

Carbon Capture at the Point Source: CO₂ Gas Bubbling vs. Bicarbonate Supplementation in Microalgal Cultivation

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Abstract

Mitigating greenhouse gas (GHG) emissions from industrial point sources is a key challenge for effective climate action. Among emerging carbon capture, utilization, and storage (CCUS) technologies, large-scale microalgal cultivation offers a sustainable pathway to converting carbon emissions into valuable biomass. This review evaluates 2 practical carbon supply strategies for microalgal systems - CO₂-based and bicarbonate-based approaches - highlighting their respective technical performance and operational requirements. By comparing these systems in the context of practical integration with industrial emitters, we aim to clarify key trade-offs and operational considerations. This assessment provides a framework for optimizing microalgae-based carbon capture technologies and informs future design and deployment of emission-integrated microalgal cultivation systems. In comparison to the CO₂-based system, the bicarbonate-based carbon supply system is a more effective choice for microalgae cultivation system in carbon capture project, according to the study's findings. The Net energy Ratio (NER) of this bicarbonate-based cultivation system is 7.29, significantly greater than that of the CO₂-based bubbling system, which only has a NER value of 0.85. This extremely high value can contribute to the project's overall financial viability.

Keywords: Carbon capture, CO₂, CCUS, GHG emission, Microalgae, Cultivation, Bicarbonate, Bubbling

Introduction

Anthropogenic greenhouse-gas (GHG) emissions, particularly carbon dioxide (CO₂) from industrial point sources, are a major driver of global warming [1]. These emissions, predominantly resulting from fossil fuel combustion, account for approximately 40% of global anthropogenic CO₂ output [2]. Therefore, reducing emissions directly at the point of release is a key priority in effective climate action strategies. Although the natural greenhouse effect, sustained by atmospheric CO₂ and CH₄, maintains Earth's habitable temperature [3], continued reliance on fossil fuels is pushing

atmospheric concentrations beyond safe thresholds. As a result, large-scale carbon capture at industrial point sources has gained increasing attention as a promising mitigation approach to accelerate the transition toward decarbonization in sectors such as power generation, aiming to limit further GHG emissions.

Among emerging carbon capture, utilization, and storage (CCUS) strategies, microalgal photobioreactor systems have attracted growing interest as a sustainable and scalable biological solution. Microalgae convert light, CO₂, and nutrients into biomass with relatively high efficiency compared to terrestrial plants, and exhibit rapid growth rates, morphological flexibility, and adaptability to varying environmental conditions

[4]. Certain species, such as *Chlorella vulgaris*, not only tolerate operational fluctuations but also accumulate commercially valuable compounds, including proteins, lipids, and carbohydrates [5]. Due to these advantages, microalgal biomass holds considerable potential across diverse sectors, from food and biofuel production to pharmaceuticals [6], positioning these systems as promising platforms for integrated carbon capture efforts.

In microalgal carbon capture systems, inorganic carbon is primarily supplied in the form of dissolved carbon dioxide (CO₂) or bicarbonate ions (HCO₃⁻) [7]. CO₂ can be sourced from ambient air, purified gas, or more practically, from industrial flue gas, and delivered through technologies such as microbubble generators, membrane spargers, or direct gas bubbling [8]. Alternatively, bicarbonate-based systems capture CO₂ into alkaline solutions, converting it chemically into HCO₃⁻, which is then supplied to the algal culture [9]. This strategy, exemplified by the Bicarbonate-based Integrated Carbon Capture and Algae Production System (BICCAPS), offers improved pH stability and reduced carbon loss, although it requires additional processing steps and chemical inputs. In both systems, the carbon supply method plays a critical role in determining energy consumption, carbon fixation efficiency, and the overall feasibility of microalgae-based carbon capture systems.

A comparison between CO₂-based and bicarbonate-based cultivation systems is essential due to their distinct operational characteristics, energy demands, and suitability for integration with industrial processes. Previous studies have reported varying outcomes in terms of biomass productivity, carbon utilization efficiency, and techno-economic performance [9-11], highlighting the need for context-specific evaluation. Such comparison are crucial for identifying optimal pathways to implement microalgal CCU technologies under different industrial and environmental conditions.

This review presents a comparative evaluation of 2 carbon capture strategies - flue gas-based and bicarbonate-based systems - for photoautotrophic microalgal cultivation. Relevant research articles were systematically reviewed, and key technical and economic data were extracted, interpreted, and compared. Additionally, the author conducted an

experiment on microalgae cultivation at the BioCCU Unit at Paiton Power Plant Units 5 & 6 in Indonesia. The experiment compared the technical performance of the bicarbonate-based system with CO₂-based system. Several parameter values generated in this experiment were used to conduct technical simulations. To ensure consistency and comparability across studies, standardized parameters were employed, focusing on carbon fixation efficiency and energy consumption for technical evaluation. Economic assessment considered energy costs, chemical costs, and the overall cost of CO₂ emission reduction per ton. Particular emphasis was placed on applications relevant to the energy sector, a major contributor to global GHG emissions.

Microalgae cultivation systems for carbon fixation

Microalgae are unicellular, photosynthetic organisms that contain organelles such as chloroplasts, where photosynthesis occurs [12]. Through this process, they capture carbon dioxide (CO₂) and convert it into organic biomass, with carbon comprising approximately 50% of the dry weight [13]. Notably, microalgae can utilize CO₂ from both the atmosphere and aquatic environments, maintaining high fixation efficiencies even under low CO₂ concentrations [14]. In the photosynthetic process, light-dependent reactions use solar energy to split water molecules, producing protons, electrons, and oxygen. The Calvin cycle then fixes CO₂ into glucose, which is subsequently converted into biomolecules such as lipids, proteins, and polysaccharides through various metabolic pathways [15,16]. Altogether, the rapid growth, high carbon fixation capacity, and the ability to thrive in diverse water sources, whether potable or non-potable, position microalgae as a highly promising platform for sustainable carbon capture and utilization [17].

Dissolved Inorganic Carbon (DIC) and its availability

In microalgal cultivation systems, carbon supply primarily relies on dissolved inorganic carbon (DIC), which consists of 4 main species: Dissolved carbon dioxide (CO₂), carbonic acid (H₂CO₃), bicarbonate ions (HCO₃⁻), and carbonate ions (CO₃²⁻). The relative distribution of these species is strongly influenced by the pH of the medium: Dissolved CO₂ is predominates under acidic conditions, bicarbonate becomes

predominant in near-neutral to moderately alkaline environments, and carbonate ions become more prevalent at high pH levels (**Figure 1**) [7]. In typical cultivation settings, where the pH is maintained around 7 - 9, bicarbonate is the most abundant and bioavailable form, supporting efficient carbon fixation. Moreover, the ability of microalgae to assimilate different forms of DIC varies by species. For example, *Nannochloropsis oculata* primarily transports HCO_3^- , whereas *Chlamydomonas reinhardtii* can utilize both CO_2 and HCO_3^- [18]. In cultivation systems utilizing continuous flue gas injection, the dynamic supply of CO_2 can also influence the pH, often resulting in acidification if not properly regulated. Therefore, a comprehensive understanding of both DIC speciation and species-specific carbon uptake mechanisms is essential for optimizing carbon fixation efficiency in microalgal cultures.

In microalgal cultivation systems supplied with flue gas, carbon assimilation occurs in 2 stages: Physical dissolution of CO_2 into the culture medium, followed by biological uptake of dissolved inorganic carbon (DIC) by the cells. CO_2 dissolution is governed by the 2-film theory, where diffusion across thin gas and liquid boundary layers limits mass transfer [19]. The transfer flux is described by:

$$T_{\text{CO}_2} = kt \cdot S \cdot (C_g - C_L) \quad (1)$$

where T_{CO_2} represents the rate of CO_2 transfer from the gas phase (C_g) to the liquid phase (C_L), driven by the

concentration difference ($C_g - C_L$), with kt denoting the overall transfer coefficient and S the effective interfacial area. The equilibrium solubility of CO_2 in the liquid is determined by Henry's law:

$$C_{\text{eq}} = H \cdot P_{\text{CO}_2} \quad (2)$$

where C_{eq} is the maximum dissolved CO_2 concentration achievable under a given partial pressure P_{CO_2} and H is Henry's constant. Due to inherently low solubility of CO_2 , several strategies such as bubble size reduction, increased gas-phase CO_2 concentration, nanobubble technology, and extended gas retention time are employed to enhance mass transfer (**Table 1**) [7,20]. Once dissolved, CO_2 undergoes hydration and ionization into DIC species ($\text{CO}_2(\text{aq})$, H_2CO_3 , HCO_3^- , CO_3^{2-}), with the distribution strongly pH-dependent [7,21]. However, at near-neutral pH, the conversion of CO_2 into bicarbonate is kinetically slow, increasing the risk of CO_2 loss to the atmosphere. To mitigate this, chemical enhancement using alkaline absorbents (e.g., NaOH) is applied to rapidly convert dissolved CO_2 into stable HCO_3^- through the following reaction:



This reaction improves both carbon retention and bioavailability. Consequently, optimizing both physical mass transfer efficiency and chemical stabilization which is crucial for effective carbon capture in microalgal flue gas systems.

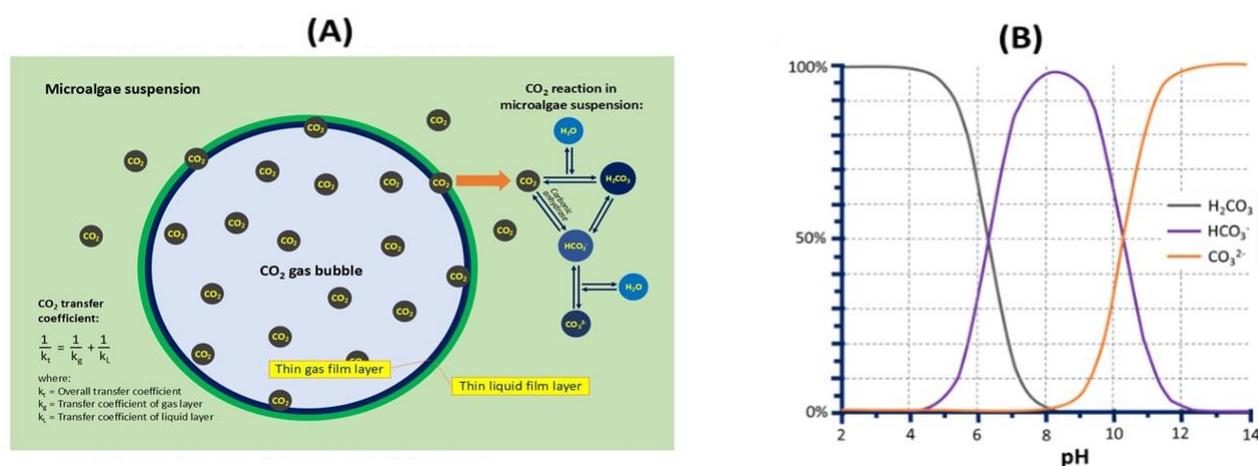


Figure 1 (A) CO_2 dissolution from the gas phase into microalgal suspension [7]. (B) The percent distribution of DIC in microalgal suspension in various pH conditions [21].

Table 1 Summary of strategies to improve CO₂ dissolutions into microalgae suspension.

Strategy	Principle	Targeted parameter in the mass transfer equation	Strategy
Use of high CO ₂ concentration gas	Increase the concentration gradient between gas and liquid phases	$C_g - C_L$	Higher equilibrium CO ₂ concentration (C_{eq}) and accelerated CO ₂ transfer
Bubble size reduction	Increase effective interfacial area (S)	S	Enhanced CO ₂ mass transfer flux
Application of nanobubble technology	Increase interfacial area, gas retention time, and maintain high internal pressure	S, C_g	Improved CO ₂ dissolution rate, extended gas-liquid contact, and higher local C_{eq}
Tall reactor design	Extend gas retention time to sustain the concentration gradient	$C_g - C_L$ (indirect)	Increased CO ₂ dissolution efficiency and improved carbon availability for microalgal uptake
Application of CO ₂ absorbent chemicals, such as monoethanolamine (MEA), 2-amino-2-methyl-1-propanol (AMP), diethanolamine (DEA) and triethanolamine [9]	Increase CO ₂ dissolution capacity by reacting it with absorbent components.	-	Increased CO ₂ dissolution capacity

DIC such as CO₂ and HCO₃⁻, is assimilated into microalgal cells through 3 principal pathways: (1) direct diffusion of CO₂ across the plasma membrane; (2) enzymatic conversion of extracellular HCO₃⁻ into CO₂ by carbonic anhydrase (CA) near the cell surface, facilitating subsequent CO₂ diffusion into the cell; and (3) active transport of HCO₃⁻ into the cytosol via bicarbonate-specific transporters such as BCT1, particularly under carbon-limited conditions [7,22,23]. Recent findings in *Chlamydomonas* have clarified that an extracellular form of carbonic anhydrase (CAH1) plays a key role in the conversion of HCO₃⁻ and CO₂ at the cell surface, thereby enhancing initial DIC uptake in aquatic environments [24]. On the other hand, the active transport of HCO₃⁻ typically serves as the initial step of carbon concentrating mechanisms (CCMs) evolved in diverse microalgal species. CCMs develop physiological strategies to elevate the CO₂ concentration around Rubisco in the chloroplast, enhancing carboxylation efficiency and reducing photorespiration losses [23,25]. In the well-established CCM pathway,

HCO₃⁻ actively imported into the cytosol is transported into the chloroplast and accumulated within the pyrenoid, a Rubisco-associated microcompartment. Carbonic anhydrase inside the pyrenoid catalyzes the conversion of HCO₃⁻ to CO₂, generating a localized high-CO₂ environment that promotes carbon fixation. A proteinaceous shell surrounding the pyrenoid acts as a diffusion barrier, minimizing CO₂ leakage and further optimizing fixation efficiency [7].

Operating a photobioreactor at large scale and maintaining stable biomass productivity requires regulation of multiple environmental parameters. Successful carbon fixation in microalgae depends on the coordinated optimization, such as: (1) energy capture via light absorption, (2) enzymatic carbon metabolism regulated by temperature and pH, and (3) the continuous supply of substrates such as CO₂ and essential nutrients. Light provides the primary energy source for photosynthesis. Microalgal growth increases with light intensity up to a saturation threshold, beyond which photoinhibition occurs [18]. Optimal light intensities

typically range between 26 and 400 $\mu\text{mol photons m}^{-2}\text{s}^{-1}$, depending on species and reactor configuration. Temperature and pH regulate the activity of carbon fixation enzymes. Most microalgae achieve optimal growth between 20 - 35 °C [26], while deviations impair carbon assimilation. Similarly, maintaining culture pH between 6 and 8 is critical to sustain DIC availability and enzymatic stability [27,28].

Nutrient supply - especially of carbon, nitrogen, and phosphorus—supports biosynthesis and biomass accumulation. Although microalgae primarily fix inorganic carbon through photosynthesis, optimizing overall productivity, particularly at industrial scales, often benefits from a flexible approach where supplemental organic carbon sources can be utilized. Microalgae's ability to grow autotrophically, heterotrophically, or mixotrophically enables strategic modulation of carbon inputs to enhance biomass yields depending on process goals [29]. Finally, CO₂ concentration directly impacts substrate availability for the Calvin cycle. Insufficient CO₂ limits growth, whereas excess CO₂ can acidify the medium, disrupting cellular metabolism [30]. Careful management of CO₂ levels is therefore essential for stable cultivation. In practice, environmental parameters often fluctuate, particularly in large-scale or outdoor systems. Moreover, the regulation of these operational parameters is closely linked to reactor energy demand, input costs, and ultimately affects the overall carbon footprint and economic feasibility of microalgae-based carbon capture technologies. Therefore, robust microalgal strains capable of tolerating environmental variations, combined with efficient reactor operation strategies, are essential to achieve sustainable and scalable cultivation systems.

Reactor design in microalgae-based carbon capture system

In microalgae-based carbon capture systems, the design of the cultivation platform significantly affects operational efficiency, scalability, and cost-effectiveness. Cultivation systems are generally classified into open ponds and photobioreactors (PBRs) (**Figure 2**), each offering distinct advantages and challenges [31,32]. Open pond systems are the oldest and most widely used method for large-scale microalgae cultivation. They are valued for their low construction and operational costs and use of simple infrastructure [33]. However, open systems require large land areas and are highly susceptible to environmental fluctuations and contamination, which can affect cultivation stability. Bicarbonate-based supplementation is particularly well suited for open ponds systems, as it provides more stable pH conditions, minimizes CO₂ volatilization losses, and avoids the direct flue gas release, thus improving both safety and carbon retention efficiency [31]. In contrast, photobioreactors (PBRs) are enclosed cultivation systems that provide precise control of environmental parameters such as light, temperature, nutrient levels, and pH. This controlled environment improves gas-liquid mass transfer efficiency and minimizes carbon loss, making PBRs compatible with both direct CO₂ supplementation and bicarbonate-based systems. PBRs also reduce the risk of contamination and can operate under a wider range of climatic conditions. However, PBRs require higher capital and operating costs and may pose scalability challenges for large-volume production [31,32].

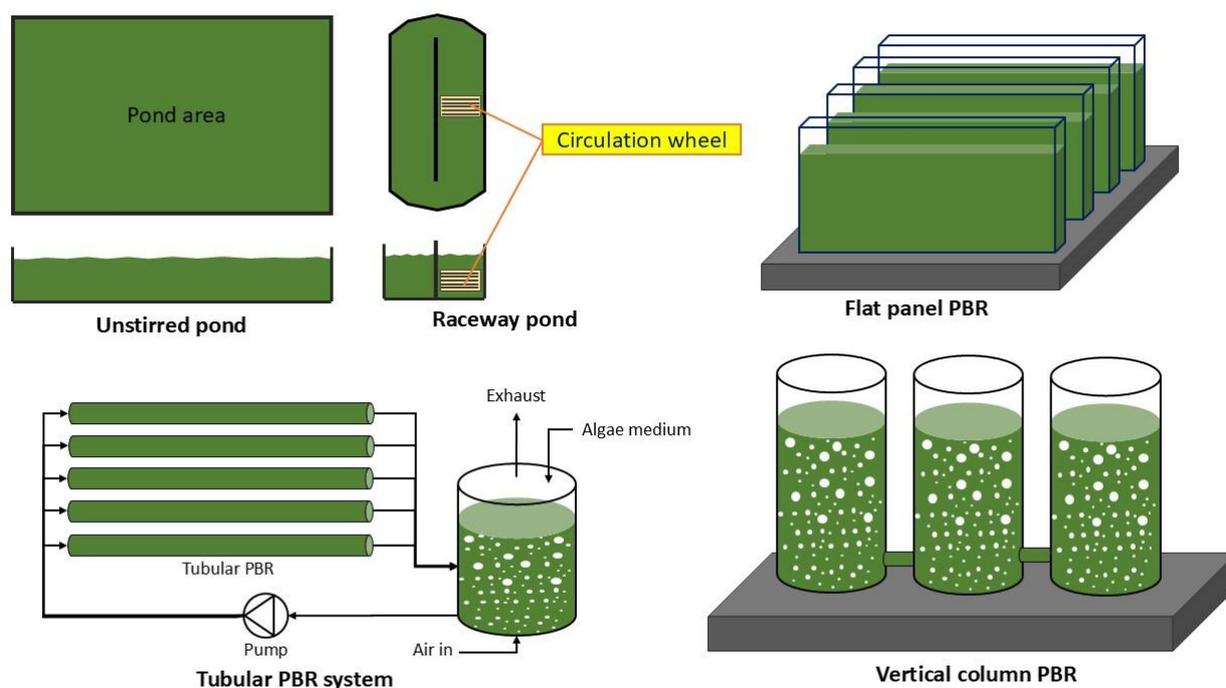


Figure 2 Several types of Open Pond ((1.a); (1.b); (1.c)) and PBR ((2.a); (2.b); (2.c); (2.d)) cultivation system [32].

CO₂-based cultivation system

In CO₂-based cultivation systems, carbon is directly supplied as CO₂ gas to the microalgae culture (**Figure 3**). Sources of CO₂ include atmospheric air, purified CO₂, or industrial flue gas. While atmospheric air is inexpensive and readily available, its low CO₂ concentration results in poor biomass productivity and carbon fixation efficiency, making it impractical for large-scale applications. In energy sector application, flue gas from fossil fuel combustion serves as the primary CO₂ source, offering higher concentrations and better alignment with emission mitigation goals. However, supplying CO₂ gas presents operational challenges. Due to its limited solubility in water, CO₂

has low mass transfer rates, and a significant portion of the supplied CO₂ escapes before being fixed by the microalgae. This reduces carbon utilization efficiency and increases operational costs [34]. Furthermore, excessive CO₂ bubbling can lower the pH of the culture medium, creating suboptimal conditions for microalgal growth. To optimize CO₂ uptake while minimizing losses and pH instability, reactor design must carefully balance gas-liquid contact efficiency with operational simplicity. Despite these limitations, CO₂-based systems remain attractive for large-scale deployment where inexpensive and concentrated CO₂ sources, such as industrial flue gas, are readily available.

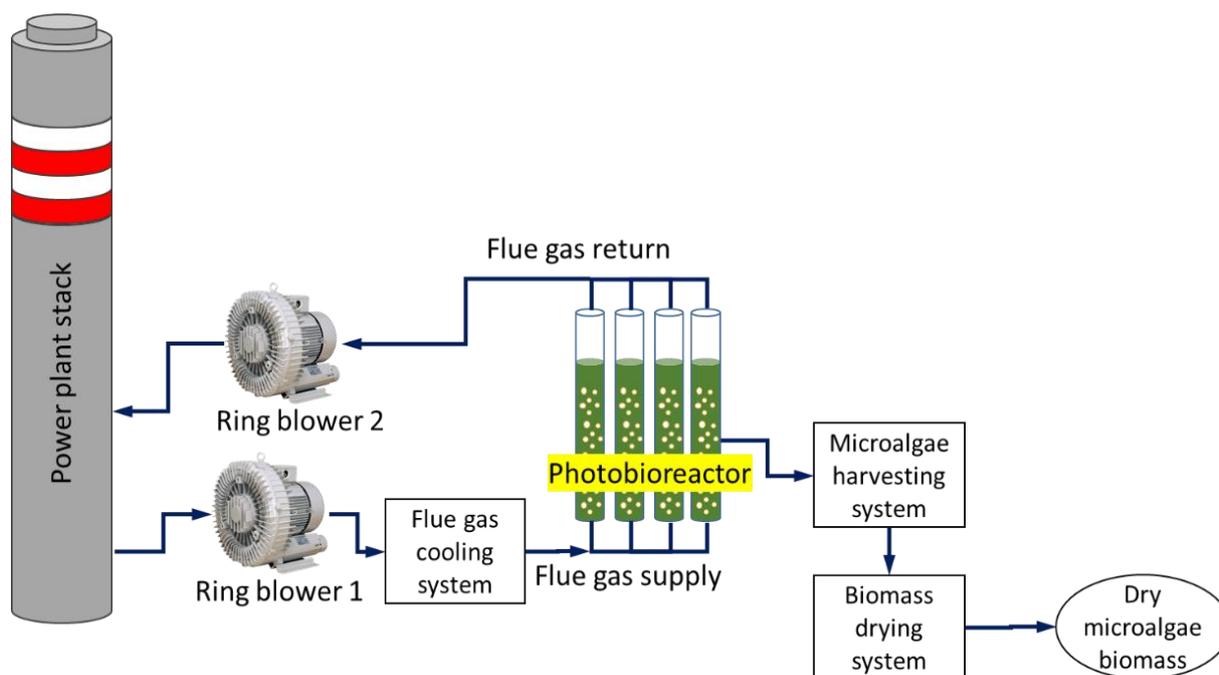


Figure 3 The schematic of the CO₂-based microalgae cultivation system in carbon capture technology [35].

Bicarbonate-based cultivation system

To address the poor mass transfer efficiency of gaseous CO₂ into aqueous culture media, bicarbonate ions (HCO₃⁻) have been proposed as an alternative carbon source, offering greater solubility and stability in solution [36]. One notable implementation of this approach is the Bicarbonate-based Integrated Carbon Capture and Algae Production System (BICCAPS), where CO₂ from flue gas is absorbed by an alkaline solution to produce a bicarbonate-rich medium for microalgae cultivation (**Figure 4**) [37]. BICCAPS offers operational advantages by eliminating the need for continuous CO₂ bubbling, allowing for simpler and more cost-effective photobioreactor designs. However, the economic feasibility of this system strongly depends on the efficient recycling of the cultivation medium and

the alkaline absorbent. Sodium hydroxide (NaOH) is often proposed as an effective CO₂ absorbent due to its high reactivity and widespread availability. Theoretically, capturing 1 ton of CO₂ requires approximately 0.9 tons of NaOH, which is more efficient than the 1.39 tons needed when using conventional monoethanolamine (MEA) solvents [37]. Moreover, NaOH is relatively inexpensive and already used at industrial scales, making it an attractive option for large-scale integration. While bicarbonate-based systems show promising potential for improving carbon fixation efficiency and operational manageability, future development must address the challenges of chemical cost management and system sustainability to enable broader deployment.

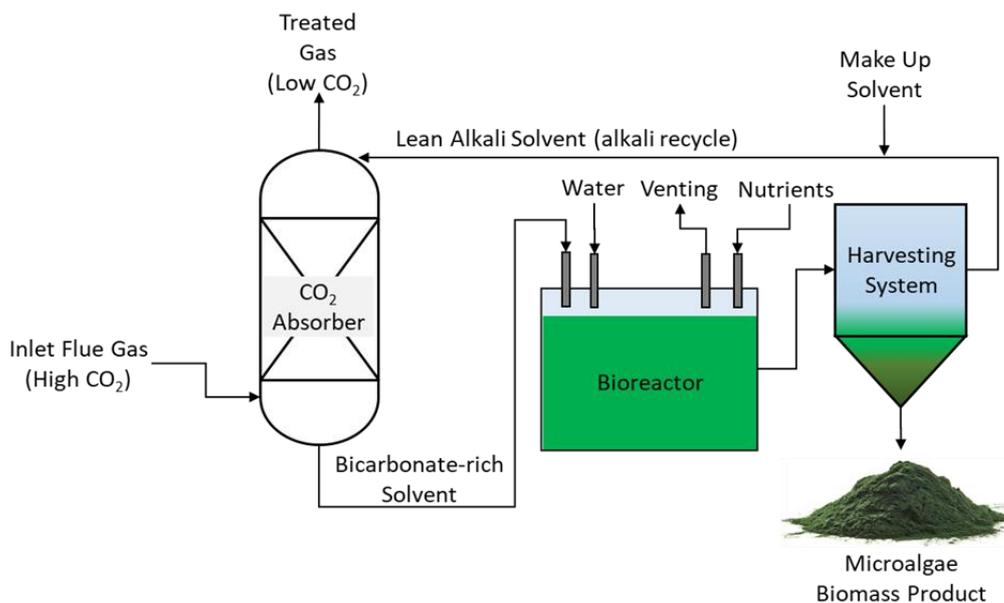


Figure 4 General process flow diagram of BICCAPS [38].

Several types of microalgae species for BioCCU

Various microalgae species have been explored for their potential in carbon capture and biomass production, each with different physiological characteristics influencing their compatibility with CO₂ or bicarbonate-based cultivation systems. *Chlorella vulgaris* is one of the most widely studied strains, demonstrating robust growth and carbon fixation capabilities under both CO₂ and bicarbonate conditions [10]. *Spirulina platensis*, known for its tolerance to high pH environments, is particularly well-suited to bicarbonate-based systems. However, CO₂ bubbling can lower the pH of the growth medium, potentially inhibiting or damaging *Spirulina* cells if pH levels drop too far [39]. *Dunaliella salina* is known for its halotolerance and flexibility in carbon source utilization, making it compatible with both strategies. The capacity of *Dunaliella salina* to thrive in extremely high CO₂ concentrations (up to 30%) is another benefit. This is because it can reduce Radical Oxygen Species (ROS) by producing antioxidants (carotenoids) [40]. *Euglena gracilis* is another promising candidate for

carbon capture agent with their benefit to be able for growth under very acidic conditions, avoiding contamination from other organisms [41].

While some species such as *Chlorella vulgaris* and *Dunaliella salina* are suitable for both CO₂-based and bicarbonate-based systems, the choice of species is not universally interchangeable between the 2. Differences in environmental conditions - such as pH stability, carbon availability, and CO₂ absorption dynamics - make certain species more favorable for one system over the other. For example, *Spirulina* performs best in bicarbonate-rich media due to its alkaliphilic nature, whereas species like *Euglena gracilis* have shown greater productivity in CO₂-enriched environments [39,41]. Therefore, selecting an appropriate species should align with the specific characteristics of the cultivation system. Ultimately, the selection of microalgal strains should also reflect system priorities, including the type of carbon source, cultivation mode, biomass productivity goals, and intended product valorization - especially in the context of industrial-scale bio-based carbon capture and utilization (**Table 2**).

Table 2 Types of microalgae that are commonly utilized in carbon capture technologies.

Microalgae species	Beneficial characteristic	Applicability	
		CO ₂ -based system	HCO ₃ ⁻ -based system
<i>Chlorella vulgaris</i>	Can grow in both CO ₂ and bicarbonate-based carbon sources, producing high biomass concentrations (> 2 g/L) [10]. According to certain experiments, <i>Chlorella vulgaris</i> has a very high lipid content (10% - 45%) [10]	Yes	Yes
<i>Spirulina platensis</i>	High protein content (50% - 70%), contains high phycocyanin pigment (up to 47%), and rich in vitamins [42]. Prefer in high pH condition [39].	Yes	Yes
<i>Euglena gracilis</i>	High protein content and high digestibility for animal feed application. Able to grow in very acidic condition [41].	Yes	No
<i>Dunaliella salina</i>	Tolerant to high CO ₂ concentration (up to 30% CO ₂) due to their ability to eliminate ROS [40].	Yes	Yes

Technical review

Key technical parameters such as biomass productivity, carbon fixation rate, carbon fixation efficiency, and net energy ratio must be thoroughly evaluated and optimized to ensure the economic viability of microalgae-based carbon capture technologies [43-45]. The design of the cultivation system and its supporting infrastructure is inherently linked to these critical factors.

This study focuses on comparing the effects of CO₂-based and bicarbonate-based cultivation methods on these parameters. Operational simulations were conducted based on a defined set of assumptions (**Table 2**), derived from previous studies with cultivation conditions similar to those used in this work. These simulations specifically focus on the carbon supply system, while other supporting subsystems assumed to operate identically in both scenarios (**Figure 5**).

The simulations involved calculating the total gas flow requirements in each cultivation scenario to determine the power requirements of each equipment. Once power requirement of each equipment was identified, the estimated energy consumption of the carbon supply system was calculated using the following formula:

$$E = P \cdot t \quad (3)$$

where E is energy consumption in kWh/day, P is power requirement in kW and t is operating hour of the equipment (hours/day). The power requirements for the equipment are estimated using the following formula:

$$P = \frac{Q \cdot \Delta P}{3600 \cdot \eta} \quad (\text{for blower}) \quad (4)$$

$$P = \frac{\rho \cdot g \cdot Q \cdot H}{1000 \cdot 3600 \cdot \eta} \quad (\text{for pump}) \quad (5)$$

where P is the power requirement (kW) for carbon supply equipment, Q is blower/pump flowrate (Nm³/h for blower and m³/h for pump), ΔP is the operating pressure (kPa), ρ is the density of fluid (kg/m³), g is gravitational constant (m/s²), H is head of the pump (meter) and η is blower/pump efficiency (no unit). The efficiency of all equipment in this simulation is assumed to be 70%.

Based on the simulation results, the CO₂-based cultivation system requires power 3,571 W of ring blower to deliver flue gas from the power plant to the PBR (**Figure 5(A)**). In contrast, the bicarbonate-based system requires a blower, a NaOH circulation pump for the CO₂ absorption system, ring blower for mixing, and a bicarbonate supply pump for delivering bicarbonate ions to the PBR, with respective power capacity of 56, 7.04, 3,571 and 0.04 W (**Figure 5(B)**).

Using the assumed inlet gas data and the ideal gas law, the mass flow rate of supplied CO₂ was calculated. Meanwhile, the carbon fixation rate for each cultivation method was estimated using the algal biomass characteristics and the following equation [9]:

$$FR_{CO_2} = F_C \cdot BP \cdot \frac{M_{CO_2}}{M_C} \quad (6)$$

where M_{CO_2} is the molar mass of CO₂ (g/mole), M_C is the molar mass of carbon (g/mole), F_C is the carbon

content in the algal biomass (%), BP is the biomass productivity (g/L/day), and FR_{CO_2} is the fixation rate of CO₂ (g/L/day).

The simulation outputs include values for carbon fixation rate, carbon fixation efficiency, estimated energy consumption, and net energy ratio for both cultivation scenarios. These results are discussed in the following sections.

Table 3 List of assumptions used in operational simulations.

Parameter	Value	Note
1. Reactor specification		
Reactor capacity	100,000 L	Determined value (representative of industrial-scale photobioreactor system)
Reactor type	Flat plate PBR	The best PBR type based on Slade and Bauen [46] study
Microalgae type	<i>Chlorella vulgaris</i>	Tolerance to elevated CO ₂ levels during cultivation, adaptability to environmental changes, simplicity of handling [47], more resilient to the coal fired power plant environment (outdoor, hot and dusty), and suitable for both the bicarbonate-based and CO ₂ -based cultivation systems [10].
Reactor placement	Outdoor	Utilize sunlight during daytime with photoperiod typical of tropical regions, avoids photoinhibition and suitable for power plant sites
Light: Dark period	12:12	
2. CO₂-based system		
Biomass productivity	0.049 g/L/day	Our experiment
Gas supply flow rate	0.1 vvm	Some references using gas flow rate between 0.1 - 0.2 vvm [48-51]
CO ₂ concentration in flue gas	5 %v/v	Most of the optimum biomass productivity of previous research were obtained in CO ₂ concentration of 5% [51,52]
Gas supply duration	10 h/day	Matches daylight hours to simulate outdoor operation
3. Bicarbonate-based system		
Biomass productivity	0.053 g/L/day	Our experiment
Bicarbonate dose	1.5 g/L per 3 days	
CO ₂ absorber column capacity	500 L	Determined value
Reactor type	Spray column	Efficient gas-liquid contact for CO ₂ absorption [53]
CO ₂ in inlet gas	15%	Typical of CO ₂ concentration in CFPP's flue gas
Gas retention time	190 s	Adopted from prior experimental study for optimal absorption [53]
CO ₂ absorption efficiency	95.25%	
Inlet gas flow rate	0.95 Nm ³ /h	Inlet Flow rate = 500 L / 190 s = 9.47 Nm ³ /h
NaOH concentration	5 %w/w	Adopted from prior experimental study for optimal absorption [53]
Liquid to Gas Ratio	90 L/m ³ gas flowrate	

Parameter	Value	Note
NaOH flow rate	0.85 m ³ /h	
4. Microalgae biomass characteristic		
Carbon content (dry basis)	50.39 %w/w	[54]
Net calorific value (dry basis)	5,303 kcal/kg	

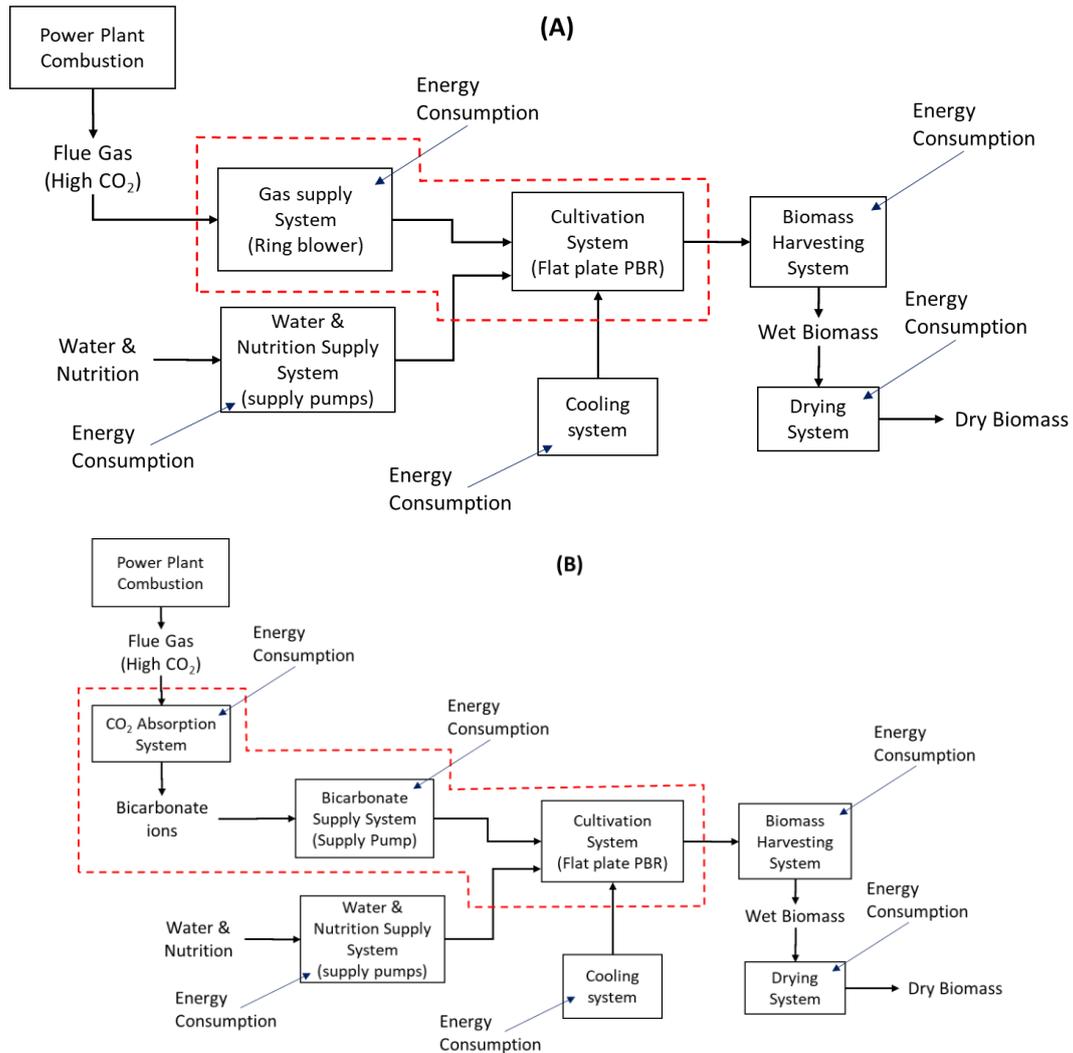


Figure 5 Process flow diagram and the boundary (dotted red lines) of the simulations of CO₂-based (A) and Bicarbonate-based (B) microalgae cultivation system for carbon capture technology.

Biomass productivity & carbon fixation rate

Microalgae biomass productivity (BP) refers to the increase in algal biomass concentration over time and is calculated using the following equation [55]:

$$BP = \frac{(X_t - X_0)}{\Delta t} \tag{7}$$

where BP is biomass productivity (mg/L/day), X_t is the biomass concentration (mg/L) at the end of the cultivation period, X₀ is the initial biomass concentration (mg/L), and Δt is the duration of cultivation (days).

BP varies across the different growth phases of microalgae, typically reaching its peak during the exponential phase and declining thereafter [52].

Therefore, it is advisable to calculate BP using data from the start of cultivation through the end of the exponential growth phase [48].

BP influenced by both reactor design and operational parameters, such as CO₂ concentration (in gas bubbling), pH, temperature, nutrient availability, illumination, and culture mixing. Reactor design is especially critical, as it affects light penetration (light path length), mixing efficiency (which affects the distribution of nutrient, light, and CO₂), and the ability to control environmental conditions such as temperature and pH—factors essential for maintaining optimal growth conditions [56,57].

The carbon fixation rate (FR_{CO₂}) can be derived from BP using the carbon content fraction (F_C) of algal biomass, as shown in Eq. (6) [9]. A positive linear relationship exists between BP and FR_{CO₂}: as BP increases, so does the carbon fixation rate. For example, if the carbon content in algal biomass is 50.39% by weight (dry basis), then a BP of 1 g of dry biomass per day corresponds to the carbon fixation rate of approximately 1.83 g of CO₂ per day.

In the context of carbon capture technology, this positive correlation offers dual benefits. First, a higher BP leads to increased biomass yield, which—if the biomass is of high quality—can enhance the economic viability of the technology. Second, a higher FR_{CO₂} results in greater CO₂ capture, thereby contributing to a larger reduction in greenhouse gas (GHG) emissions. These environmental benefits can be monetized if the emissions reductions are registered within a carbon credit program.

Many studies show CO₂-based generally yield higher BP and maximum algal cell concentrations than bicarbonate-based cultivation systems. Lam and Lee [10] found that cultivating *Chlorella vulgaris* with 5% CO₂ bubbling yielded a BP value of 0.072 g/L/day, but bicarbonate-based culture yielded only 0.014 g/L/day. Other example, Do *et al.* [9] reported a maximum BP of 0.639 g/L/day and a peak cell concentration of approximately 3.4 g/L in a CO₂-based system using *Scenedesmus acuminatus* TH04, compared to just 0.186 g/L/day under bicarbonate-based conditions. Several research, however, reveal the opposite results, such as the study by Zhu *et al.* [11], which found that the BP of bicarbonate-based cultivation of *Trebouxioiphyte*

microalgae was 0.8 g/L/day, which is greater than CO₂-based cultivation with 2% CO₂ concentration at 0.61 g/L/day. Similarly, the results of our experiment demonstrate that the BP value of the bicarbonate-based system was 0.053 g/L/day, slightly higher than that of the CO₂-based system at 0.049 g/L/day. This disparity is primarily attributed to differences in system optimization. In our experimental setup, the bicarbonate-based system was specifically optimized to enhance productivity, while the CO₂-based system was maintained under more generic conditions without targeted optimization. This highlights the importance of system-specific parameter tuning, as performance outcomes may significantly vary depending on operational conditions and cultivation strategies.

Higher cell concentrations in CO₂-based systems also benefit downstream processes by reducing harvesting volumes, thus improving operational efficiency. Although it can produce algal cultures with high cell concentrations, the CO₂-based cultivation method takes more energy for carbon supply system. This is due to the very poor carbon fixation efficiency value, which will be detailed further in the next section. However, the current study focuses specifically on the technical and economic comparison of carbon supply systems and does not delve into other subsystems or downstream processes.

Based on simulation results using previously established assumptions, the CO₂-based system consumed 3.57 kWh/day to operate the ring blower for carbon supply system, resulting in a dry biomass yield of 0.49 kg/day. In comparison, the bicarbonate-based system required 0.67 kWh/day for carbon supply system—via both a ring blower and a bicarbonate pump - producing 0.53 kg/day of dry biomass. When normalized to biomass output, the energy requirements were 7.29 kWh/kg dry biomass (DBM) for the CO₂-based system and 1.27 kWh/kg DBM for the bicarbonate-based system. The lower energy demand per unit biomass in the bicarbonate-based system indicates superior energy efficiency, which is a critical factor in assessing the feasibility of carbon capture applications. The comparison of BP, FR_{CO₂} and maximum algae cell concentration of CO₂-based and bicarbonate-based cultivation system is shown in **Table 4**.

Table 4 Comparison of BP value between CO₂-based and bicarbonate-based system.

Reference	Microalgae type	Cultivation condition	BP Value (g-DBM/L/d)	FR _{CO₂} * (g-CO ₂ /L/d)	Max. cell concentration (g/L)
1. CO₂-based cultivation system					
Do <i>et al.</i> [9]	<i>Scenedesmus acuminatus</i>	Erlenmeyer flask 500 mL	0.639	1.171	3.4
Lukyanov <i>et al.</i> [58]	<i>Chlorella vulgaris</i>	Flat plate PBR with a working volume of 3 L and 5 cm of light path	0.45	0.825	3.72
Our experiment	<i>Chlorella vulgaris</i>	Flat plate PBR with total reactor capacity of 100,000 L	0.049	0.091	0.508
2. Bicarbonate-based cultivation system					
Do <i>et al.</i> [9]	<i>Scenedesmus acuminatus</i>	Erlenmeyer flask 500 mL	0.186	0.341	1.5
Ratomski <i>et al.</i> [59]	<i>Chlorella vulgaris</i>	Vertical tubular PBR with a working volume of 80 L	0.013	0.024	0.62
Our experiment	<i>Chlorella vulgaris</i>	Flat plate PBR with total reactor capacity of 100,000 L	0.053	0.098	0.385

*Based on the assumption that the carbon content of microalgae biomass is 50.39 %w/w [54], the calculation was performed using Eq. (6).

Carbon fixation efficiency

Carbon fixation efficiency, often referred to as CO₂ fixation efficiency, indicates how effectively microalgae convert inorganic carbon (typically CO₂ or bicarbonate) into organic compounds through photosynthesis. It is calculated by comparing the amount of carbon fixed in biomass to the total carbon supplied, as shown in the following equation [9]:

$$E_{CO_2} = \frac{F_{CO_2}}{m_{CO_2}} \quad (8)$$

where E_{CO_2} is the CO₂ fixation efficiency (%), F_{CO_2} is the amount of CO₂ fixed during the entire cultivation period (g), and m_{CO_2} is the amount of CO₂ supplied to the system over the same period (g).

Carbon fixation efficiency is influenced by both internal and external factors. Internal factors are species-specific and relate to the inherent efficiency of the photosynthetic machinery and carbon assimilation pathways of a given microalgal strain. External factors include cultivation conditions such as CO₂ concentration, light intensity and photoperiod, temperature, pH, and nutrient availability [18,26,30].

Improving fixation efficiency from an internal standpoint involves selecting microalgal strains with high carbon assimilation capacity, rapid growth rates, and resilience to environmental fluctuations. Techniques such as random mutagenesis, adaptive laboratory evolution (ALE), and genetic engineering are widely used to enhance specific metabolic traits and stress tolerance, in addition to selecting naturally superior strains [18].

Externally, optimization of cultivation parameters is key to improve fixation efficiency. Suboptimal conditions reduce carbon assimilation and lower biomass productivity, which in turn diminishes biomass yield per unit volume or area. This increases operational costs due to the need for more energy input - e.g., prolonged lighting, extended cultivation periods, or higher CO₂ dosing rates to compensate for inefficiencies. Consequently, low carbon fixation efficiency negatively affects both technical and economic performance, ultimately reducing return on investment (ROI) and limiting commercial feasibility.

In CO₂-based systems, large volumes and concentrations of CO₂ gas are typically required, especially in photobioreactors (PBRs) and open pond systems.

However, due to limited solubility of CO₂ in water and the low carbon utilization rate of microalgae, only a small fraction of the supplied CO₂ actually fixed and most of it lost to the atmosphere. This evidenced by the typically low fixation efficiencies reported in CO₂-based systems, often around 10% or even below (Table 5) [9,11]. Additionally, increasing the CO₂ concentration (in bubbled gas) can significantly lower the culture pH of medium and potentially inhibiting algal growth. To mitigate this, a pH control system involving alkaline reagents must be implemented, adding to both capital and operational costs.

Despite these limitations, some studies demonstrate that fixation efficiency in CO₂-based

systems can be significantly improved through reactor arrangements. For example, arranging PBRs in a cascade or series configuration has been shown to enhance CO₂ utilization. Do *et al.* [9] achieved a fixation efficiency of 64.8% by connecting ten PBRs in series using *Scenedesmus acuminatus*. This was further improved to 93.9% by introducing triethylenetetramine (TETA), a CO₂ absorption enhancer, into the cultivation medium. However, this setup increases the complexity of reactor construction and operation. The need for a highly intricate CO₂ distribution system - with multiple interconnected blowers and pipelines - significantly elevates both capital and maintenance costs (Figure 6).

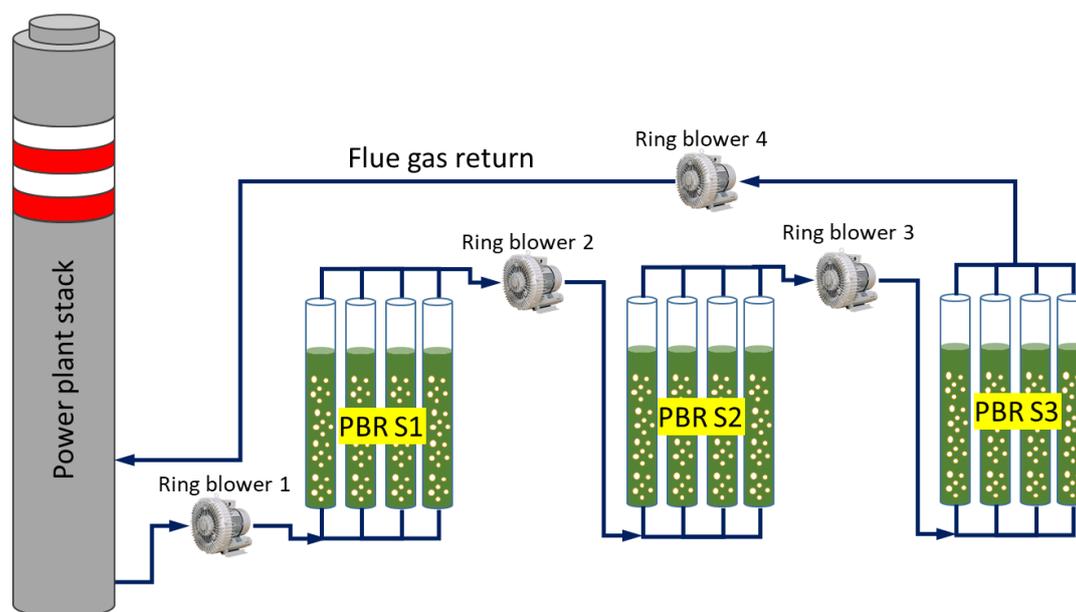


Figure 6 Process flow diagram of a CO₂-based cultivation system using 3 photobioreactors (PBRs) in series. Increasing the number of PBRs in series necessitates a more complex construction design and additional equipment. PBR S1: photobioreactor Series 1, and so on.

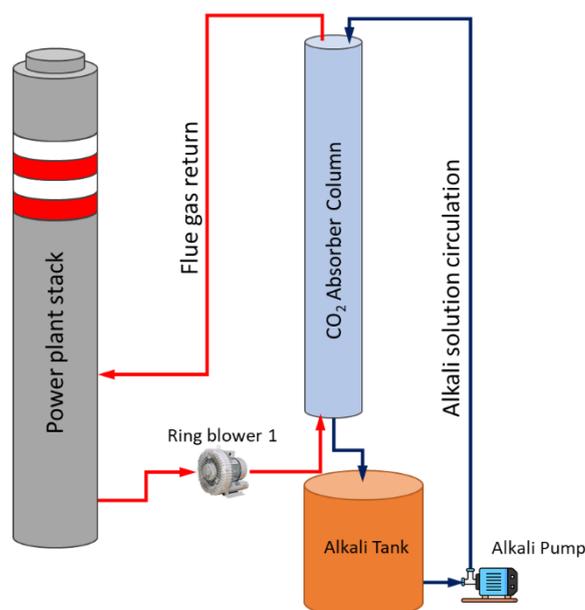


Figure 7 Process flow diagram of a CO₂ absorber column to produce bicarbonate ions from power plant's flue gas.

Alternatively, bicarbonate-based systems offer notable advantages in improving carbon fixation efficiency. Bicarbonate has higher solubility in water compared to gaseous CO₂, resulting in improved carbon availability for algal uptake and more stable pH conditions - favorable for algal growth. This benefit illustrated in Do *et al.* [9], who reported a carbon fixation efficiency of 100% when cultivating microalgae *S. acuminatus* with 4.2 g/L sodium bicarbonate (**Table 5**).

Moreover, bicarbonate-based cultivation can be integrated with a CO₂ absorption system that uses flue gas and an alkaline solution to generate bicarbonate ions. When properly designed, this approach can be more compact, cost-effective, and operationally efficient (**Figure 7**). Unlike the complex piping and gas distribution systems required for CO₂ bubbling into multiple PBRs, bicarbonate systems involve a more centralized CO₂ absorption unit followed by a simpler bicarbonate solution distribution line for delivering bicarbonate-enriched media to the reactors (PBR).

Table 5 Summary of various study on carbon fixation efficiency: bicarbonate-based vs CO₂-based.

Strain	Carbon Fixation Efficiency	System description	Reference
1. Bicarbonate-based			
<i>Chlorella vulgaris</i>	29.6%	Bicarbonate-based	[60]
<i>Spirulina platensis</i>	26.71%	Bicarbonate-based	[61]
<i>Dunaliella salina</i>	91.4%	Bicarbonate-Based with 5 g/L of NaHCO ₃	[21]
<i>Chlorella sorokiniana</i> SU-1	84.5%	Bicarbonate-based with 5 g/L of KHCO ₃	[62]
<i>Scenedesmus acuminatus</i> TH04	100%	Bicarbonate-based with 4.2 g/L of NaHCO ₃	[9]
<i>Parachlorella kessleri</i> , <i>Vischeria cf. stellata</i> , and <i>Porphyridium purpureum</i>	> 85%	Bicarbonate-Based 6 g/L of NaHCO ₃	[44]

Strain	Carbon Fixation Efficiency	System description	Reference
<i>Spirulina sp.</i>	58%	Bicarbonate-based	[63]
<i>Chlorella vulgaris</i>		Flat plate PBR	Simulation result
2. CO₂-based			
<i>Scenedesmus acuminatus</i> TH04	9.8%	CO ₂ -based with optimal concentration of 5% CO ₂ (v/v)	[9]
<i>Dunaliella salina</i>	3.59%	CO ₂ -based	[21]
<i>Chlorella sorokiniana</i> SU-1	11.1%	direct CO ₂ injection	[62]
<i>Chlorophyta</i>	15.6%	Closed PBR	[64]
<i>Phorphyridium purpureum</i>	13.5%	Tubular PBRs	[65]
<i>Chlorella vulgaris</i>		Flat plate PBR	Simulation result

Net energy ratio

The net energy ratio (NER) is a system calculated by dividing the total energy generated (i.e., the energy content of the product - in this case, algal biomass) by the total energy consumed during the production process [45]. This study compares the NER values of CO₂-based and bicarbonate-based systems using the operational simulation data described previously. To focus on the core aspect of our study, only the energy consumption of the carbon supply system is considered in the simulation, as shown in **Figure 5**. Energy use from other subsystems excluded under the assumption that these are identical in both scenarios. The NER in this study calculated using the following equation [45]:

$$\text{NER} = \frac{\sum \text{Energy generated (calorific value of DBM)}}{\sum \text{Energy requirements (for carbon supply system only)}} \quad (9)$$

As shown in **Figure 5**, the CO₂-based system's energy consumption includes only the energy required to operate a ring blower that transports flue gas from the power plant to the PBR. In contrast, the bicarbonate-based system accounts for the energy used by the ring blower, the alkali solution circulation pump in the CO₂ absorption system, and the bicarbonate distribution pump, which delivers the bicarbonate solution from the absorber to the PBR. Energy demands for other subsystems - such as harvesting, drying, and nutrient supply - are not included in this analysis.

The NER calculation in this study specifically focuses on the energy consumption of the carbon supply system, excluding energy inputs from downstream processes such as biomass harvesting and drying. These stages are widely recognized as significant contributors to the total energy demand in microalgae production systems. As such, the resulting NER values primarily reflect partial energy efficiency specific to the carbon supply stage. To obtain a more comprehensive assessment of overall system viability, a full life cycle energy balance approach would be necessary - one that includes all production stages, particularly downstream operations. Incorporating these elements in future analyses may yield NER estimates that are more representative of real-world industrial applications.

According to our simulations results, the total energy usage per day in the CO₂-based system is 35.71 kWh, while in the bicarbonate-based system is 4.23 kWh. These values calculated using Eq. (3). While the energy content in algae biomass of each scenario assumed to be the same of 5,303 kcal/Kg or 6.16 kWh/Kg DBM [54]. The total energy generated was calculated by multiplying the energy content of the biomass with BP value. Based on this calculation, the NER value is 0.85 for the CO₂-based system and 7.72 for the bicarbonate-based system, indicating that the bicarbonate-based system is superior to the CO₂-based

system in terms of energy efficiency of the carbon supply system.

For a microalgae cultivation project to be considered energetically and economically viable - particularly for energy applications such as biofuel or biomass fuel production - the NER must be greater than one. A higher NER indicates greater energy efficiency and feasibility [45]. However, if the biomass product intended for non-energy applications (e.g., food, nutraceuticals, or chemicals), a low NER may still be acceptable, as the value lies in the product's functionality rather than its energy content.

The NER strongly influenced by the design and complexity of the carbon capture system. Systems with multiple energy-intensive components typically result in lower NER values. Conversely, systems that produce biomass with high calorific value (e.g., lipid-rich strains) can improve the NER. Additionally, operational efficiency - achieved through reduced energy consumption - can also enhance NER values [45].

A comparative simulation by Jorquera *et al.* [45] illustrates this concept well. They evaluated the NER of 3 microalgae cultivation systems - raceway ponds, flat-plate PBRs, and tubular PBRs - each designed to produce 100,000 kg of dry biomass (DBM) per year. Their results showed high NER values for raceway ponds (8.34) and flat-plate PBRs (4.51), while the tubular PBR system exhibited a much lower NER of 0.20, indicating it was not viable for net energy production. This demonstrates that the appropriate carbon capture system design has a significant impact on the NER value.

Slade and Bauen [46] reviewed several Life Cycle Assessment (LCA) studies of microalgae cultivation projects which covers all of production aspects such as cultivation, harvesting and drying systems. Their findings indicate that 6 out of 8 raceway ponds cultivation project reviewed in their study have shown energy input less than energy generated in biomass content which indicates that these systems might attain a positive energy balance. However, in the same study, most PBR projects have shown energy generated less than energy consumed in all cases of their study which

indicates negative energy balance. The top-performing PBR in their study is the flat-plate system, which outperformed tubular PBRs due to its extensive illumination surface area and reduced oxygen accumulation.

From the perspective of NER, and based on the 2 references above, the order of potential project feasibility based on reactor type is: Raceway pond, PBR-Flat plate and, the least feasible, is tubular PBR. However, the use of raceway pond is generally infeasible for carbon capture application in coal-fired power plants due to space limitations, layout constraints, the complexity gas distribution piping, and safety concerns - particularly the risk of hazardous gases such as SO₂, escaping into the environment and posing risk to workers. Due to this infeasibility of using raceway ponds, the PBR flat plate (flat planar) emerges as the most viable option.

To improve the overall feasibility of the project, alternative strategies to the conventional CO₂-based system are being explored, with particular emphasis on the development of bicarbonate-based system. One of the most well-known technological developments based on the bicarbonate-based system is BICCAPS (The bicarbonate-based integrated carbon capture and algae production system) as explained previously. This process enables a more sustainable and cost-effective means of collecting and supplying the nutrients for cultivating microalgae [38].

Cordoba-Perez and de Lasa [60] evaluated the performance of *Chlorella vulgaris* grown with NaHCO₃ as the inorganic carbon source. The study reported a maximum carbon conversion efficiency of 29.6%, demonstrating that nearly one-third of the supplied bicarbonate was assimilated into microalgal biomass, reinforcing the potential of bicarbonate-based systems for biofuel and carbon capture applications. These improvements in carbon fixation efficiency will directly enhance the NER value and consequently, improve the overall feasibility of the project. The following table (**Table 6**) presents a comparison of the NER results obtained from our simulation.

Table 6 The comparison of NER value between CO₂-based and bicarbonate-based.

Parameters	CO ₂ -based system	Bicarbonate-based system
I. Energy requirements		
- Ring blower for supplying flue gas to PBR	35.71 kWh/day	0 kWh/day
- Blower in CO ₂ absorption system	0 kWh/day	0.55 kWh/day
- Alkali circulation pump	0 kWh/day	0.07 kWh/day
- Ring blower for PBR mixing	0 kWh/day	3.57 kWh/day
- Bicarbonate supply pump	<u>0 kWh/day</u>	<u>0.00004 kWh/day</u>
Total energy requirements:	35.71 kWh/day	4.19 kWh/day
II. Energy generated		
- Biomass productivity (dry basis)	4.90 Kg/day	5.30 Kg/day
- Calorific value of biomass	<u>6.16 kWh/Kg</u>	<u>6.16 kWh/Kg</u>
- Total energy generated	30.20 kWh/day	32.67 kWh/day
Net Energy Ratio (NER)	0.85	7.79
Specific Energy Consumption	7.29 kWh/Kg DBM	0.79 kWh/Kg DBM

Technical, economical and environmental comparison

The selection of carbon supplementation strategies - whether through direct CO₂ or bicarbonate-based delivery - plays a pivotal role in determining the overall feasibility and sustainability of microalgae-based carbon capture systems. Each approach presents distinct trade-offs in terms of technical design, energy requirements, operational complexity, and environmental performance [66]. Technically, bicarbonate-based systems provide greater carbon fixation efficiency and better pH stability, as CO₂ converted into bicarbonate via chemical absorption. This allow for more controlled carbon dosing and reduced carbon loss. This system minimizes gas stripping and energy consumption related to continuous aeration, making it more suitable for open pond systems [67]. In contrast, CO₂-based systems are simpler in infrastructure and lower in initial cost, utilizing direct flue gas injection into the photobioreactor. However, these systems often suffer from inefficient CO₂ utilization and pH fluctuations, which can hinder algal productivity. Closed PBR systems are compatible with both approaches but require careful gas management in CO₂-based setups to maintain cultivation stability [66,67].

Economically, these approaches associated with different cost structures. CO₂-based systems typically involve lower upfront capital investment and chemical

cost but incur higher long-term operational expenditures (OPEX) due to the energy demands of gas compression, storage, and distribution [67,68]. In contrast, bicarbonate supplementation requires additional investment in absorber units and alkaline reagents such as NaOH. Nevertheless, this system can significantly reduce energy consumption - by as much as 80% - 90% compared to conventional CO₂ systems - due to the minimal power requirements for liquid dosing rather than gas injection. This leads to significantly lower OPEX and addresses a major bottleneck in the economic scalability of algae-based production [69,70]. From an environmental perspective, bicarbonate supplementation associated with lower upstream carbon footprints, particularly when integrated with industrial waste streams or recycling systems. CO₂-based systems, while chemically simpler, tend to exhibit higher carbon intensity in upstream processes due to energy use in gas handling. Moreover, they suffer from high fugitive emissions - over 90% of unabsorbed CO₂ and other gases can be lost during cultivation - whereas bicarbonate systems localize emissions to the absorption stage, allowing for easier monitoring and mitigation. In terms of resource consumption, CO₂ systems may require intermittent alkalinity addition to correct acidification, while bicarbonate systems involve routine chemical input that can be minimized through recycling strategies [66,70]. These comparative insights are summarized in **Table 7**.

Table 7 Comparison of technical, economical and environmental aspects.

Comparison aspects	CO ₂ -based system	Bicarbonate-based system	Reference
1. Technical aspects			
Operational aspects	Carbon rapidly available but can fluctuate due to poor dissolution. Requires tight pH control since CO ₂ can cause acidification.	More stable and better control carbon availability. Acts as buffer, provide pH stability.	[66-68]
Maintenance	More complex maintenance activity due to more complex interconnection line of gas bubbling system. More costly due to corrosion risks to the metal components.	Lower maintenance requirements.	
Scalability	Well-established for industrial scale.	Still under optimization for large-scale system.	
2. Economical aspects			
Investment cost (CAPEX)	Commonly, conventional bubble reactor design with low efficiency requires low investment cost. More complex design for efficiency improvement (Figure 6) requires significantly higher investment cost.	Need additional investment for CO ₂ absorption system.	[68-70]
Operational cost (OPEX)	CO ₂ -based system has low carbon fixation efficiency and Net Energy Ratio (NER). This results in elevated energy consumption costs.	Bicarbonate-based systems outperform conventional CO ₂ -based systems in terms of carbon fixation efficiency and Net Energy Ratio (NER). This advantages will reduce the energy cost significantly. Additional cost will come from alkalinity consumption which can be minimized significantly by the implementation of alkalinity recycling system.	
3. Environmental aspects			
Carbon footprints	Lower carbon footprints in upstream process.	Higher carbon footprints in upstream process which come from alkalinity production.	[66-69]
Other emission issues	High fugitive emissions (more than 90% of CO ₂ and other unabsorbed components from feed gas) will be released from PBRs.	Emission point is concentrated in CO ₂ absorption system which is easier to be controlled.	
Resource consumption	Commonly, no additional chemical is required but in some cases alkalinity	Routine alkalinity consumption for CO ₂ absorption system. It can	

Comparison aspects	CO ₂ -based system	Bicarbonate-based system	Reference
	addition is required for pH maintenance due to continuous media acidification by CO ₂ bubbling.	be minimized by the implementation of alkalinity recycling system.	

Future perspectives

The transition toward more sustainable and energy-efficient carbon capture strategies necessitates further development and scaling up of bicarbonate-based microalgae cultivation systems. As demonstrated in this review, bicarbonate-based systems outperform conventional CO₂-based systems in terms of carbon fixation efficiency, net energy ratio (NER), and operational stability. Future research should focus on enhancing the integration of CO₂ absorption technologies with microalgal cultivation units, particularly through the optimization of absorber design, reagent regeneration, and bicarbonate dosing control. Genetic and metabolic engineering of microalgal strains to further improve bicarbonate uptake kinetics and stress tolerance could also enhance system performance. Moreover, techno-economic and life cycle assessments (LCA) must be expanded to include the entire production chains - from flue gas conditioning to downstream biomass utilization - to validate long-term feasibility of these systems. Innovative systems such as BICCAPS offer promising solution, and future pilot-scale or industrial demonstrations will be critical to establish commercial viability. Ultimately, advancing bicarbonate-based BioCCU technologies will support the dual goals of mitigating industrial CO₂ emissions and producing valuable bio-based products, contributing to global efforts toward a circular carbon economy and net-zero targets.

Conclusions

Based on technical comparison in this study, the bicarbonate-based system superior to the CO₂-based system in terms of simplicity of construction and operation. This system also has a very high carbon fixation efficiency (can reach 100%), which has an influence on lowering particular operational costs in the carbon supply system, supporting the economic viability of the technology. On the other hand, the CO₂-based system, while having a poor carbon fixation efficiency (below 10%), produces algal biomass with high cell

densities, making harvesting process easier and more efficient. Although the carbon fixation efficiency of CO₂-based system can be improved by PBR arrangement, it necessitates a highly extensive PBR structure, making the building and operation processes extremely complex and expensive, rendering it ineffective.

In terms of economic efficiency, the bicarbonate-based system outperforms the CO₂-based system, with a NER value of 7.79 vs 0.85 for the CO₂-based system. It was further backed by a low specific energy consumption of 7.29 kWh/Kg DBM generated for the bicarbonate-based system, as opposed to 0.79 kWh/Kg DBM for the CO₂-based system. Although bicarbonate-based carbon supply systems use less energy than CO₂-based systems, it is crucial to highlight that in this system, the alkali material recycling process must be used to reduce chemical purchase costs.

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Declaration of Generative AI in Scientific Writing

AI was used in writing this paper to help streamline the language style because the authors are not native English speakers.

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