable-flow patterns (Guieysse et al., 2011). Nevertheless, comparative performance evaluations reveal the species and status-specific outcomes. In a recent biomass production experiment with *C. sorokiniana*, BCR reached maximum biomass productivity of 0.097 gdw L^{-1} d^{-1} in comparison to 0.072 gdw L^{-1} d^{-1} in airlift reactors operated under the exact same conditions and therefore 26% lower than in airlift constructions (Uyar et al., 2024b).

In the case of airlift configurations, this is at the expense of higher construction complexity because of draft tube placement, but both types operate at similar power consumption levels (29.4–49.1 W m^{-3}air) for aeration factors tested (Uyar et al., 2024b). Tubular photobioreactors, with a high surface-to-volume ratio to capture light, have been reported to show higher volumetric productivities, typically in the range from 0.05 to 1.9 g L^{-1} d^{-1}. Such long tubular geometries, however, may experience some axial gradients for dissolved oxygen, and they usually involve large pumping/circulating energy needs in comparison with simpler flows (Maroneze and Queiroz, 2018). Flat-plate photobioreactors should provide optimal photon capture efficiencies at minimal optical path lengths, with productivities ranging from 0.16 to 4.3 g L^{-1} d^{-1} (Benner et al., 2022; Maroneze and Queiroz, 2018). Figure 3 shows the Different types of photobioreactors and their biomass productivity.

EFFECT OF VARIABLES ON BIOMASS PRODUCTION IN BUBBLE COLUMN REACTORS

A number of environmental and operating factors govern the biomass productivity in bubble column reactors. Uyar et al. (2024a) designe a system to compare parameters for bubble column, airlift, and stirred tank photobioreactors for microalgae production have been compared by indicating that operational variables can considerably influence growth performance at several aeration rates (0.9–1.2–1.5 L/min); results from their work demonstrated an increase in gas holdup and volumetric mass transfer coefficient with an increase in air flow rate. The Bubble column reactor had the largest volumetric mass transfer coefficients with optimal sparger geometry and gas distribution in the case of the three reactors studied. Low mixing times (< 10 s) in all conditions indicated good photo-bioreactor homogenization. In fact, even at moderate biomass density,

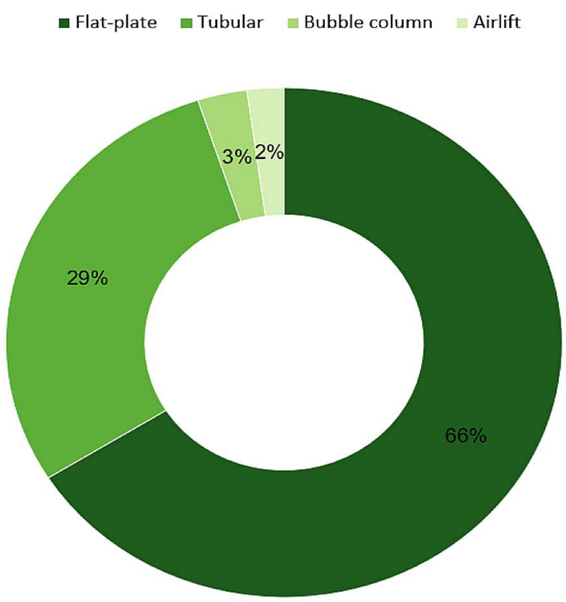

Figure 3. Different types of photobioreactors for biomass productivity

they can give rise to substantial rheological and optical alterations since microalgae sometimes only account for a small fraction of the reactor volume, causing non-Newtonian shear-thinning characteristics. These factors are worth to second guess those important relative to cultivation condition control as well as biomass maximization. After this, essential parameters impacting microalgae growth performance in bubble column systems are reviewed (Benner et al., 2022).

Light distribution and intensity

Light is vital and the most important remaining environmental factor determining growth and productivity of photoautotrophic microalgae. Bubble column geometry leads to complex patterns of light distribution in which incident photons travel through the culture suspension to reach cells dispersed throughout the reactor volume (Saccardo et al., 2022; Wang et al., 2014). Various pigments absorb solar spectrums at a particular wavelength giving them the colour as illustrated in Table 3 (Carvalho et al., 2011; Mauseth, 2014).

Light attenuation within bubble column photobioreactors is commonly described by the Beer–Lambert law, which states that light intensity decreases exponentially with increasing optical path length and biomass concentration. According to this principle, the transmitted light intensity (I) is related to the incident intensity (I_0) by the expression $I = I_0e^{-kcl}$, where k is the extinction coefficient, c is the biomass concentration, and l is the optical path length. Consequently, increasing cell density progressively reduces photon availability in the inner regions of the reactor, creating light-limited zones that restrict photosynthetic activity (Hu, 2013; Zittelli et al., 2013).

Optimal light intensity range: Shankar et al. (2025) studied flashing white light and came to the conclusion that the light intensity maximum for microalgal photosynthesis is usually within 100–400 µmol photons m^{-2} s^{-1}, but varies greatly between species. This range is a trade-off between having enough photon flux for photosynthesis and not inducing photoinhibition.

Light compensation point: Mahmood et al. (2023) Flow regimes in bubble columns have further been reviewed by noting that the light compensation point separating net photosynthetic carbon fixation from respiratory carbon loss may differ among species, but has been measured as low as 0.3–5 µmol photons m^{-2} s^{-1} in marine habitats with minimum theoretical requirements of 0.01 µmol photons m^{-2} s^{-1}. However, Shankar et al. (2025) indicated that most microalgae need much greater light intensity for optimal growth (26–400 µmol photons m^{-2} s^{-1}).

Photoinhibition threshold: Photoinhibition threshold varies dramatically across species. Wang et al. (2014) and Shankar et al., (2025) work on *Phaeodactylum tricornutum, Chlorella vulgaris, and Scenedesmus obliquus* were also reported to be highly inhibited above 150 µmol photons m^{-2} s^{-1} in comparison to other species, which experienced little or no inhibition up to around 1000 µmol photons m^{-2} s^{-1}. Photoinhibition is the result of photodamage to photosystem II reaction centers that outpaces cellular repair mechanisms.

Self-shading effects: Main disadvantages, such as self-shading, limit the biomass productivity in bubble column photobioreactors (BCPBRs). Gao et al. (2024) performed a screening of biofilm culturing systems with continuous illumination, demonstrating substantial effects of self-screening in thick biofilms on cell architecture and physiology. Saccardo et al. (2022) in ultra-thin steady state continuous photobioreactors showed that self-shading causes the optical density to grow linearly depending on the cell concentration for a particular range and reduces the penetration of light. This results in regions of light saturation for photosynthesis next to the walls of the reactor and dark (light-limited) zones inside the reactor generating extreme spatial heterogeneity in photosynthetic activity.

The optical path length is closely related to reactor diameter and represents a key design parameter in bubble column photobioreactors. Increasing reactor diameter extends the distance that photons must travel before reaching cells located near the reactor center, thereby intensifying light attenuation and self-shading effects. Although larger reactor diameters increase cultivation volume, they may reduce light utilization efficiency unless compensated by improved mixing, lower biomass concentrations, or enhanced illumination strategies. Therefore, an appropriate balance between reactor size and optical path length is essential for maximizing volumetric biomass productivity (Benner et al., 2022; Saccardo et al., 2022).

Dynamic light regimes - optimal approach: Su (2021) and El-Sheekh et al. (2024) showed further that dynamic light regimes due to mixing in bubble columns can relieve photoinhibition and photo-limitation through the “flashing light effect”.

Table 3. Summary of the most important pigments present in microalgae (Mauseth, 2014)

Pigment group	Color	Ranges of absorption bands (nm)	Pigments
Chlorophylls	Green	450–475 630–675	Chlorophyll a Chlorophyll b, c1, c2, d
Carotenoids	Yellow, orange	400–550	β-Carotene, α-Carotene, Lutei, Violaxanthin, Fucoxanthin
Phycobilins	Blue, red	500–650	Phycocyanin, Phycoerythirn Allophycocyanin

Shankar et al. (2025) Experimental evidence of enhanced growth and fatty acid accumulation in microalgae was provided by under high intensity illumination cycles with flashing white light. The light management solution is a combination of pulsed light, ideally with optimal frequencies of the light/dark cycles, to recuperate the photosynthetic machinery while preserving average rates of carbon fixation. This strategy provides higher photosynthetic activity than continuous illumination at the same average light intensity.

Recent advances have also introduced internal illumination systems, including optical fibers and LED light guides, to overcome the limitations of external lighting. These systems distribute light more uniformly throughout the culture volume, reducing dark zones and improving photon availability in dense cultures. Internal illumination has been shown to enhance photosynthetic efficiency and biomass productivity, particularly in large-diameter photobioreactors where external light penetration is limited. However, the higher capital cost, increased energy consumption, and additional maintenance requirements remain important challenges for their large-scale industrial application (Penloglou et al., 2024b; Wan Mahari et al., 2024).

Gas flow rate and CO_2 supply

Translational dynamics, which describes the gas flow behavior in bubble column reactors, is arguably one of the most important dynamic behaviors that can strongly modulate hydrodynamic mixing characteristics and gas–liquid mass transfer performance – two critical drivers for microalgal growth and biomass productivity. López-Rosales et al. (2019) studied the characterisation of a bubble column photobioreactor (PBR) for shear sensitive microalgae culture. Sparging systems configure the gas introduction point near to the bottom part of the column, generating bubbles with an ascending trajectory due to gravity and producing bubbling clouds that promote bulk liquid circulating patterns and mixing without mechanical agitation. Almani et al. (2023) studied the global characterization of hydrodynamics and gas-liquid mass transfer in thin-gap bubble columns. Strong dependence on operating conditions and fluid properties for gas holdup and flow regimes by Sun et al. (2025b) synthesized mechanistic insights for enhancing microalgal CO_2 fixation, in which the hydrodynamic behavior is dependent on operational parameters. Abdelkarim et al. (2025) focused on the evaluation of the following variables: physiological, biochemical, and morphological responses to biomass-specific photon supply rates, and the identification of the hydrodynamic variable, which controls the bubble column, as superficial gas velocity. Uyar et al., (2024a) compared specific growth rates and biomass productivities for different reactor types under aeration and determined that specific growth rates and biomass productivities of *Chlorella sorokiniana* are higher in bubble column reactors than in the airlift or stirred tank reactors. Benner et al. (2022) validated that the volumetric mass transfer coefficient and changes in gas flow rate had affected the hydrodynamics. Guieysse et al. (2011) provided an overview of airlift bioreactors, where they pointed out that hydrodynamic conditions for shear-sensitive dinoflagellate species were crucial. Michels et al. (2016) used tubular photobioreactors to demonstrate that even more relatively shear tolerant microalgal species can experience serious damage at very high levels of turbulence and shear stress.

A compromise between optimizing gas flow rates for mass transfer enhancement and keeping the shear stress below the species-specific threshold studied by Aditya et al. (2023). The importance of pH management in balancing CO_2 input with light intensity to maximize microalgae growth rate was studied by Sun et al. (2025b), while strategies to increase productivity through optimization of bioreactor operational strategies were also highlighted by Li et al. (2015) using *Chlorella* sp. enhanced high carbon dioxide tolerance, through adaptive laboratory evolution at growth-limiting, yet much elevated (exact concentrations not given) CO_2 concentrations above ambient air. Liu et al. (2013) shows the knowledge of their optimal CO_2 growth conditions is also vital for assessing their commercial viability, therefore high-throughput screening methods were developed using GasPak bags to prepare the strains. Optimal CO_2 supply strategies utilize evolved or naturally tolerant strains, implemented in conjunction with a carbonate-bicarbonate buffering system to maintain pH at optimal values (Table 4).

Nutrient availability

Adequate supply of essential nutrients is central to the growth and biomass accumulation in microalgae, being required under such conditions as photobioreactors. Truong et al. (2024) revisited nitrogen, a limiting factor that leads to fucoxanthin productivity. Liu et al. (2022) carried out biochemical and morphological changes experiments of *Chlorella vulgaris* under nitrogen stress conditions. The N/P ratio is one of the major factors regulating metabolic activity and growth performance (Abrha et al., 2025).

Nitrogen and phosphorus limitation

Nitrogen availability is a key factor governing microalgal metabolism and biomass composition. Under nutrient-replete conditions, microalgae allocate a substantial proportion of assimilated carbon to protein synthesis and cellular growth. In contrast, nitrogen limitation triggers metabolic reprogramming that suppresses protein synthesis and redirects carbon flux toward the accumulation of storage lipids. Consequently, lipid contents can increase significantly under nitrogen-starved conditions, often at the expense of growth rate. For example, lipid accumulation in *Chlorella vulgaris* increased from approximately 14–16% under nitrogen-sufficient conditions to around 30% of dry biomass following nitrogen deprivation, while optimized two-stage cultivation strategies have achieved lipid productivities as high as 45.1% in Scenedesmus obliquus (Abdelkarim et al., 2025; Abrha et al., 2025; T. Liu et al., 2022; Mujtaba et al., 2012; Trivedi et al., 2022).

Phosphorus availability also influences biomass composition and cellular metabolism. Microalgae are capable of luxury phosphorus uptake, storing excess phosphorus as intracellular polyphosphate granules when environmental concentrations are high. Although phosphorus deficiency can stimulate lipid accumulation, its effect is generally less pronounced than that of nitrogen limitation and is frequently accompanied by reduced biomass productivity (Bossa et al., 2024; Liu et al., 2022; Maltsev et al., 2023; Plouviez and Brown, 2024; Raj et al., 2025; Solovchenko, 2025).

Overall, a two-stage cultivation strategy that combines an initial nutrient-replete growth phase with a subsequent controlled nitrogen-limitation phase provides one of the most effective approaches for balancing biomass production and lipid accumulation. This strategy offers a superior compromise between volumetric productivity and lipid content compared with continuous nutrient starvation (Maltsev et al., 2023; Trivedi et al., 2022).

Utilization of wastewater in growth medium

Using municipal, agricultural, and industrial wastewaters as nutrient sources for microalgae

Table 4. Summary of the effects of gas flow parameters on biomass productivity in bubble column photobioreactors (Fu et al., 2019; Rezvani and Rostami, 2023).

Parameter	Effect on biomass productivity	Main considerations
Superficial gas velocity	Improves mixing, gas holdup, and volumetric mass transfer coefficient (kLa), leading to enhanced CO_2 transfer and biomass production.	Excessively high velocities increase turbulence and energy consumption.
Bubble size	Smaller bubbles provide a larger gas–liquid interfacial area and longer residence time, improving CO_2 dissolution and mass transfer efficiency.	Bubble coalescence reduces interfacial area and carbon transfer efficiency.
CO_2 concentration	Higher CO_2 availability enhances photosynthesis and carbon fixation, increasing biomass productivity when maintained within species-specific tolerance limits.	Excessive CO_2 may lower culture pH and inhibit sensitive microalgal species.
Aeration rate	Adequate aeration supplies CO_2, removes dissolved oxygen, and maintains homogeneous cell suspension.	Insufficient aeration limits mass transfer, whereas excessive aeration increases shear stress and operational costs.
Shear stress	Moderate shear improves mixing and nutrient distribution.	Excessive shear may damage shear-sensitive microalgae and reduce biomass productivity.

opens up a variety of options to integrate biomass production and environmental remediation. Bulynina et al. (2023) focused only on the growth performance of *Chlorella sorokiniana* and contrasted the efficiencies of pure synthetic media and domestic wastewaters that were unsterile, in addition to Hamidian and Zamani (2022) which analyse nutrition aspects with biomass production of *Chlorella sorokiniana* cultivated on dairy. Singh et al. (2024) and Liu et al. (2026) work on a microalgae-driven wastewater treatment for bioproduct recovery and contaminant removal *C. sorokiniana* produced biomass productivity of 4.64 g/L with nitrogen and phosphorus removal efficiencies of 77.6% and 87.1%, respectively, from dairy wastewate.

Phytoremediation ability for COD removal was shown 70.4% solvent removal rate, where *C. sorokiniana* was able to maintain comparable or even better growth rates in unsterilized domestic wastewater as compared with synthetic media, confirming practical feasibility (Bulynina et al., 2023). In the work of Liu et al. (2021), *Scenedesmus obliquus* was grown under mixotrophic growth conditions using real municipal wastewater, obtaining relatively high lipid products with acceptable nutrient removal rates. El-Sheekh et al. (2023) showed the comparable success of nitrogen and phosphorus removals in different wastewater systems. de Souza Silva et al. (2025) Systematic review of microalgae for brewery wastewater treatment and biomass valorization. Pérez Mesa et al. (2025) aimed to assess the techno-economic aspects of microalgae (*Scenedesmus* sp.) based biofertilizer production from municipal wastewater. Kumar et al. (2025) unified understanding of algal growth through a statistical single-parameter (ψ) approach, showing that compared to pure photoautotrophic culture, mixotrophy can increase relative cell growth rates and lipid accumulation. They are photosynthetic microorganisms that simultaneously hetero-assimilate organic constituents in the wastewater matrix.

Although wastewater provides a low-cost nutrient source, several limitations should be considered for practical implementation. The composition of wastewater varies considerably according to season, geographic location, and industrial activities, resulting in inconsistent cultivation performance and biomass composition. In addition, cultivation in non-sterile wastewater increases the risk of contamination by competing microorganisms and pathogens, which may reduce culture stability. The accumulation of heavy metals, pharmaceuticals, and other emerging contaminants in algal biomass may also restrict its downstream applications, particularly for food and feed production. Furthermore, regulatory requirements governing wastewater reuse and biomass utilization differ substantially among countries, representing an important barrier to large-scale commercialization (Gupta et al., 2024; Pereira et al., 2024).

The most effective way according to Hamidian and Zamani (2022), s to cultivate *Chlorella sorokiniana* in the dairy manure effluent and achieve high productivity of 4.64 g/L and the nutrient removal rate of 77.6% N, 87.1% P and significant COD reduction (70.4%). The mixotrophic growth of Scenedesmus obliquus in municipal wastewater allows for the best balance between growth rate, lipid accumulation and nutrients removal, providing optimal conditions for sustainable production of lipids (Liu et al., 2021). This synergistic value proposition of wastewater-based cultivation, integrating biomass production and environmental treatment services, greatly improves economic viability compared to synthetic media culture.

STRATEGIES FOR IMPROVING BIOMASS YIELD

The optimization through investigating and modifying operational parameters or reactor configuration is a systematic requirement to achieve the biomass productivity in the bubble column reactors, which can be combined with carbon capture applications. In this section, we review established strategies to optimize cultivation performance via operational control, physical design changes, and application of concentrated CO_2 streams.

Operational optimization

Aeration rate

In bubble column systems, superficial gas velocity is the main operational descriptor controlling hydrodynamic mixing and mass transfer characteristics, as well as productivity (Uyar et al., 2024a). A separate aspect of their optimization is aeration rate, which should be balanced between the CO_2 supply needed, O_2 removal efficiency, mixing to prevent sedimentation, and overall energy consumption and shear stress minimization (Kumar et al., 2025). Unlimited extra copy. Comparative studies show that the best biomass productivity from bubble column reactors is reached with appropriate gas flow rates at which the volumetric mass transfer coefficients are maximized, along with satisfactory hydrodynamic conditions (Ji et al., 2025). An excessive aeration produces turbulence that can be harmful to shear-sensitive species, whereas inappropriate flow induces poor mixing and mass transfer limitations (Ji et al., 2025; López-Rosales et al., 2019).

Light/dark cycles and pH-temperature control

Optimizing light regime goes beyond maximizing photon flux density to include selection of phasmophore as well as exploitation of light/dark cycling effects, which have been demonstrated to tremendously improve biomass and generate lipid productivity in comparison to continuous illumination (Díaz-Santos et al., 2025). For maximum microalgae growth rates, culture solution pH plays a crucial role in ensuring an adequate match between the input of dissolved inorganic carbon or CO_2 and light intensity, thereby acting as an important operational control parameter to supersede carbon limitation and avoid ammonia toxicity (Sun et al., 2025a). Temperature regulation with optimal ranges commonly within the 20–30 °C range for mesophilic species plays a significant role in metabolic rates and biomass compositions, as observed through variations in triacylglycerol synthesis (Feng et al., 2025; Li and Zhou, 2024). It is possible to monitor pH and inject CO_2 automatically to hold shear and optimize the conditions for further enhancing CUE by high-frequency feedback loops (Isiramen et al., 2022). Likewise, outdoor growing systems are required to buffer against temperature swings during the day, and some systems may require active temperature management (active heat exchanger or evaporative cooling) to grow through the year without culture crash when the sun is intense (Rasheed et al., 2023).

Packing media and techniques for immobilization

Effect on surface area and retention of biomass

Adding packing media to bubble column photobioreactors alters cultivation dynamics by creating surfaces for biofilm attachment, enhancing biomass retention, and achieving higher effective cell densities. Notably, solid media alter the hydrodynamic flotation patterns of bubbles by decreasing the mean bubble diameter, lowering the rising velocity of bubbles, and increasing gas holdup to increase both specific gas–liquid interfacial area available for CO_2 transfer. As such, packing materials fulfil both a hydrodynamic-enhancing function for mass transfer and provide support for microalgal biofilm colonization (Sastaravet et al., 2020; Wongwailikhit et al., 2018). It includes various carrier geometries such as glass Raschig rings, polypropylene rings, cylinders, spheres, and conical helix baffle structures. When selecting the suitable packing media, surface properties able to promote cell adhesion, material biocompatibility, light penetration, and gas–liquid mass transfer efficiency should be considered. Examples include ring and cylindrical polypropylene carriers, which have consistently shown superior performance, such as the 10–15% volumetric loading of ring media, which has been reported to increase (kLa) by 28–56% in bubble column configurations compared to no addition (Sastaravet et al., 2020; Wongwailikhit et al., 2018). This improvement is due to the knife-edged geometry of ring particles that promotes bubble break-up by edge forces at the localized scale, followed by their hollow interior trapping bubbles as they ascend and increasing their residence time in the liquid phase (Díaz et al., 2023).

The addition of packing media increases the surface-to-volume ratio available for biomass attachment, thus allowing significant overall biomass densities compared to conventional suspended culture systems. In addition to the more well-known example of moveable media, structured internal elements such as portable conical helix baffles (PCHBs) incorporated in column photobioreactors have been shown to yield similar advantages with respect to surface area and mass transfer. Through helical vortex flow patterns, a PCHB compels ascending CO_2 bubbles to traverse an extended helical path within the column, thereby minimizing bubble diameter and maximizing gas–liquid contact time. The (kLa) was increased by 21%, and the dry biomass yield of *Limnospira fusiformis* showed 48% improvement in comparison with an unmodified control column (Kumar et al., 2025). Likewise, granular column packing in photosynthetic biogas upgrading systems improved CO_2 and CH_4 mass transfer by preventing bubble coalescence and increasing interfacial area, while additionally preserving a microalgal community that acted as a biological CO_2 sink (Gonçalves et al., 2025).

Biofilm versus suspended growth

Cultivation in biofilm systems relates to several operational benefits over suspended growth systems. In immobilized microalgal biofilm arrangements, there are specific advantages in lowering harvesting costs which arise from the fact that attached cells can be harvested through mechanical scrubbing of carrier surfaces, significantly minimizing (or eliminating) energy-demanding centrifugation needs characteristic of suspended culture systems. Furthermore, biofilm systems can operate continuously without frequent cell separation, improving process stability and reducing operational complexity. Packed bubble column photobioreactor studies have shown that a combination of counter-current *Chlorella vulgaris* culture and glass bead packing leads to CO_2 transfer efficiencies above 30% (Zame, 2010).

Due to the higher algal concentration, which further increases uptake by maintaining a steep concentration gradient via constant photosynthetic CO_2 assimilation. Optimized biofilm systems have shown increased productivity in comparative studies. The packed-bed biofilm photobioreactor of (Díaz et al., 2023) demonstrated that simultaneous 56 ± 5% COD, 12 ± 2% nitrogen, and 20 ± 6% phosphorus removal could be obtained by the cooperative action of a spontaneously developed microalgal-bacterial consortium containing *Tetradesmus obliquus*, *Bacillus* spp., and *Pseudomonas putida*. Immobilization of this consortium on glass Raschig ring carriers stabilized community composition and treatment function throughout 1500 hours of continuous operation.

Microalgal photosynthesis provided dissolved oxygen, maintaining aerobic bacterial decomposition of the organic matter, while bacterial respiration released CO_2 rich in nutrients aimed to microalgae growth; a mutualism that led to a strong reduction of external demand for aeration (Díaz et al., 2023). Nevertheless, biofilm systems have unique operational challenges due to mass transfer limitations within compact biofilms, light penetration limitations in thick biofilms, and an uneven distribution of biomass on support surfaces. The establishment of the biofilm process takes a long start-up period (Díaz et al., 2023), it took around 1000 h in order to reach stabilized productivity and full nitrification. Thus, the choice of either biofilm or suspension culture mode is based on the requirements of individual applications, the characteristics of target species and economics.

Principles of moving bed biofilm reactor (MBBR) operation, free floating polypropylene carriers that increase both bubble hydrodynamics (Sastaravet et al., 2020; Wongwailikhit et al., 2018) and provide carrier surface area for biofilm development (Díaz et al., 2023) are a more pragmatic compromise between these approaches as they deliver the mass transfer gains associated with movable solid media while still retaining biomass through attached growth at carrier fill fraction of only 10–15% v/v.

Principles of moving bed biofilm reactor (MBBR) operation — free floating polypropylene carriers that increase both bubble hydrodynamics (Sastaravet et al., 2020; Wongwailikhit et al., 2018) and provide carrier surface area for biofilm development are a more pragmatic compromise between these approaches as they deliver the mass transfer gains associated with movable solid media while still retaining biomass through attached growth at carrier fill fraction of only 10–15% v/v (Díaz et al., 2023).

In addition, long-term operation of biofilm-based systems may be affected by biofilm detachment resulting from hydrodynamic shear, which reduces biomass retention and process stability. Biofouling of carrier materials may also increase mass transfer resistance and reduce reactor performance over time. Moreover, as biofilm thickness increases, uneven light penetration creates internal dark zones, decreasing photosynthetic efficiency and causing heterogeneous metabolic activity. These operational challenges highlight the need for optimized carrier design, periodic biofilm management, and improved hydrodynamic control during scale-up (Mateos and Spilling, 2026).

CO_2 enrichment and flue gas utilization

Carbon capture efficiency

One of the strategies directly integrated to elevate carbon capture efficiency and microalgal productivity is the incorporation of elevated CO_2 concentrations into the gas supply stream of bubble column photobioreactors. At ambient atmospheric carbon concentrations (approximately 0.04% CO_2), the supply of carbon is often rate-limiting for photosynthetic growth, especially at high densities. This allows for carbonate mineralization without losing the advantages of using an aeration stream, and a combination of supplying inorganic carbon into the culture increases the dissolved inorganic carbon pool in the culture medium, leading to more active photosynthesis and higher rates of carbon fixation (Sun et al., 2025a). Flue gases from industries with 5–15% CO_2 in volume are a low-cost and abundant source of carbon, providing a dual benefit through carbon capture that can divert atmospheric emissions (Chiu et al., 2009).

Li et al. (2015), highlighting that high CO_2 tolerance and the ability to fix CO_2 also increase significantly in *Chlorella sp*. during adaptive laboratory evolution. through sequential acclimation. CO_2-tolerant strains able to grow on the higher end of this range (20–40%) have been identified using high-throughput screening approaches (Liu et al., 2013). CO_2 capture efficiencies approaching 30% have been achieved with *Chlorella vulgaris* in packed bubble column photobioreactors, and improvements are possible through increases in algal concentrations and decreases in gas flow rates, resulting in increased bubble residence time for gas–liquid mass transfer, all while maintaining biological demand for CO_2 (Zame, 2010).

Impact on biomass productivity

Microalgae can effectively fix about 1.8 kg CO_2/kg dry biomass produced at optimal CO_2 concentrations (Sun et al., 2025a), (Kumar et al., 2025). Gonçalves et al. (2025) revealed an important trade-off for packed bubble columns used in photosynthetic biogas upgrading: higher mixing rates yielded higher values of O_2, while lower gas flow resulted in a greater total mass transfer of CO_2. The granular packing improved both CO_2 and CH_4 mass transfer due to disrupted bubble coalescence and an increased interfacial area, whilst the largely retained microalgal community provided a concurrent biological fixation sink. These findings emphasise the need to combine CO_2 enrichment level, sparer selection, packing geometry, and biological activity in order to maximize carbon capture and biomass productivity.

Despite these promising results, direct utilization of industrial flue gas remains challenging under practical conditions. In addition to elevated CO_2 concentrations, flue gas frequently contains sulfur oxides (SO_x), nitrogen oxides (NO_x), particulate matter, and trace heavy metals that may inhibit photosynthetic activity, reduce biomass productivity, or accumulate in the harvested biomass. Furthermore, the high temperature of untreated flue gas generally requires cooling before introduction into photobioreactors, increasing operational complexity and energy consumption. Therefore, efficient flue gas pretreatment and the selection of pollutant-tolerant microalgal strains remain essential for large-scale implementation (Padhi et al., 2025).

APPLICATIONS OF BUBBLE COLUMN REACTORS FOR MICROALGAE-BASED TREATMENT

Wastewater treatment

Nutrient removal (N, P)

Biomass production and nutrient removal occur simultaneously, in contrast to the cultivation of microalgae on bubble column photobioreactors that are fed with municipal or industrial wastewater. During photoautotrophic growth, microalgae assimilate the three main macronutrients, nitrogen and phosphorus, which can then be removed from a given effluent through this biomass assimilation pathway as a cheap and sustainable substitute to regular chemical or biological nutrient removal systems (Sutherland et al., 2020; Su, 2021). The process for the assimilation of nitrogen and phosphorus nutrients differs among different species of microalgae. Ammonium is preferentially assimilated over nitrate as an energetic advantage of direct incorporation into cellular material. Phosphorus is assimilated in its orthophosphate form and utilized for biological nucleic and phospholipid synthesis, and energy metabolism structures (Su, 2021; Díaz et al., 2023), nitrogen removal of 12 +/- 2% and phosphorus removal of 20 +/- 6%, respectively, by biomass assimilation using a spontaneous microalgal-bacterial consortium dominated by *Tetradesmus obliquus*.

High-rate algal ponds arranged in series have also shown improved nutrient removal and productivity relative to single-stage systems (Sutherland et al., 2020). Cultivation media based on diverse wastewater streams have been studied extensively. It has been shown that wastewater from dairy industries can be used for microalgal cultivation, with effective use for nutrient removal and generation of high biomass and lipid yield (Kusmayadi et al., 2023; Singh et al., 2024). Further, microalgae-based brewery wastewater treatment has also shown significant biomass protein valorization potential (de Souza Silva et al., 2025), and the use of

Scenedesmus sp. has been investigated as a circular economy option for concurrent nutrient recovery and biomass use (Pérez Mesa et al., 2025).

Organic and phenolic compound removal

BCR systems not only achieve removal of inorganic nutrients in the form of nitrogen and phosphorus but also effectively degrade dissolved organic matter, such as recalcitrant phenolic compounds and complex organic pollutants, through microalgal-bacterial consortia. The removal of COD depends largely upon the activity of heterotrophic bacteria and molecular oxygen transfer resulting from microalgal photosynthesis. (Díaz et al., 2023) All the inoculated strains significantly contributed to the COD removal, with reported removals of 56 +/- 5% in a packed-bed photobioreactor, supported by *Pseudomonas putida*, *Bacillus* spp. and *Sphingopyxis chilensis* involved in organic matter degradation. Wastewater treatment coupled with biomass production has proven to be an efficient approach in producing biodiesel feedstock from green microalgae (El-Sheekh et al., 2023; Liu et al., 2026). Further refined the value of microalgal-based wastewater treatments not just for recovering high-value bioproducts, but also effectively removing emerging contaminants, such as pharmaceuticals and endocrine disruptors.

Treatment of gaseous streams and carbon capture

CO_2 fixation efficiency

Bubble column photobioreactors combine the mass transfer benefits associated with a BCR design and the photosynthetic ability of microalgae to fix CO_2 thereby establishing an extremely promising platform for gas treatment and biological carbon capture. Mechanistically, CO_2 fixation occurs by generation through dissolution at the gas-liquid interface, followed by equilibration to bicarbonate within the liquid phase, and cellular uptake through carbon-concentrating mechanisms, followed by enzymatic fixation via the Calvin cycle (Sun et al., 2025a). The overall CO_2 fixation efficiency is therefore determined by both the physical mass transfer limitations of the reactor and the biological demand for inorganic carbon growth of the microalgal culture (Kumar et al., 2025; Sastaravet et al., 2020; Wongwailikhit et al., 2018). Based on Barahoei et al. (2020) (Barahoei et al., 2020) developed a process of capturing CO_2 in a bubble column photobioreactor using *Chlorella vulgaris* as algae. The bubble size effect on CO_2 removal efficiency and microalgal growth rate was studied in a controlled cultivation system. The diagram depicts the integrated system for gas supply, CO_2 monitoring, illumination, and cultivation of microalgae to obtain optimal biological fixation of carbon dioxide. Figure 4 is a schematic diagram of the photobioreactor process.

Fed-batch cultivation with vigorous mixing in laboratory-scale bubble column photobioreactors, for example, yielded CO_2 transfer efficiencies of 10–30% with the microalga *Chlorella vulgaris* under semi-continuous conditions, and >30% was obtained at higher algal concentrations (Zame, 2010). Lactate synthesis by selected species of microalgae is the focus of carbon management; indeed, microalgal culture performs photosynthesis that keeps dissolved CO_2 on a deficit relative to equilibrium in the liquid phase and preserves (Partial pressure Difference) PD necessary for additional gas absorption. Photosynthetic biogas upgrading is an innovative and potentially disruptive application for BCR technology in the context of gas treatment. Gonçalves et al. (2021) proved that packed bubble columns with microalgal suspensions, produced from biogas-formed wastewater, could efficiently recover CH_4 (as a purified fuel gas) and achieve beneficial CO_2 bio fixation to them (proving positive energy balance under tested conditions). The potential for circular bio economy from BCR photobioreactor systems is demonstrated by the integration of HRAP-based wastewater treatment with photosynthetic biogas upgrading.

Removal of emerging pollutants

Heavy metals microalgae

possess an inherent capacity for heavy metal removal through biosorption, rapid physicochemical binding of metal cations to negatively charged functional groups on the cell surface and bioaccumulation slower active intracellular uptake (Figure 5). BCR systems are well-suited for heavy metal removal applications because the high specific surface area of microalgal cells provides an extensive reactive surface for metal binding (Liu et al., 2026). Biofilm-based BCR configurations are especially promising for heavy metal biosorption, because of the large biomass densities on the surface of the carrier, which results in a high total biosinging capacity in a small

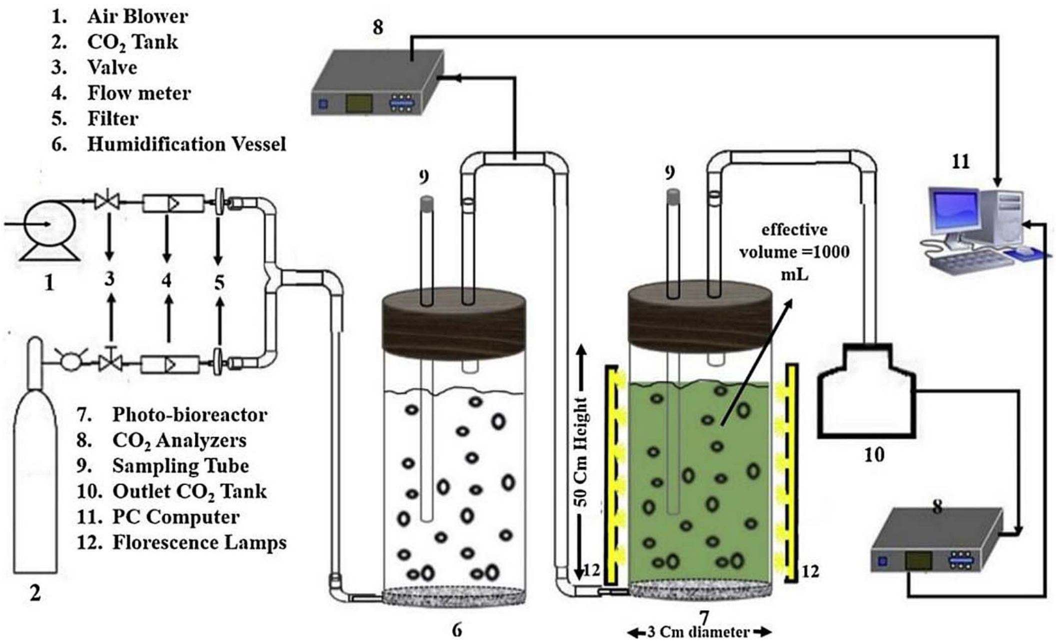

Figure 4. Block scheme of the carbon capturing system (Barahoei et al., 2020)

volume of the reactor (Díaz et al., 2023). The bacterial component of microalgal-bacterial consortia contributes additional heavy metal removal capacity through EPS-mediated biosorption. The bacterial genera identified by Díaz et al. (2023), including *Sphingopyxis* spp are recognized for their capacity to survive in metal-contaminated environments and to degrade xenobiotics that frequently co-occur with heavy metal contamination in industrial effluents.

Hydrocarbons and dyes

Petroleum hydrocarbons, PAHs, and synthetic dyes are persistent organic pollutants that have been in focus for removal by microalgae-based BCR treatment technology. Direct metabolic co-oxidation, biosurfactant production, and photolytic degradation mediated by reactive oxygen species (ROS) formed during photosynthesis have all been shown to play a role in hydrocarbon degradation by microalgae. The aerobic bacterial consortia associated with microalgae in biofilm systems at BCR, including *Pseudomonas*, *Bacillus,* and *Sphingopyxis* are known hydrocarbon degraders sustained by oxygen generated via photosynthesis (Díaz et al., 2023; Liu et al., 2026). Synthetic dyes released from the textile, paper, and food industries are also suitable for treatment using microalgae in BCRs through mechanisms of biosorption onto cell surfaces, enzymatic biodegradation, and photodegradation. Microalgal photosynthesis enables high concentrations of dissolved oxygen, suitable for aerobic decolorization pathways that are not available in anaerobic treatment systems (Liu et al., 2026). Thus highlighted the increasing evidence for microalgae-driven removal of emerging contaminants such as pharmaceuticals, personal care products, and microplastics from wastewater and described BCR photobioreactor systems as having significant potential due to high biomass density, efficient mass transfer, and synergistic treatment capability within the native microbial consortium.

HARVESTING AND BIOMASS PROCESSING

Biomass separation challenges

Harvesting of biomass is one of the foremost technical and economic obstacles associated with large-scale microalgal cultures in bubble column photobioreactors. With small cell size (3–30 micrometres), low suspension biomass concentration (typically 0.5–5 g L^{-1}) and buoyancy of near neutral cells, separation is inherently difficult and energy-intensive. Harvesting costs account for approximately 20–30% of total production costs (Díaz et al., 2023; Singh and Patidar, 2018), and the choice of an effective strategy needs to balance separation performance with energy

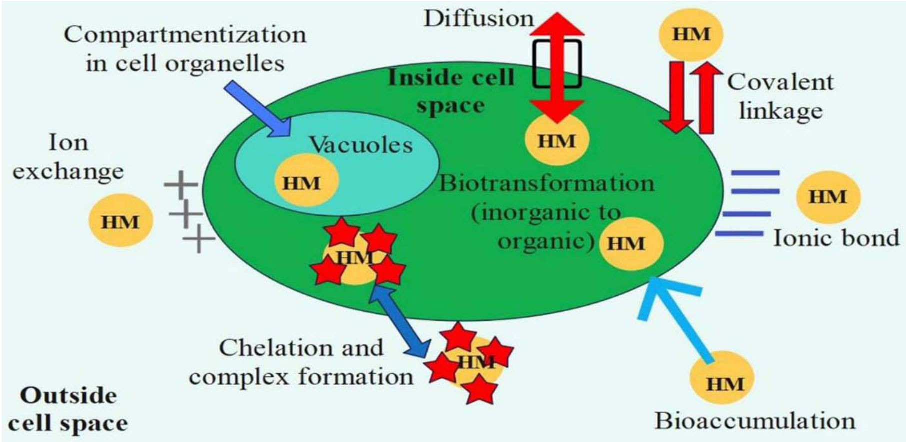

Figure 5. Various mechanisms of heavy metal removal by microalgae (Singh et al., 2024)

requirement(s) and capital cost, as well as compatibility with downstream product specifications. Harvesting over suspended-growth versus biofilm BCR configurations varies significantly. In biofilm systems like that of (Díaz et al., 2023). Most of the biomass remains attached to the carrier surfaces and can be removed by periodic mechanical scrape or controlled hydraulic detachment at a very low energy cost. In that system, the suspended biomass was only 5–34 mg L^{-1}, significantly below the concentrations requiring energy-intensive centrifugation.

Flocculation, sedimentation, and filtration

Flocculation-sedimentation, which is the most studied low-energy recovery and harvesting technology among various options for suspended-growth BCRs, was the applicable method to be selected here. Inorganic coagulants are the most effective chemical flocculants for destabilizing negatively charged microalgal cell surfaces and producing settleable flocs. Nevertheless, chemical flocculants could lead to metal contamination, which would restrict subsequent usages of the biomass targeting food, feed, or pharmaceutical applications (Eppink, 2013).

Dissolved air flotation (DAF) has also emerged as an effective harvesting technique for suspended microalgal cultures. In this process, fine air bubbles attach to microalgal cells, decreasing their apparent density and promoting flotation. Compared with sedimentation alone, DAF generally provides faster biomass recovery and is particularly suitable for harvesting small, low-density microalgal species. However, its efficiency depends on bubble size, hydraulic conditions, and the use of coagulants or flocculants, which may increase operational costs and limit certain downstream applications (Agarwalla and Mohanty, 2024; Rao et al., 2023)

Bioflocculation, which is an organic aggregation of microalgal cells in a self-ordered manner induced by the extracellular polymeric substance released from bacteria, is a low-cost and contamination-free solution, naturally developed when microalgal-bacterial consortia are long-term operated in BCR systems (Díaz et al., 2023). As a result, single-unit membrane filtration directly associated with biological carbon removal (BCR) bioreactor operation has been incorporated in the configuration of membrane photobioreactors (MPBR), facilitating continuous biomass retention and permeate withdrawal, Díaz et al. (2023) integrated this on the basis of an immersed hollow fiber ultrafiltration membrane in a packed-bed BCR, allowing continuous permeate production while microalgal-bacterial biofilm biomass was retained within glass Raschig ring carriers. Membrane fouling, mostly due to biofilm growth on the membrane surface, was reported as the main operational constraint leading to regular chemical cleaning and necessitating critical control of transmembrane pressure. Despite their high separation efficiency and continuous operation capability, membrane technologies remain constrained by membrane fouling, frequent cleaning requirements, membrane replacement costs, and flux decline during long-term operation, all of which increase operational complexity and overall harvesting costs (Agarwalla and Mohanty, 2024; Vatanpour et al., 2024).

Centrifugation is widely applied for laboratory-scale cultivation and the recovery of high-value microalgal products because it can achieve biomass recovery efficiencies exceeding 90%. The technique relies on centrifugal forces to rapidly separate cells from the culture medium. Nevertheless, its high energy demand and operating costs make it economically unsuitable for large-scale biofuel production, although it remains attractive for pharmaceutical, nutraceutical, and pigment applications (Barros et al., 2015; Milledge and Heaven, 2012).

Electrocoagulation has recently gained attention as an alternative harvesting technology. The process generates metal hydroxide coagulants in situ using sacrificial electrodes, promoting rapid aggregation and sedimentation of negatively charged microalgal cells without the need for large quantities of chemical additives. Although high harvesting efficiencies have been reported, electrode consumption, electricity demand, and possible residual metal contamination remain important challenges for commercial-scale implementation (Abuhasheesh et al., 2025; Visigalli et al., 2021).

Magnetic harvesting is another emerging approach in which magnetic nanoparticles are attached to microalgal cells and subsequently recovered using an external magnetic field. This technique enables rapid biomass separation with minimal mechanical stress and offers potential for process automation. However, its large-scale application is currently limited by the high cost of magnetic materials, the need for nanoparticle recovery and recycling, and concerns regarding their environmental safety (de Lima Barizão et al., 2021; Wang et al., 2015).

Integration with reactor operation

The best coupling of harvesting with BCR operation is dependent on the cultivation mode, batch, semi-continuous or continuous, and desired product. In a continuous system, equal amounts of biomass are harvested and replaced by supplying a bleed stream at a rate that balances growth and dilution and ensures an optimal culture density, which keeps volumetric productivity high without excessive self-shading. Semi-continuous operation (Zame, 2010). It is similar to batch systems with an interval between harvesting and medium replacement, making it easier to manage operations in packed bubble columns. As the harvesting technique will affect the quality, purity, and processability of the final biomass (Schade and Meier, 2021), downstream processing, including cell disruption, lipid extraction, protein isolation or, pigment purification, needs to be integrated into BCR system design.

APPLICATIONS OF MICROALGAL BIOMASS

Biofuels

Microalgal biomass cultivated in bubble-column photobioreactors is used as feedstock for several biofuel production pathways: biodiesel generated from lipid trans-esterification, bioethanol produced via carbohydrate fermentation, biogas accumulated through anaerobic digestion and biohydrogen processed via photobiological means. Microalgal triacylglycerol-fueled biodiesel has received the most interest in research; some oleaginous species can achieve 20–50% lipid contents of dry weight with nutrient limitation (e.g., nitrogen) (Babu et al., 2022; Mallick et al., 2016). Nitrogen starvation also consistently emerges as the best trigger of lipid accumulation, albeit loosely, in striving for a lower biomass growth rate. Marine microalgal species, with diverse lipid profiles (Li and Zhou, 2024), provide specific advantages as biodiesel feedstocks. The range of theoretical lipid potential is broad across phytoplankton species, highlighting the significance of species selection for biofuel uses (Morales et al., 2021). The integration of microalgal cultivation with the treatment of wastewater in BCRs greatly lowers lifecycle environmental costs by avoiding freshwater and nutrient costs (El-Sheekh et al., 2023; Mallick et al., 2016).

Animal feed and fertilizers

Microalgal biomass produced from BCR cultivation systems has a high protein content and a favorable amino acid profile, which supports their applications in animal feeds and aquaculture nutrition. The protein content of microalgae products is typically 40–60% (dry weight) under nutrient-replete conditions, and the quality of protein is comparable to conventional sources like soy meal (Saeed et al., 2025; Wong et al., 2025). In particular, the use of *Arthrospira platensis* (Spirulina) in feed markets is focused due to its high protein content and the presence of B-vitamins, while production at a large scale has been the target of production systems involving photobioreactors (Thevarajah et al., 2022). Microalgal biomass recovered from wastewater-treating BCRs is particularly suitable for use as fertilizer because it contains a lot of nitrogen and phosphorus, which are captured from the wastewater stream, along with active microbial populations that can promote soil health. Biofertilizer production from *Scenedesmus* sp. cultivated from municipal wastewater has been characterized as a feasible circular economy strategy for concurrent nutrient recovery and biomass valorization (Pérez Mesa et al., 2025).

High-value products (pigments and antioxidants)

Microalgal biomass produced in BCRs can be used to manufacture high-value biochemical compounds, such as photosynthetic pigments, polyunsaturated fatty acids (PUFAs), antioxidants, and vitamins. One of the most valuable natural pigments commercially is phycocyanin from *Arthrospira* (*Spirulina*), with market prices reported between US$500 and >US$10,000/kg depending on purity grade (Thevarajah et al., 2022).

Kumar et al. (2025) showed that portable conical helix baffles improving both CO_2 mass transfer and liquid mixing inside column photobioreactors led to higher phycocyanin content of *Limnospira fusiformis* by 18% and chlorophyll-a (31%), demonstrating the direct link between optimized BCR hydrodynamics and productivity of high-value pigments. Polyunsaturated fatty acids (PUFAs), and specifically eicosatetraenoic (EPA) and docosahexaenoic (DHA) acids, are high-value substances having established markets in nutraceuticals, pharmaceuticals, and aquafeeds (Adarme-Vega et al., 2012). Marine microalgae grown in BCR systems are considered sustainable sources of omega-3 PUFAs with numerous advantages over fish oil (Adarme-Vega et al., 2012). Beta-carotene, astaxanthin, and lutein carotenoids exert high market prices as natural antioxidants and colorants for food (Fernandes and Cordeiro, 2021). The biorefinery strategy, consisting of a step-wise extraction of high-added value pigments and lipids from microalgal biomass before purification for bulk valorization as biofuel or feed, is considered key to the economic feasibility of BCR microalgal production at large scale (Khan et al., 2018; Matos, 2017).

CONCLUSIONS

This review has shown that the bubble column PBR is a highly promising and versatile cultivation system for microalgae that could simultaneously solve the CO_2 capture, wastewater treatment and renewable biomass problems in an integrated system. The primary objective of this review was to comprehensively evaluate the factors governing biomass production in bubble column photobioreactors and to integrate recent advances in reactor engineering, cultivation strategies, harvesting technologies, and industrial applications. This objective has been successfully achieved by synthesizing current knowledge into a unified framework that highlights the interactions among reactor design, operational parameters, and downstream processing for enhanced microalgal biomass production. They have many inherent advantages, such as low energy consumption, no mechanical agitation, little hydrodynamic shear stress, and simplicity and scalability of design, making them well-suited to cost-sensitive applications in both the laboratory and industry. One of the most promising strategies achieved for improving BCR performance involves optimizing mass transfer using packing media, structured baffles within the internal structure, and co-optimization of the sparger design, which can increase the volumetric mass transfer coefficient by up to 56% and provide considerable improvement in the biomass productivity with no extra energy input. These reactor designs can be used to efficiently fix CO_2 when used in combination with CO_2-enriched gas streams or industrial flue gases to make a significant contribution to the biological carbon capture targets.

In recent years, microalgal-bacterial consortia in BCR systems have been shown to effectively achieve concurrent removal of organic carbon, nitrogen, phosphorus, and heavy metals from various wastewater streams, as well as emerging micropollutants, and the use of biofilm cultivation on packing media aids in reducing energy requirements for harvesting algal biomass while improving process stability.

A wide portfolio of products output, which includes biodiesel, biogas, animal feed, biofertilizer, and high-value pigments and omega-3 fatty acids from BCR-cultivated biomass, underpins the biorefinery process necessary for commercial viability, while there have been some sizeable advancements, considerable issues still exist in biomass harvesting efficiency, scale-up of light distribution and CO_2 delivery for heterotrophic growth, alongside long-term ongoing stability of the photobioreactor. Unlike previous reviews that primarily focused on individual aspects of bubble column photobioreactors or specific microalgal applications, this review integrates engineering design, cultivation optimization, biomass harvesting, wastewater treatment, carbon capture, and biomass valorization within a single comprehensive framework. Consequently, it helps bridge the gap between laboratory-scale research and industrial implementation by identifying the major technical bottlenecks and highlighting integrated strategies for improving biomass productivity and process sustainability.

Future investigations should emphasize CO_2-tolerant high-productivity microalgal strains, forward process control systems, and hybrid biofilm-suspended growth reactor configurations. Overall, the findings synthesized in this review provide a comprehensive reference for researchers and engineers seeking to optimize bubble column photobioreactors and support their transition from laboratory-scale studies to economically viable and environmentally sustainable industrial applications.

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