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ORIGINAL RESEARCH ARTICLE

Review study for carbon dioxide capturing technologies

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ABSTRACT

Greenhouse gas emissions, particularly CO_2, continue to drive global warming and threaten energy security. This review evaluates current CO_2 capture technologies—including membrane separation, cryogenic separation, chemical absorption, adsorption using porous solids, chemical looping, and microalgae-based carbon capture. While advanced, conventional CCS methods face challenges such as high energy demand, costly infrastructure, solvent degradation, and environmental risks. Among emerging alternatives, bioenergy with carbon capture and storage (BECCS) and microalgae cultivation show strong potential for achieving negative emissions. Vertical tubular photobioreactors and flue-gas-fed cultivation systems demonstrate high biomass productivity and effective CO_2 biofixation. This review summarizes the advantages and limitations of each technology and highlights the need for developing low-energy solvents, durable membrane materials, optimized adsorption media, and cost-effective microalgae cultivation systems. These insights support future efforts to improve the economic viability and environmental sustainability of CO_2 mitigation technologies.

Keywords: microalgae-based CO_2 sequestration; bioenergy; negative emissions technologies; bioreactors; BECCS, microalgae-based CO_2 sequestration, negative emissions technologies.

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1. Introduction

Every year, human activity releases roughly 7 gigatons of carbon into the atmosphere. Carbon dioxide makes up the majority of this carbon, with fossil fuel power plants accounting for 30% of it. One of the primary causes of global warming is carbon dioxide, which is being emitted quickly due to industrialization [1]. Before the era of industrialization, the atmospheric CO_2 concentration was about 280ppm, which increased to 380ppm afterwards[2]. Moreover, the rise in CO_2 levels has stimulated concerns about climate change, as its further increase can destroy human civilization [3]. Energy consumption is on the rise, which leads to two major issues of [1] pollution of the environment caused by burning fossil fuels and [3] exhaustion of fossil fuel supplies.

The latest report of the Intergovernmental Panel on Climate Change (IPCC) [4] , states that in order to prevent the global average temperature from increasing by 1.5°C above pre-industrial levels, greenhouse gas emissions must be reduced immediately.

Despite the implementation of a high CO_2 price and existing CO_2 reduction measures, total residual CO_2 emissions across many industries (e.g., transport, buildings, energy sources) are expected to remain at 850-1150 $GtCO_2$ between 2016 and 2100, [5] This is due to the growth of the world's population expansion, food production, and rising energy use. Therefore, CO_2 must be removed from the atmosphere [5].

The IPCC released four scenarios (Fig .1) that describe how global average temperature could be limited to 1.5 degrees Celsius. The assumptions made regarding food and energy consumption were the main cause of the differences across the scenarios, and the stringent enforcement of climate regulations [4], in which CO_2 removal is of paramount importance. CO_2 removal involves two categories: CCS and CCU. The idea is simple: by 2100, the world could follow a path to reduce carbon emissions. The diagram shows four images, each with a different rate of reduction and reliance on different carbon removal technologies. Each color represents the amount of carbon dioxide emissions.

The gray area: emissions from fossil fuels and industry.

The brown area: emissions from agriculture and forestry (often remaining close to zero).

The yellow area: carbon capture and storage in biomass.

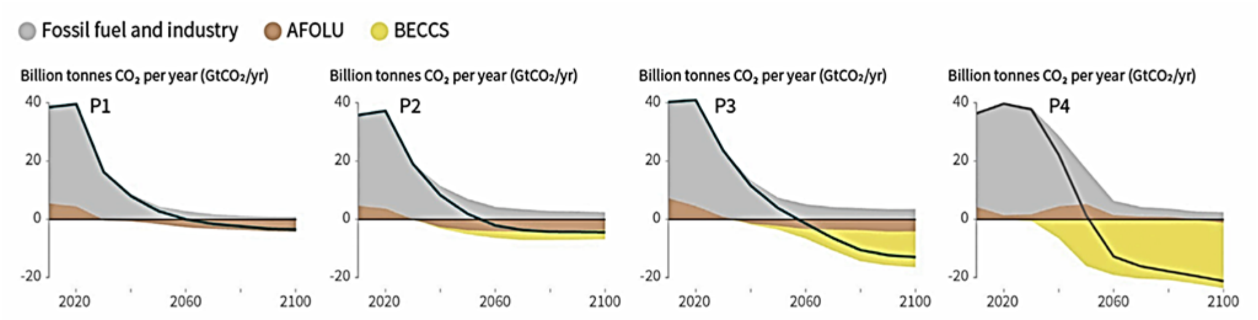


Figure 1. An analysis of the sources contributing to Global net carbon dioxide emissions under four emission reduction scenarios aimed at restricting the average global temperature increase to 1.5 °C.

Scenario 1 (P1): AFO LU serves as the sole CO_2 removal strategy, depending on innovations that require less energy. Scenario 2 (P2): Society transitions to sustainability through health-conscious habits, low-emission technologies, and a limited role for BECCS. Scenario 3 (P3): Society and technology adhere to historical trends, with minor reductions in energy demand and a larger BECCS contribution than in the P2 scenario. Scenario 4 (P4): Extensive energy and resource utilization occur alongside elevated energy demands and livestock production, with significant emissions removal facilitated by BECCS [6] .

Biological methods are considered to be the most economical, sustainable, and ecologically favorable approach to carbon capture and storage. Plants, microalgae, and other organisms are frequently employed for the sequestration of biological carbon. On a general level, Plants only reduce carbon emissions by about 3–6%, but under the right circumstances, microalgae such as green algae and cyanobacteria have the potential to be 50 times more effective[7].

1.1. Carbon capture, storage, and utilization (CCS and CCU) overview

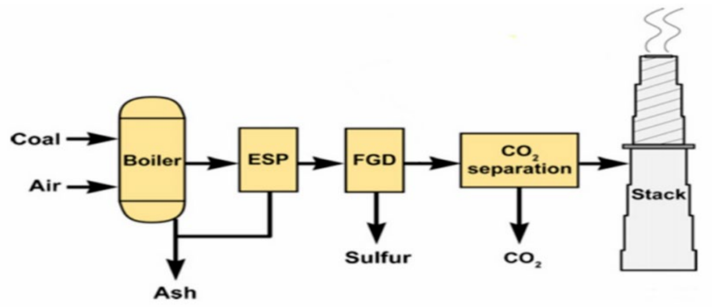
There are three primary processes in carbon capture systems: 1) CO_2 capture and storage; 2) CO_2 gas compression and transportation; 3) CO_2 storage in a storage facility or use of captured CO_2 in the production of energy sources or chemical products. Post-combustion, pre-combustion, and oxy-combustion are the three primary categories into which the numerous capture procedures fall (Table 1).

1.2. Post-combustion technology

Technology used after combustion is typically used only on flue gases and can capture high concentrations of CO_2 in various applications, such as enhanced oil recovery [8]. Membrane separation, cryogenic distillation, adsorption, and chemical absorption are examples of modern post-combustion systems.(Fig 2.a) Schematic diagram of a simplified flue gas cleanup process for post-combustion carbon capture [9]. The high temperature of exhaust gas further limits the CO_2 capture efficiency. Furthermore, pollutants like NOx, SOx, or fly ashes may be present in the flue gas, which raises the cost of separation using current technology [[9],[10]. This figure is the crucial stage where carbon dioxide is separated and isolated from other gases using various techniques (such as chemical absorption or membranes).Final stage - outlet (stack): The remaining clean gases are released into the atmosphere through the stack, while the separated carbon dioxide is transported for storage or use in other applications. In short, this process transforms conventional power plants into environmentally friendly ones by capturing carbon before it reaches the atmosphere.

1.3. Pre-combustion technology

Initially, the fuel is transformed into a flammable gas. This gas is used to generate energy [11] . Before combustion, CO_2 is separated and sequestered from this gas, which is produced from fossil fuels [12]. Figure 2 shows a schematic diagram of the process. Syngas is produced from fossil fuels and consists primarily of H2 and CO, with trace amounts of CO_2. Steam is added to the fossil fuel to do this. We refer to this procedure as steam reforming[13]. Figure 2.b: Schematic diagram of the pre-combustion CO_2 capture process [14]. The separated carbon dioxide is transported to underground geological storage facilities (in deep layers of earth or sealed wells), where it remains permanently trapped and does not return to the atmosphere.



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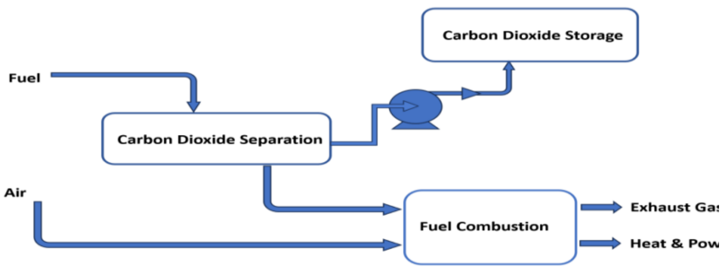

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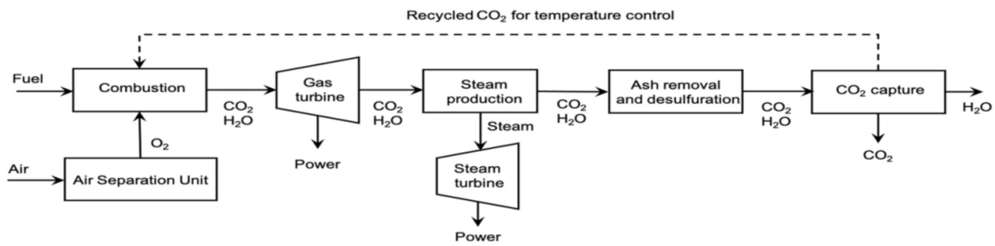

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Figure 2. (a) Schematic diagram of (a) simplified flue gas cleanup process for post-combustion carbon capture [9], (b) pre-combustion carbon capture process [14], and (c) Oxy-combustion with CO_2 capture applied to a combined cycle power plant[15]

2. Oxy-fuel combustion

Oxy-fuel combustion refers to the combustion of a fuel using pure O_2 instead of air. In the case of oxy-fuel combustion, the products of fuel combustion are CO_2 and H_2O, and instead of air, pure oxygen is supplied via cryogenic or membrane methods, in which water is separated by condensation[16]. Oxy-combustion was developed at the beginning of the 1980s and gained interest in the 1990s due to the environmental impact of fossil fuels [17]. Nowadays, there are a few pilot plants (TRL-7) operating on a commercial scale. Some examples are the 30 MW coal plant promoted by Endesa, CS Energy, and Vattenfall, or the 35 MW oil plant of Total SA [18]. Fig. 2 c. Oxy-combustion with CO capture applied to a combined cycle power plant, instead of burning fuel with ordinary air (which contains 79% nitrogen), the fuel is burned with pure oxygen (O_2). This radically changes the nature of the emissions. Since the emissions consist primarily of CO_2 and H_2O, separating the carbon becomes very easy. Water (H_2O) is easily separated from carbon dioxide. The ultimate use of the captured CO_2 can be divided into two main pathways: carbon capture and storage (CCS) and carbon capture and utilization (CCU). CCS is estimated to contribute more to negative net emissions, whereas CCU reuses CO_2 in industrial operations to generate economic benefits [19]. Table 1 presents the main categories of carbon mitigation technologies along with their associated benefits and limitations.

Table 1. List of categories of carbon mitigation technologies with their benefits and downsides [20,21]

Category of capture	Summary	Benefits	Downsides
Post_ combustion	•Removes CO_2 from exhaust gases after fuel combustion	• Easy integration with current industrial infrastructure; risk reduction from the most advanced technology	•The lower pressure of CO_2 in the flue gas leads to an increase in the consumption of energy and the cost of capture; large equipment is necessary for this. • Location specific
Pre_ combustion	•produces H_2 and CO_2 when it reacts with oxygen or water vapor to remove CO_2 from fuel.	•Less regenerative energy; little equipment is required to capture it •The output stream can have a high concentration of CO_2.	•Implementation of this technology is difficult in existing power plants. • Complex procedures and lack of operational knowledge
Oxy-fuel	•Use pure oxygen to burn fuel rather than air.	•High concentration of captured CO_2; less NOx formation	•Costs money to maintain, and requires an expensive air filter. •Reduced efficiency and greater energy loss

3. Carbon capture technologies

3.1. Chemical absorption-stripping process

The most sophisticated technology is chemical absorption for removing carbon dioxide from flue gas. It has been widely used for the removal of carbon dioxide and hydrogen sulfide from natural gas for more than 60 years, and has also been used for post-combustion capture in recent decades [22] . Solvent absorption and stripping system. The standard procedure in a power plant for chemical absorption and stripping (Figure 3) first passes the flue gas through a tower filled with an amine aqueous solution to absorb carbon dioxide. After the amine solution is saturated, it is moved into a stripper and heated to 100–120 °C, typically with the help of power plant waste steam, to be converted back into a reusable solution [23]. Following its release, after compression, the CO_2 is moved for usage or sequestration.

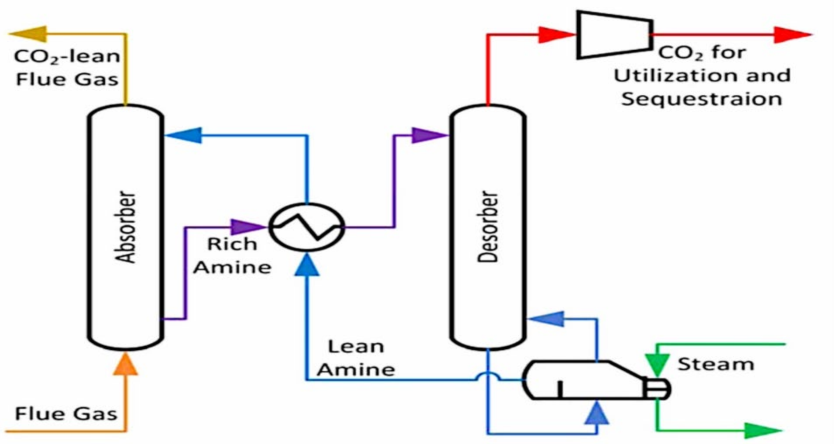

Figure 3. illustrates the process of an absorption-stripping unit. The carbon dioxide absorber is usually an amine solution. The absorber separates the captured carbon dioxide from the amine solution. Before returning the amine solution to the absorber, it is passed to a cooler [23].

As technology develops, the technology of capturing carbon dioxide using organic amine solutions is becoming more and more efficient. Researchers have conducted numerous investigations of how organic amine solutions absorb CO_2 because of their superior capture capacity and separation efficiency [24].

Despite the organic amine solution's exceptional capacity to absorb CO_2, the desorption process requires a significant amount of energy, and this energy consumption makes up roughly 70% to 80% of the total energy required for CO_2 capture. Consequently, one of the most important steps in the future development of CO_2 capture technology is resolving the energy consumption issue of organic amine solution desorption [25]. Four monoethanolamine-based absorbents (MEA/water, MEA/ethanol, and two types of MEA/ethanol/water) were tested for their absorption and desorption performance. According to the results, the MEA that was mixed with ethanol had a higher desorption effect, a lower desorption temperature, and a good capacity for regeneration.

The process is referred to as chemical absorption if the solvent and CO_2 combine to form chemical compounds. Later, CO_2 is extracted from the chemical components. However, if the solvent is chemically inert, it does not react with CO_2. It soaks the CO_2 physically. This process is called physical absorption [14]. After that, it is saved and compressed. The lean solvent from the CO_2 regeneration is returned to the absorber [26].

3.2. Adsorption

This is the method of employing a solid surface to extract a component from a mixture. In contrast to absorption mechanisms, the solid phase adsorbent surface and CO_2 create physical or chemical connections. Intermolecular forces between the surfaces of the gas and the solid are what propel adsorption [27].

One or more layers of gas can be taken in depending on the size of the adsorbent's pores, as well as factors such as temperature, pressure, and surface forces [28]. Initially, the column is packed with the adsorbent material. Next, a gas stream containing CO_2 is directed through this column. As the gas flows, the CO_2 attaches itself to the adsorbent's solid surface until the material reaches saturation. Once the surface is fully saturated with CO_2, it is extracted and desorbed through various cycles for CO_2 adsorption [27].

Pressure swing adsorption is one type of post-combustion based adsorption technology, vacuum pressure swing adsorption, temperature swing adsorption, and electric temperature swing adsorption. Solid adsorbents can be divided into two categories: Amine-based adsorbents are chemical (chemisorption), whereas metal-organic materials and zeolites are physical (physisorption)[10]. While the latter takes advantage of non-bonded contacts, the former releases CO_2 through a selective reaction with surface-bound amine groups [29].

3.3. Membrane-based system

Membranes function similarly to a filter, and how well they work depends on how permeable and selective they are to particular molecules [30]. Both pre- and post-combustion CO_2 collection processes can benefit from membrane-based technology. Membrane contractor (MC) and membrane gas separation (MGS) are the two primary choices (Fig. 4). The former diffuses into the permeate side using ion-conducting membranes or selective surface diffusion to desorb through a dense membrane matrix [31], Whereas the latter promotes mass transfer using a highly hydrophobic microporous membrane, where the solvent dominates the CO_2 selectivity [32]. MGS systems are widely used to separate natural gas from CO_2 /CH_4 [33] .

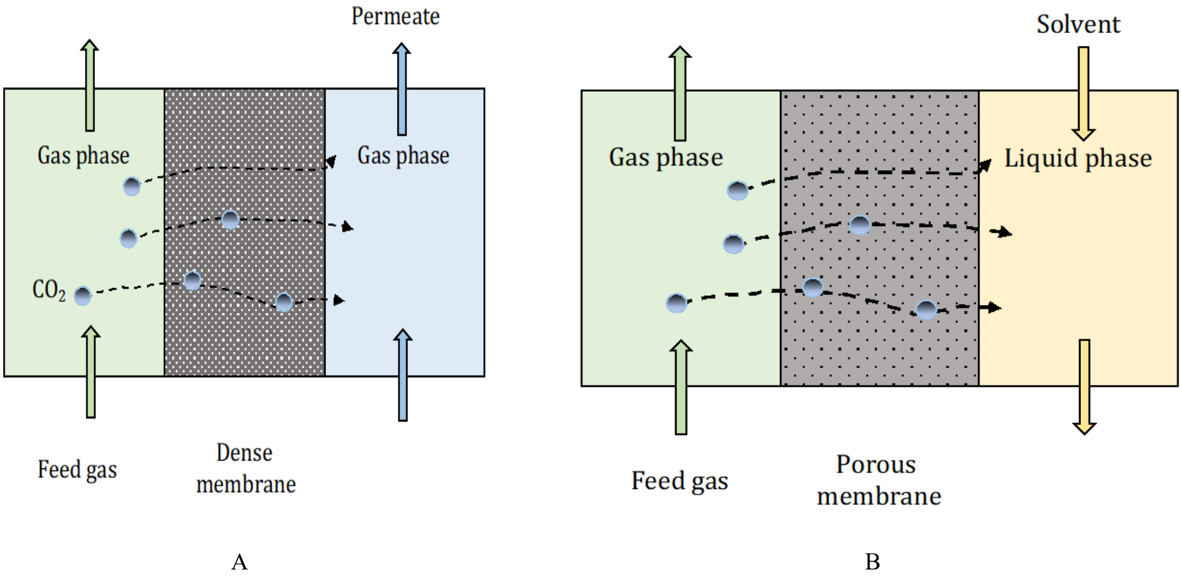

Figure 4. A; membrane gas separation (MGS) and B; Schematics for membrane contractors (MC). While MC employs porous membranes with a liquid solvent on the other side that has good CO_2 selectivity, MGS uses a dense membrane with the gas phase on the other side that uses selective surface diffusion.

Membranes can be categorized into two classes: organic membranes, which are made of polymer material, and inorganic membranes, which are composed of mineral material. Today, polymeric membranes are involved in numerous applications that involve CO_2 differentiation. However, they have suboptimal CO_2 selectivity, making them unsuitable for large-scale CO_2 separation and purification [[34],[35]]. On the other hand, inorganic membranes are a promising separation membrane material because of their superior stability, resistance to corrosion, and separation performance [35]. Membranes, however, have a number of drawbacks: Because of their short lifespan, the membranes require periodic replacement and are costly. High temperatures in the stream output can cause the modules to deteriorate, and fouling can lower their permeability. As a result, the flue gas needs to cool down before passing through the membrane. Furthermore, moisture and traces of acidic substances can affect membranes [[36],[37],[38]].

3.4. Chemical looping

Chemical looping combustion is a new method of carbon capture that is innovative in the field. This approach has the potential to be the most effective and budget-friendly method for capturing CO_2 for power plants that use fossil fuels. The IPCC considered this method to be among the least priced carbon removal[39] . It has the benefits of CO_2 detection with a minimum amount of energy required. The air and fuel cannot communicate directly with one another; this is why the practice is also called unmixed combustion [11]. The primary benefit of the air and fuel are not combined in the chemical loop, which results in no dilution of the products of fuel transformation using nitrogen [40]. It removes the requirement for a second Separation Unit. However, the intricate process engineering design, which includes intricate interactions between substances and gases, the stability of the material, and the design of the reactor, presents several challenges to the technology's implementation [41].

3.5. Cryogenics

The cryogenic method of removing CO_2 from flue gases uses distinct gas condensation and desublimation properties to extract CO_2 with a purity of greater than 99.99%[42] . The collected CO_2 can be utilized for chemical purposes, including fertilizers or food. Physical sorbents and chemical solvents are not needed when using cryogenic CO_2 capture [43]. Compared to other technologies, CO_2 removal is made possible by low-temperature techniques; certain cryogenic systems have attained a 99.99 percent purity level [44]. The flue gas is cooled until it is below the boiling point of CO_2, which is around 75°C [37]. This process's benefit is that it makes it possible to recover pure CO_2 in a transportable liquid form [38]. Even though the cryogenic separation method produces extremely high levels of CO_2 purity, it is typically only useful in situations where the concentration of CO_2 is high [37]. High temperature, low partial pressure, and low CO_2 concentration flue gas are not suitable for the cryogenic separation process [45].

3.6. Bioenergy with carbon capture and storage (BECCS)

BECCS is seen as a potentially effective negative emissions technology (NET) due to the fact that the total CO_2 taken from the atmosphere through biological processes, combined with CO_2 captured during the conversion of biomass to energy, exceeds the CO_2 emissions generated from the energy utilized in this conversion (Figure 5). BECCS can serve as a suitable replacement for current coal-fired power facilities that save jobs and boost the economy without requiring government help [46], alongside facilitating job growth [47]. BECCS is expected to be more socially embraced due to its environmentally friendly and sustainable image when compared to fossil fuel CCS [48] .

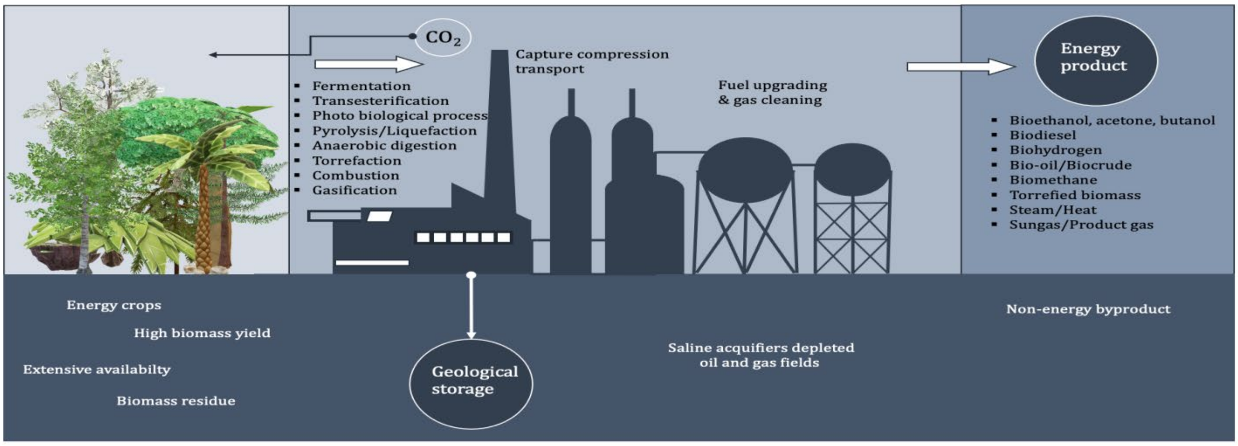

Figure 5. Diagram illustrating the BECCS process, starting from plantation, through the fixation of atmospheric CO_2 with high biomass output, to the transformation into energy products. Once harvested, biomass is moved for processing via combustion, fermentation, gasification, or anaerobic digestion. During the conversion phase, the CO_2 that is released is caught and kept in storage. Electrical power, biofuels, or heat are examples of the energy output[49].

In this framework, BECCS (bioenergy with carbon capture and storage) becomes an important technology, notably because it provides negative emissions [[50],[51]]. BECCS is a set of procedures that capture, move, and store carbon dioxide produced during the production of bioenergy in deep geological formations [[51],[52]]. Installing carbon capture and storage systems at bioenergy facilities has the potential to generate negative emissions because biomass growth through photosynthesis absorbs carbon dioxide that is normally released back into the atmosphere during bioenergy production [52].

Environmental issues such as overuse of land, excessive use of water, and deteriorating soil health and biodiversity pose obstacles to bioenergy with carbon capture, storage, and sequestration (BECCS)[53].

4. Critical comparison of CO2 capture technologies

To strengthen the quantitative comparison, this section has been expanded to include capture cost ranges, energy penalties, and maturity levels for major CO_2 capture technologies. Conventional CCS systems, such as amine absorption, typically have capture costs of ~70–200 US$/t$CO_2$ with energy penalties of 5–15 percentage points, while advanced membranes and cryogenic systems show lower reported costs in favorable conditions. Microalgae-based systems currently have higher implied CO_2 capture costs unless coproducts are valued, but offer co-benefits such as wastewater treatment and potential for negative emissions when integrated with BECCS pathways.

Every one of the aforementioned CO_2 capture technologies has benefits and drawbacks (Table 2). This subsection offers prospects and suggested directions for various technologies while comparing and analyzing a number of capture technologies.

Table 2. Comparison and analysis of CO_2 capture technologies.

Capture Technology	Benefits	Boundary	Future expectations	Ref.
Chemical absorption	•A relatively developed technology, outstanding CO_2 selectivity, and superior CO_2 capture performance	•The release of absorbed solvents, high running costs and energy consumption, and high equipment corrosion rates will all contribute to pollution of the environment.	•Create novel absorbent solvents that have low corrosion and high absorption capacities. For desorption, use energy-efficient machinery and absorption techniques.	[54]
Solid adsorption	•Multiple methods of adsorption (TSA, PSA, and ESA); low regeneration energy consumption; nearly non-corrosive; appropriate for low-concentration CO_2 capture; reasonably easy operation.	• Due to its lower capture capacity compared to chemical absorption, industrial flue capture gases should be enhanced.	•The adsorption material must be changed, and multiple adsorption technologies must be optimized to improve the CO_2 capture efficiency even more.	[35]
Membrane separation	• Highly effective purification, low cost, low energy consumption, and a simple process that is friendly to the environment.	• Most membranes have a short service life and are readily destroyed; the separation purity is low; the permeability of the polymer membrane is more affected by moisture; and a bigger membrane area is needed for industrial applications.	• Create cutting-edge novel membrane materials to increase the effectiveness of CO_2 separation; further funding for industrial pilot research is required.	[55]
Cryogenic separation	It works well for capturing CO_2 at high partial pressures and concentrations, and the separation purity is very good.	• Expensive and difficult to operate; unsuitable for capturing low CO_2 volume fraction; pipeline blockages due to low-temperature CO_2 solidification.	•The issue of CO_2 solidification obstructing the pipeline must be resolved, and a simpler, more efficient, low-temperature process must be designed and optimized.	[56]

Capture Technology	Benefits	Boundary	Future expectations	Ref.
Microbiological method	• Direct conversion of CO_2 into organic matter, low cost, high return value, and no need for a convoluted process.	• It is still in the theoretical stage and there are not many related studies.	•To advance the development of microbiological techniques for CO_2 capture, more experimental research is required.	[57]

Table 2. (*Continued*)

In addition to being costly and complicated, conventional CCS technologies have the potential to produce secondary pollution. Algae technologies for carbon capture are of great interest.

One of the most crucial elements to reduce GHG emissions is the use of microalgae to sequester CO_2 using biomass energy. Removing CO_2 from stack gases and then storing it in microalgae ponds for a long time is a straightforward and straightforward method of mitigating greenhouse gas emissions.

5. Photosynthesis, microalgae and cyanobacteria

5.1. Photosynthesis

The biochemical process that fixes CO_2, photosynthesis, is powered by photons, or light energy. It produces about 140 billion tons of oxygen as a reaction byproduct and transforms about 200 billion tons of CO_2 into intricate organic substances every year [58] .

Essentially, microalgae use photosynthesis as a mechanism to convert CO_2 into glucose and use sun energy for material and energy exchange with their environment [59]. It can be expressed by Equation (1):

$$CO_2+H_2O \rightarrow (CH_2O)+O_2 \quad (1)$$

Additionally, there are two stages to photosynthesis: the photoreaction stage, which converts light energy into chemical energy that is active, and the dark reaction, which converts chemical energy from active to stable.

Equations (2) and (3) demonstrate that to immobilize and convert CO_2 to sugar, the dark reaction needs the strong reductant (NADPH) and the energy (ATP) produced by the light reaction. Through the PSII and PSI photosystems, the light energy is transformed into chemical energy to reduce NADPH into $NADP^+$. The pH gradient was produced by the thylakoid membrane and subsequently utilized to produce ATP [60] .

$$H_2O+ADP+ P_i+NADP \xrightarrow{Light} O_2+ATP+NADPH+H^+ \quad (2)$$

$$H_2O+ATP+NAPPH+H^2 \rightarrow (CH_2O)+ADP+P_i+NADP^+ \quad (3)$$

There are three stages to the cycle:

1) Fixation of carbon: Inside the chloroplast, the enzyme ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCo) catalyzes the reaction of gaseous CO_2 with RuBP, resulting in the production of six molecules of 3-phosphoglycerate (3PGA), also referred to as three-carbon organic acids [61] .

$$3\ RuBP+ 3\ CO_2 \rightarrow 63\text{-}phosphoglycerate$$

2) Reduction reaction: 3PGA undergoes a reduction reaction with ATP and NADPH to create single 3-carbon molecules (G3P), of which one of its six components is extracted for the plant's use or storage.

$$63\text{-}\ phosphoglycerate+6\ ATP+6NADPH \rightarrow 5\ G3P+1\ G3P$$

3) Regeneration of ribulose-1, 5-biphosphate (RuBP): the remaining G3P is recycled back into the cycle to produce more RuBP, which powers the stage of carbon fixing [62].

$$5\ G3P + 3ATP \rightarrow 3\ RuBP$$

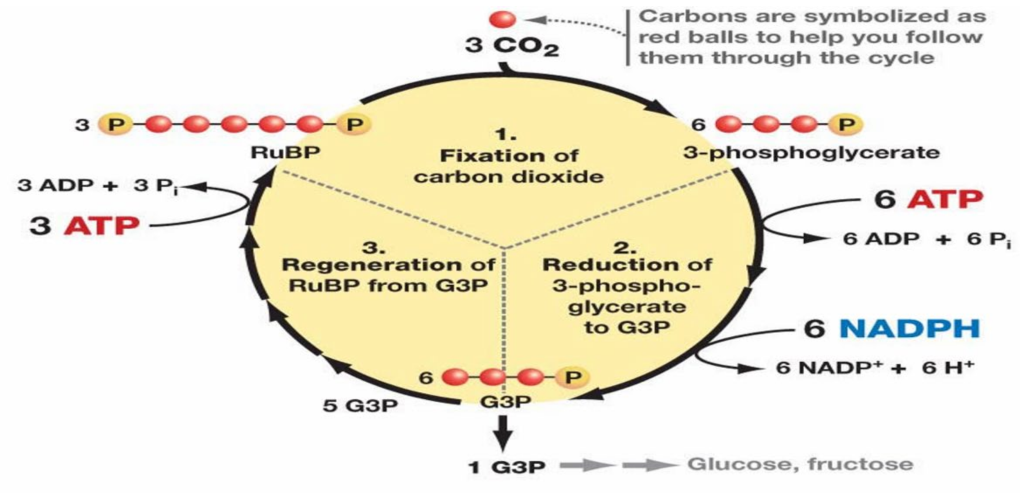

Figure 6. A Calvin-Benson-Bassham cycle schematic using RuBisCo. Three steps include 1) CO_2 fixation, 2) reduction of 3-phospho-glycerate to G3P, and 3) regeneration of RuBP from G3P. ATP and NADPH molecules are supplied by the light dependent reaction [63].

5.2. Microalgae for carbon capture

Single-celled microorganisms called microalgae transform the energy from solar radiation into chemical energy through a process known as photosynthesis [64]. Many bioactive compounds with great potential for commercial and industrial use can be found in their biomass. Numerous cellular metabolites, including premium Vitamins, proteins, lipids, carbohydrates, and colors for the alternative energy, food and feed, and cosmetics industries, can be produced by microalgae [65].

Because they can replicate 100 times more quickly than terrestrial plants, microalgae can produce more biomass[66]. Every kilogram of microalgae biomass generated may fix about 1.83 kg of CO_2 [67].

The effectiveness of ribulose 1,5-bisphosphate (Rubisco) carboxylation/oxygenation,

a photosynthesising enzyme that is crucial for carbon assimilation and sequestration, is enhanced by the elevated CO_2 levels surrounding thylakoid membranes. Rubisco has a low CO_2 binding affinity, having evolved in CO_2-rich and O_2-poor environments. Therefore, the pyrenoid works to keep the ideal conditions for a higher capacity to bind CO_2 [68]. [69] examined how light intensities affected Chlorella vulgaris using two CO_2 concentrations (2 and 13% v/v). At 13% v/v CO_2 and light intensity of 180 Hmol m-2 s-1, the greatest CO_2 removal rate was 0.98 g CO_2 L^{-1} day^{-1} utilizing two sources of CO_2: a blend of pure 11% v/v CO_2 and flue gas from a municipal trash incinerator that contains 10–13% v/v CO_2 and air—[70] employed *C. vulgaris* to produce biomass. Compared to the control gas, the CO_2 fixation rate was greater when the flue gas was used (4.4 g CO_2 L^{-1} d^{-1}).

Applications of microalgae-harnessing systems in engineering and environmental protection are becoming more and more popular, particularly in the areas of technology for biofuel production, wastewater treatment, flue gas (including CO_2) reduction, and solid waste neutralization (Figure 7) [71], This figure illustrates the complete cycle of an algae-based circular economy, where carbon dioxide is captured from the atmosphere or industrial sources, used to cultivate algae, and then converted into a variety of clean biofuels. This technology represents a comprehensive and sustainable solution to both the energy and climate crises.

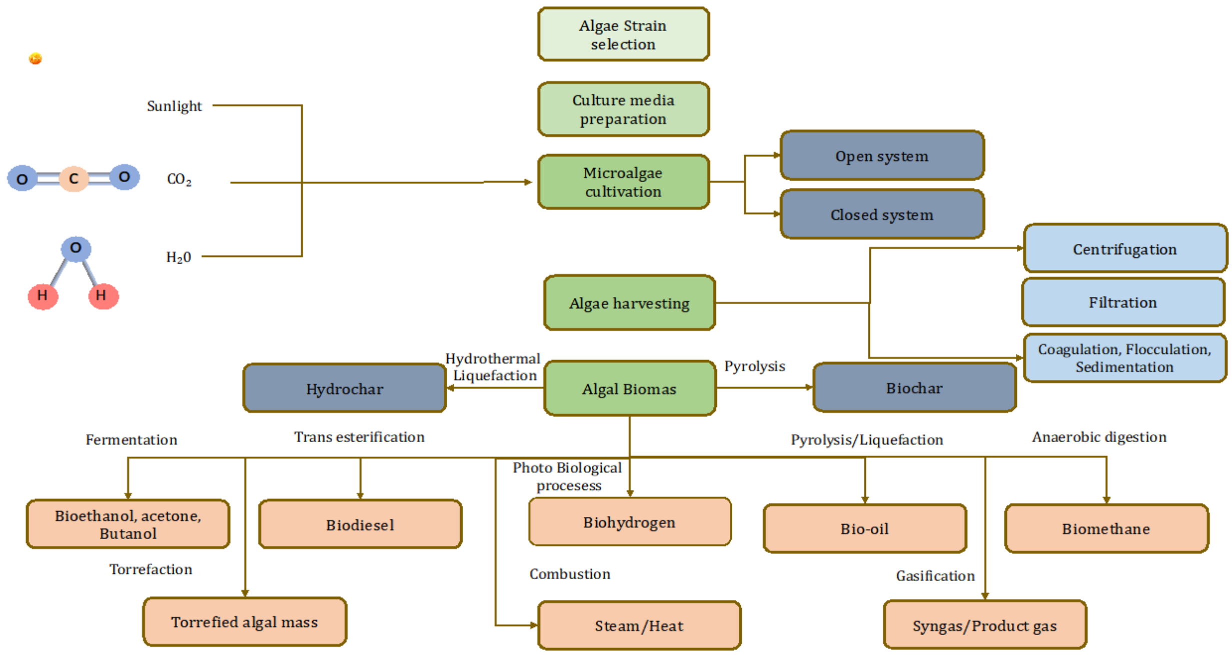

Figure 7. Methods and directions for using microalgae biomass [71]

6. Application of carbon dioxide fixation technology in microalgae

6.1. In the Atmosphere

Because of their high rate of development and ability to fix CO_2, microalgae cultures are thought to be a potential method of removing CO_2 from the environment. The atmospheric concentration of CO_2 hit 418 parts per million in December 2022 [72].

Carbon dioxide is used by the microalgae concentration control system to accomplish carbon fixation by raising the CO_2 concentration close to the Rubisco, Rubisco is an important enzyme in photosynthesis in algae and plants. This enzyme is the key factor in the first stage of the Calvin cycle, which fixes carbon dioxide (CO_2) and converts it into organic compounds used as energy by the plant or algae [73]. Tsai et al. demonstrated that the highest CO_2 consumption efficiency occurs when microalgae and a natural medium coexist, and favorable CO_2 fixation ability [74]. A photobioreactor can achieve aseptic operation, have relatively stable culture conditions, and prevent the evaporation of water, but its construction and operation costs are higher. The efficiency of carbon sequestration is relatively low and influenced by environmental factors, even though direct air capture doesn't require any energy or equipment [75].

6.2. Flue gas

Natural gas has 4–8% CO_2 by volume (vol%), whereas coal flue gas contains 12–15 vol% of CO_2. [[82],[65]]. Flue gas is an inexpensive and plentiful source of CO_2 [[76],[57]]. The type of combustion raw materials will determine the composition of flue gas, which is more complicated and often contains a high percentage of N_2 and CO_2, a little quantity of H_2O and O_2, and a small amount of dust, heavy metals, nitrogen and sulfur oxides, and other pollutants. Despite the great potential of using microalgae to reduce CO_2 emissions in flue gas (as Figure 8). Certain pollutants, such SOx and NOx, can have detrimental effects on microalgae cells when they are present in high concentrations, preventing them from growing and from sequestering carbon [77].

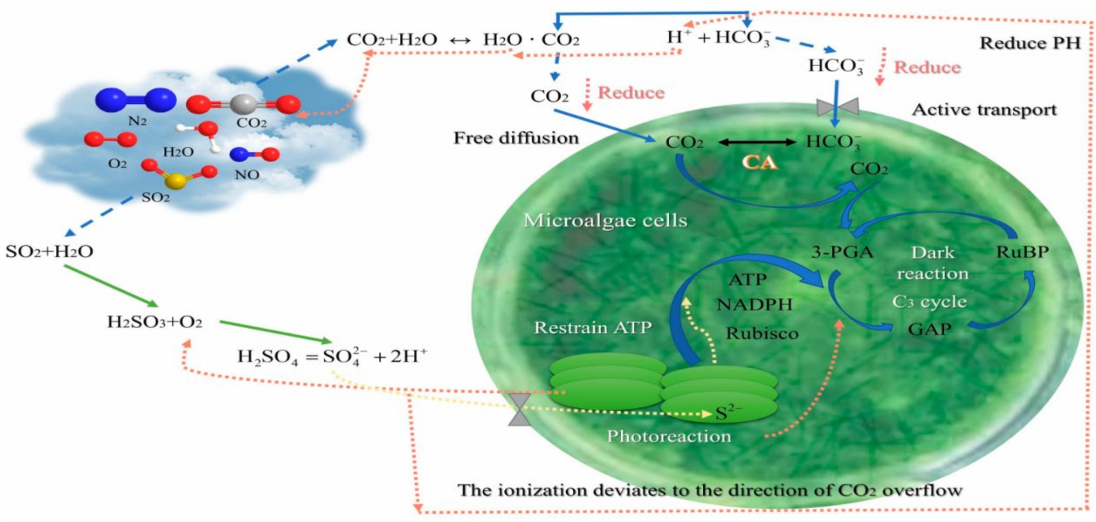

Figure 8. Mechanisms via which Sox inhibits microalgae CO_2 fixation [77].

Acidification is frequently linked to the decreased growth rate at high CO_2 concentrations, which results in the inactivation of important C3 cycle enzymes. Homeostatic reactions allow CO_2 -resistant strains to regulate their pH [78]. According to Yen et al., Chlorella sp. demonstrated a high CO_2 tolerance by reaching its maximum growth rate at a 10% CO_2 concentration [79]. The maximum quantity of CO_2 biofixation in flue gas each day was shown by Chlorella fusca LEB 111 [80].

6.3. In waste water

Water usage has sharply increased as a result of global population expansion and urbanization, making the treatment of wastewater one of the world's biggest challenges. Systems for treating wastewater using microalgae are far more valuable than traditional techniques, which raise greenhouse gas emissions and depend on costly energy and chemicals [81]. Ammonia, phosphate, iron, copper, zinc, and other trace metals are among the majority of the nutrients needed for microalgae growth and photosynthesis. , are found in wastewater.

Waste water purification, CO_2 capture, and microalgae cultivation can all work together to cut sewage treatment costs, utilize fewer chemicals during processing, and slow down CO_2 emissions. Sustainable and cost-effective wastewater treatment technique combines CO_2 removal from flue gas combined with wastewater treatment using microalgae culture to produce biofuels [82] .

7. Current technologies for algae

The three primary technologies for growing algae are closed (PBRs), open (ponds and raceways), and biofilm systems. The choice of the best growing system is influenced by several factors, including cost, the source of CO_2 capture, the desired products, and the source of nutrients [59].

7.1. Open ponds

Artificial ponds and natural waters (lakes and ponds) are the two categories of open systems. Over the past few decades, biomass production has been achieved globally by the mass growing of microalgae in open settings [83]. It is frequently carried out in raceway ponds, circular ponds, and large ponds [84] .

For commercial cultivation, raceway ponds are the most commonly utilized (Figure 9.a). Usually, the depth is between 15 and 25 cm, and agitation is achieved with a paddle wheel to promote circulation and facilitate nutrient medium mixing. The local climate and latitude determine the light environment, and pond temperature is often uncontrolled [85] .

Wastewater treatment tests were conducted in an open space on a 40,000 L multi-layer bioreactor open pond system (Figure 9.b) [86] . The nutritive medium flowed under gravity and was pushed back to the top of the multilayer bioreactor, which was made up of multiple tiers of tanks stacked on top of one another (Figure 9 b).
Reports indicate that the biomass productivity ranged from 19 to 23 g m^{-2} d^{-1}[87]. which exceeded that of traditional open pond systems [88] .

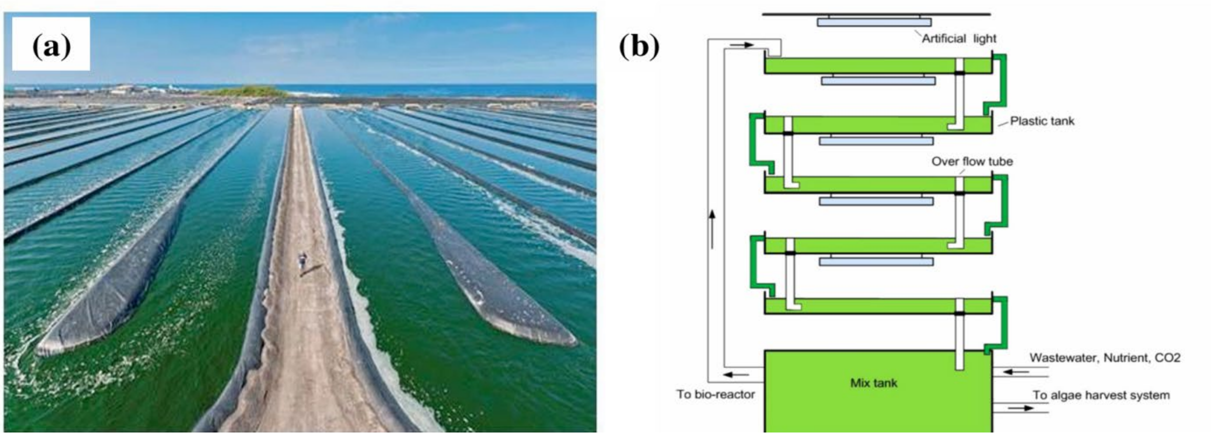

Figure 9. (a) pond of algae[89] and (b) a bioreactor with layers [90].

A transparent cover over a raceway may boost CO_2 fixation efficiency to 95%, according to[91].

7.2.Closed photobioreactors (PBRs)

Many of the drawbacks of open systems have been addressed by the development of enclosed PBRs [92], As well as to reduce light shading, increase photosynthesis, and mass transfer CO_2 and O_2 [66], Tubular, airlift, flat panel, and bags are examples of PBR designs. According to some research, some PBRs had CO_2 capture potential that was on par with solvent absorption based on amines.

7.2.1. Tubular photobioreactors

Transparent glass or plastic tubes with a diameter of 5 to 20 cm are used to make tubular PBRs. For optimal circulation and to enable efficient CO_2 and O_2 exchange between the liquid medium and the aeration gas, the system is typically connected to a sizable reservoir and above tubes. An airlift device can also be employed [93]. To ensure proper distribution of light to individual cells, prevent cell deposition, and provide adequate mixing, flow rates are usually between 30 and 50 cm s^{-1} [94]. Long tubes can create a significant gradient in CO_2 concentration, which can in certain cells and cause a pH gradient, which interferes with carbon fixation. This is one of the primary issues with tubular PBRs [95] .

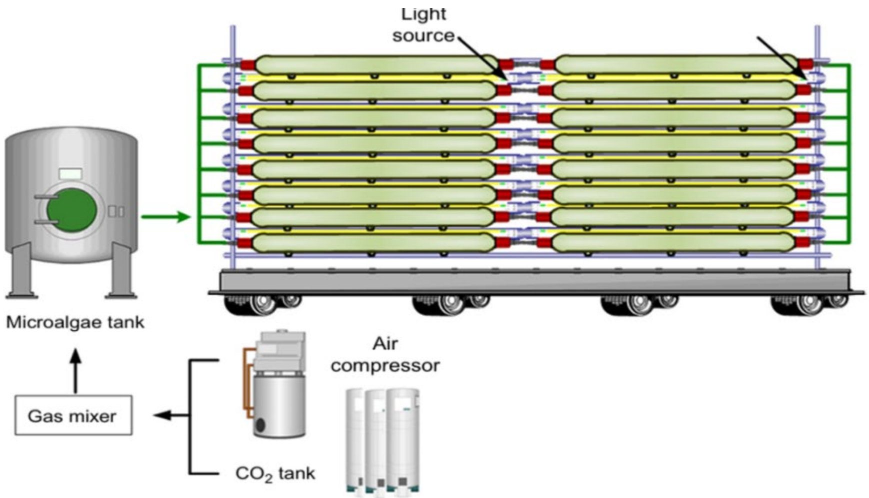

Figure 10. Microalgae growth in photobioreactors with horizontal tubing [95].

7.2.2. Airlift bubble column photobioreactors

Using a baffle or draft tube, an airlift PBR separates fluid volume into two connected zones. Gas mass transfer is enhanced and light exposure is increased by the liquid's circular motion and micro-macro bubbles [96]. The biological performance of certain microalgae may be impacted by high shear stress, but increasing the aeration rate can efficiently distribute CO_2 and prevent O_2 accumulation [97].

However, scaling up this aeration mode is challenging because of its intricate flow patterns[91]. The scale-up problem was recently resolved with the development of a split-column airlift PBR, whose biomass productivity was found to be 15–30% higher than that of traditional bubble column systems [98].

7.2.3. Flat plate photobioreactors

Because of their exceptionally high surface area to volume ratios, flat plate PBRs can transmit enough light to sustain a high biomass production. Baffles can be added for aeration, and reactors are usually built with short light paths in mind [99]. At the reactor's bottom, a perforated tube is used to admit gas. Aeration rates between 0.023 and 1.000 vvm are appropriate for a CO_2/air mixture of 5–10% v/v [100]. However, there are disadvantages, including hydrodynamic stress, growth restriction close to the wall region, and difficulty controlling temperature [94]. Because of their flat shape, these reactors may expose a vast surface area to light. They are frequently employed in small-scale applications and research because of their excellent CO_2 capture efficiency.

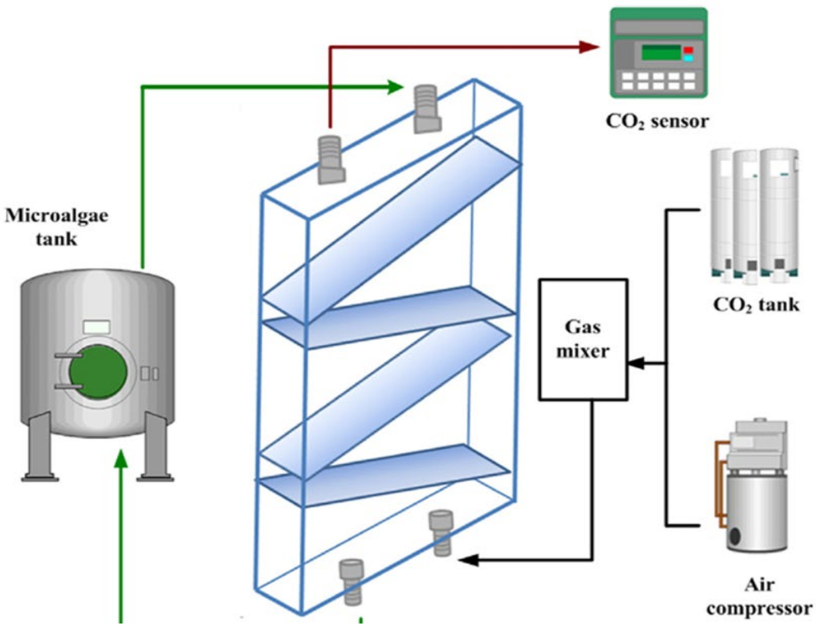

Figure 11. Photobioreactors with plates for growing microalgae

7.2.4. Membrane photobioreactors

Modified versions of tubular or airlift PBRs, membrane PBRs use a membrane to circumvent the mass transfer restriction. To help the CO_2 dissolve in the liquid, the membrane produces microscopic bubbles [101]. The mechanical strength, oxygen buildup restriction, CO_2 distribution, and corrosion and fouling resistance of a good membrane PBR are all important. However, fine bubbles could make the reactor hazy, which would make it impossible for light to enter. Separating gas and light supply systems into separate parts was recommended; however, this would be costly and challenging to scale. In order to provide a broad surface area for gas exchange, these reactors use hollow fibers. They are frequently employed in cutting-edge research applications and are effective at trapping CO_2 [102]. *Chlorella vulgaris* cultures' ability to absorb CO_2 from the atmosphere was evaluated by [105]. In the membrane-treated air, the CO_2 levels were correlated with the CO_2

collection efficiency. Table 3 summarizes the different Chlorella species and their corresponding CO_2 fixation rates or removal percentages under various cultivation conditions.

Table 3. Chlorella species and their CO_2 fixation rate or removal percentage. Adapted from[103]. (PBR = photobioreactor).

Chlorella type	Initial CO_2 (%) (v/v)	CO_2 fixation rate (g L−1 d−1)	% of removal accomplished (v/v)	Cultivation system	References
C. vulgaris	0.03 (Air)	0.06	92.2	Sequential bioreactor	[104]
	0.09 (Air)	3.55	96.9	Membrane sparged helical tubular bioreactor	[105]
	5	1.5	35	Sequential bioreactor	[104]
	0.106	3.55	80	Lab scale PBR	[106]
	5	0.86	0.86	Bubble column	[107]
Chlorella sp.	15	0.75	85.6	Air lift PBR	[108]
	10	0.89	46	Open way pond	[66]
	5	0.7	1.5	Vertical tubular bioreactor	[109]

8. Environmental factors affecting microalgal growth

Environmental Factors Affecting Microalgae Growth Figure 12 displays the effects of different environmental factors on the rate of microalgae growth. Each species of microalgae has a different range of ideal conditions for attaining high growth efficiency and CO_2 fixation rates. The following summarizes how the microalgae's growing circumstances have an impact on how well they sequester carbon and biomass production.

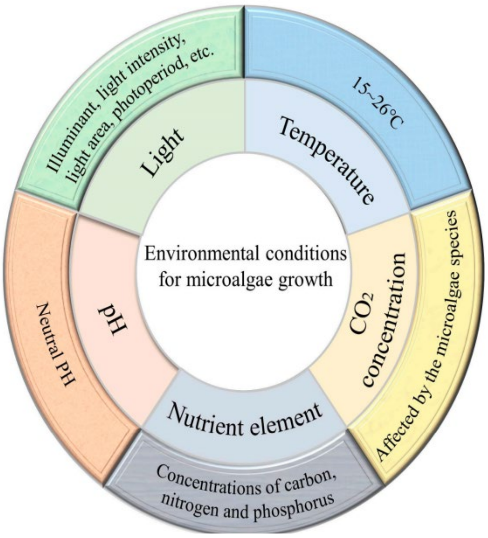

Figure 12. The rate at which microalgae grow is affected by various growth environment conditions [57].

8.1. Light

The primary energy source that affects photosynthetic dynamics is light in microalgae. Modifying the light source, intensity, interval, area, etc., it can influence cell growth and metabolism [110]. An excessive amount of light might cause photooxidation. The primary energy source influencing microalgae's photosynthetic dynamics is light, it regulates the light source, light intensity, interval, area, etc. to influence cell growth and metabolism [36]. Too much light can cause photooxidation and photoinhibition, while too little light would restrict growth [111]. According to the majority, the main factor lowering algal output is photoinhibition. The microalgae growth rate at low light levels increases linearly with increasing light intensity until light saturation is reached. Microalgae typically grow best at light intensities between 26 and 400 mol photons m^{-2} s^{-1}[112].

8.2. Temperature

Temperature is another crucial environmental component for microalgae growth and target-product production in commercial microalgae cultivation systems. Temperature variations for outdoor microalgae cultivation are heavily influenced by seasonal variations and light exposure, or the day/night cycle. In Taiwan, the temperature variation range is between 25°C and 45°C. While microalgae biomass production would decline at high temperatures mainly because of denaturation of vital proteins and enzymes and inhibitory effects on cellular physiology, microalgae growth could be encouraged by the right cultivation temperature. The effect of temperature on the growth rate of microalgae has been reported for a variety of microalgae species. For example, when *Chaetoceros pseudocurvisetus* was cultivated at 25°C, its growth rate peaked [113].

8.3. PH

An additional crucial environmental factor for the growth of microalgae and the creation of target products is pH. For the majority of cultivated microalgae species, a pH of 7 to 9 is ideal [114]. Because it largely determines the solubility and availability of carbonates and CO_2 as well as the optimal operation of intracellular and cell-wall-associated enzymes, the pH of the culture medium has a significant impact on the growth of microalgae. The majority of microalgae can be grown in environments with a pH of neutral [115], with some exceptions, like *Spirulina* at pH 11 and *Chlorococcum* at pH 4.0 [51]. found that the ideal pH range for *Nannochloropsis oculata* growth was between 5.5 and 6.5 [116] . The highest lipid content and CO_2 fixation rate were found in Graesiella sp. WBG-1 at pH 8.0–9.0, at 46.28% and 0.26 g/L/d, respectively [117].

8.4. Nutrient element

Phosphorus, carbon, and nitrogen are essential for biomass growth and the synthesis of microalgae cells. In microalgae, the species, morphology, and nutrient quality all affect photosynthesis. One of the key elements influencing biomass accumulation, value-added component productivity, and carbon fixation efficiency is the carbon–nitrogen ratio (C/N). *Spirulina platensis* was cultivated in particular cultures after being exposed to nuclear radiation. The hybrid process's carbon utilization efficiency could reach 40.45% when NH_4HCO_3 to $NaNO_3$ was fixed at a ratio of 1:4. However, microalgae will also become poisonous due to an overabundance of NH_4HCO_3, which lowers the biological yield [118].

8.5. Carbon dioxide capture and sequestration by microalgae

Algal mass culture pond systems can be used to convert CO_2 from a variety of industrial sources, including power plants, cement, steel, and chemical industries, among others, into biomass. It is possible to send flue gases straight to microalgae production or to remove the CO_2 from the flue gases before injecting it. Indirect stimulation of land species by flue gases is an alternate method that may be cost-effective while being much less direct and efficient than applying CO_2 directly to terrestrial crops via enclosures, which is likely to be prohibitively expensive. Because of these factors, many people think that the only viable way to produce biodiesel is through microalgae [23, 29], even though there is a lot of debate concerning it [119].

The carbon-concentrating mechanism (CCM) is a mechanism used by microalgae to absorb CO_2, utilizing a particular organelle (pyrenoid) to boost CO_2 levels surrounding thylakoid membranes [120] . Due to its evolution in both CO_2-rich and O_2-poor environments, rubisco has a low affinity for binding CO_2. Therefore, the pyrenoid works to preserve ideal circumstances for a higher CO_2 binding capability [68].

Figure 13 displays the typical coal combustion flue gas composition both before and after it enters the 2,000-liter pilot-scale PBR microalgal photobioreactor. When the culture was kept at pH 7.5, the mass calculations show that the microalgal culture was able to absorb around 70% of the available CO_2. Examination of the coal combustion gases both before and after they pass through the pilot-scale photobioreactor [121] .

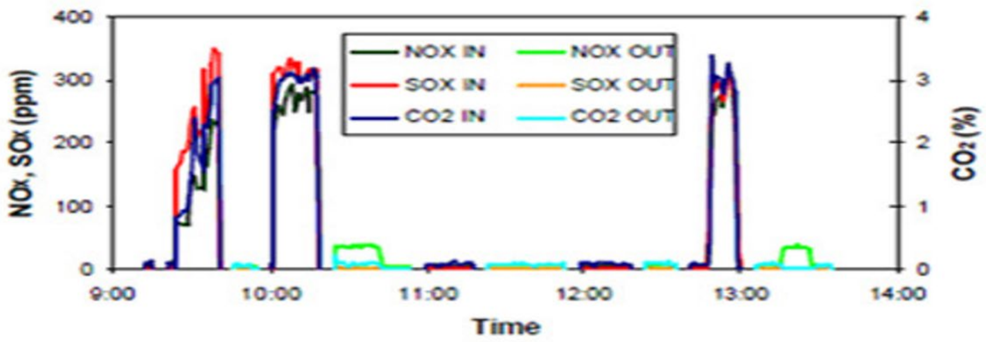

Figure 13. shows the composition of the flue gas before and after entering the tubular reactor. It is demonstrated in this report that [121].

- Microalgae have the capacity to absorb anthropogenic CO_2 from real coal and combustion gasses as well as from a wide range of simulated flue gases.
- Under a broad range of pH and gas concentrations, microalgae may absorb anthropogenic CO_2.
- The pH of the culture has a direct impact on the microalgae's ability to collect CO_2, but variations in the gas composition have no effect.
- The procedure can be scaled up to industrially meaningful levels.

9. Conclusion

The usage of fossil fuels is growing along with the demand for energy, which leads to carbon emissions. This makes a commercially feasible carbon conversion technology even more necessary. The three main techniques for capturing CO_2 (adsorbents, solvents, and membranes) were determined. It was described how algae are used to collect and sequester CO_2 during photosynthesis. An approach to capturing carbon and using it to potentially create biodiesel has been made possible by algae growing systems. Although closed systems are superior because they offer a controlled environment and a higher biomass productivity, open systems are frequently employed since they are easier to use and less expensive. Research on the suitability of microalgae species for CO_2 sequestration is required. Closed systems have higher production costs than open systems, while the latter have higher operating costs. Additionally, compared to the open system, the close cultivation system requires a smaller plant capacity, but the closed system produces a vast amount of microalgae. Future progress in microalgae-based CO_2 capture requires addressing several research gaps. First, the development of low-cost and energy-efficient photobioreactor designs is essential to reduce capital and operational expenses that currently limit large-scale deployment. In addition, hybrid systems that integrate conventional CCS technologies with microalgae cultivation could enhance overall capture efficiency while enabling simultaneous production of high-value biomass. Further investigation is also needed to optimize microalgae strains capable of tolerating fluctuating flue-gas compositions and harsh industrial environments.

From a policy perspective, supporting frameworks and incentives are crucial to accelerate the adoption of microalgae-based carbon capture. Policies that encourage carbon pricing, renewable-energy integration, and circular-bioeconomy strategies can significantly improve the feasibility of these systems. Moreover, coupling microalgae cultivation with renewable-energy sources such as solar or waste-heat recovery can reduce the carbon footprint of the process and enhance long-term sustainability. These directions highlight the need for coordinated scientific, technological, and policy efforts to advance microalgae-driven CO_2 mitigation.It is still necessary to investigate the CO_2 sequestration technique's cost-effectiveness for microalgae cultivation and harvesting in light of current economic realities. For the technology to compete favorably with current technologies, cost-effectiveness should be the primary focus of both design and operation.

Nomenclature

CCM	CO_2 concentrating mechanism
3PGA	3-phosphoglycerate
AFOLU	Agriculture, forestry and other land us
ATP	Adenosine triphosphate
BECCS	Bioenergy with carbon capture and storage
CCS	Carbon capture and storage
PBRs	Photobioreactors
RuBP	Ribulose-1, 5- biphosphate
ATP	Adenosine triphosphate
DAC	Direct air capture
IPCC	Intergovernmental Panel on Climate Change
RuBisCo	Ribulose-1,5-bisphosphate carboxylase/oxygenase

Conflict of interest

The authors declare no conflict of interest

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