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Progress in Microalgae Application for CO_2 Sequestration

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ABSTRACT

The use of microalgae for CO_2 sequestration helps in mitigating global warming. This paper reviews the application of microalgae for CO_2 sequestration with emphasis on performance evaluation, lifecycle, economic assessment, as well as environmental impact. The CO_2 sequestration mechanism is done during photosynthesis, via bioconcentration. Performance evaluation revealed that the efficiency of capture and sequestration of CO_2 by microalgae ranges between 40% and 93.7%. However, the macro performance of microalgae in carbon emission reduction has not yet been fully understood, and therefore requires more studies. Also, the cost-effectiveness of the CO_2 sequestration by microalgae cultivation still needs more research based on recent economic realities. It is recommended that design and operation be focused on cost-effectiveness so the technology can compete favourably with existing technologies. Overall, it can be surmised that the application of microalgae for CO_2 sequestration is an effective technique for carbon capture, but still has interesting areas for development for greater global environmental impact.

1. Introduction

The ever-rising world population has warranted an increase in the demand for energy (Rangabhashiyam et al., 2021). This increase in energy demand has resulted in increased emissions of carbon dioxide into the atmosphere, ultimately amplifying the threat of climate change on the planet (Jaiswal et al., 2021). Carbon dioxide (CO_2), a major environmental pollutant, constitutes 68% of total greenhouse gas emissions to the atmosphere (Bhola et al., 2014). In the last three decades, carbon emissions have increased by about 50% (Singh et al., 2013) and have continued to do so with the ongoing global industrialisation and urbanisation (Ajala et al., 2021). If the continuous release of this dangerous gas into the atmosphere is left unabated, it could lead to severe consequences on the planet (Eshiemogie et al., 2022). As a result, carbon emissions to the atmosphere must be significantly reduced to acceptable levels. To reduce carbon emissions, nations around the world, as well as other concerned bodies, have explored alternative sources of energy, which minimise carbon emissions to the atmosphere (Ighalo et al., 2021). However, issues of low energy efficiency associated with the use of alternative energy leave fossil fuels to become the most viable option capable of effectively meeting the current global energy demand. Since reliance on fossil fuel is still high, reducing the carbon emissions through carbon capture and sequestration technologies need to be explored.

Carbon capture and sequestration technology have emerged as an important technique, which has the potential to sustainably tackle issues of carbon emissions to the atmosphere (Wilberforce et al., 2021). In this technology, carbon is captured and either stored or utilised for other purposes. Physical and biological carbon capture and sequestration technologies are two broad carbon capture technologies that have gained prominence in recent years (Bhola et al., 2014). Despite being a promising technology, the physical method of carbon capture and sequestration has been found to have several disadvantages, such as high operational costs due to its high energy consumption. As an example, the carbon capture unit of the Shanghai power plant in China was recorded to have an energy consumption cost of about 40% of the total cost of running the power plant itself (Xu et al., 2019b). Also, carbon sequestering usually involves storage, transportation, mineralisation, and ocean-deep injection of carbon, which makes the physical method of carbon capture a cumbersome process with many technical, environmental, economic, and even safety issues (Singh et al., 2013).

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While the physical method of carbon capture and sequestration comes with numerous challenges (Xu et al., 2019b), the biological method has however proven to be a cost-effective and environmentally friendly means of capturing and sequestering carbon (Bhola et al., 2014). The biological method of carbon capture involves using green plants to convert carbon into energy needed for plant survival. Originally, terrestrial plants such as trees were used to perform this process but, more recently, it has been found that microalgae have a better potential for carbon capture and sequestration than terrestrial plants. Bhola et al. (2014) reported that the efficiency of microalgae in capturing and sequestering carbon is 10 to 50 times higher than that of terrestrial plants. As a result, the use of microalgae for the capture and sequestration of carbon could be said to have significant advantages over other methods of carbon capture and sequestration technologies.

Microalgae, which are photosynthetic unicellular and multicellular microorganisms (Altomonte et al., 2018), have seen a surge in interest in the past decade. These organisms, which have a very rapid growth rate compared to terrestrial plants, find a good application in carbon fixation via photosynthesis and when they become grown in size, they find application as feedstock materials in the production of biofuels (Pignolet et al., 2013). This trait makes microalgae a sustainable biomaterial for carbon capture and sequestration as they contribute zero pollution to the environment.

So far, literature investigations in this area have largely focused on issues such as the efficiency, microalgae cultivation, and cost implication of utilising microalgae for carbon capture and sequestration. However, issues of lifecycle assessments and techno-economic analysis of the subject matter have not been effectively reviewed. Therefore, this paper reviews the application of microalgae for CO_2 sequestration with emphasis on performance evaluation, lifecycle and economic assessment, as well as the environmental impact and implications of utilising microalgae for carbon capture and sequestration.

2. Microalgae species and processes for CO_2 sequestration

2.1. Microalgae used for carbon sequestration

Algae is one of the most effective organisms in the domain of carbon sequestration and photosynthesis. They are classified into macroalgae and microalgae, which vary in size and structure. (Chen et al., 2010). Microalgae are mostly classified depending on their surroundings and morphology. In some cases, they can be autotrophic or heterotrophic, or perhaps both. Autotrophic microalgae require salts, inorganic chemicals, and a suitable light source to develop, whereas heterotrophic microalgae rely on organic molecules and nutrients from outside sources for energy. The primary classification of microalgae is based on their cellular structure, colour, and life cycle (Brennan et al., 2010; Greenwell et al., 2010). There are two prokaryotic groups and nine eukaryotic groups of microalgae. These organisms have significant potential for the production of value-added goods and biofuels (Brennan et al., 2010; Del Campo et al., 2007; Khan et al., 2009). Microalgae, by nature, can withstand high CO_2 concentrations, making them suitable for using CO_2 from power plant exhaust systems (Bhola et al., 2014; Farrelly et al., 2013). It is important to remember that photosynthesis was the first biological mechanism that fixed carbon we utilise today. Carbonates such as $NaHCO_3$ and Na_2CO_3 are known to be used by numerous microalgal species for cellular growth (Huertas et al., 2000). The oil concentration vary by species and can get up to 80%. As a result, microalgae can be utilised to store CO_2 and convert it to energy (Arenas et al., 2014). Microalgae may survive in a variety of carbon-rich environments, as evidenced by the wide range of cellular lipids derived from them. Researchers analysed the effects of high CO_2 levels on various species, focusing on those that can sustain high concentrations while producing a lot of biomolecules, such as lipids or triglycerides. (Saifuddin et al., 2015)., *Botryococcus braunii, Chlorella kessleri, Dunaliella tertiolecta, Isochrysis galbana, Cholorococcum littorale, Spirulina platensis, Nannochloropsis, Dunaliella salina, Scenedesmus obliquus* and Chlorella sp. have all been studied for bio sequestration. Freshwater microalgae such as *Scenedesmus, Spirulina platensis*, and *Chlorella* are commonly employed for carbon capture (Alami et al., 2020; Mondal et al., 2016; Wang, S. et al., 2018). Cheah et al. (2015b) reported that cultivated microalgae can fix 1.83 kg of CO_2 per kg, and they offer a high potential for CO_2 sequestration. *Chlorella vulgaris* and *Anabaena sp*. for example, may fix CO_2 at rates of 6.24 g/L/d, respectively (Ghorbani et al., 2014). CO_2 concentration in the atmosphere ranged from 0.03 to 0.06% (v/v), but CO_2 concentration in flue gas can range from 6% to 20% (v/v) (Abd Rahaman et al., 2011; Brilman et al., 2013; Pires et al., 2012). Furthermore, microalgae cultures are likely to be planted near large CO_2 emissions, such as generating stations and processing plants. The biofixation of CO_2 and the production of algal biomass fluctuate greatly depending on microalgae species characteristics, culture system impacts, and physicochemical process effects. The cultivation of selected microalgae species is important to the success of CO_2 bioconversion for biomass production. An excellent algal species has a high bio sequestration rate as well as a high tolerance for CO_2, temperature, pH, nutrient levels, and contaminants (Singh et al., 2013). When selecting important microalgae species, their CO_2 tolerance is taken into account. According to a report, *Scenedesmus* sp. CO_2 tolerance, allowing it to grow at CO_2 concentrations ranging from 10% to 20% (v/v), even though the optimal CO_2 concentration is just 2% (v/v). The amount of CO_2 to which the microalgal species was exposed has a considerable effect on biomass output. (Jiang et al., 2013). *Chlorella* sp., a microalgae, can grow at 40% CO_2 at pH 5-6 and 30°C (Chen et al., 2014). Under cultivation at 15% (v/v) CO_2, *Nannochloropsis* sp. grew at a rate of 58% faster, from 0.33 to 0.52 per day (Jiang et al., 2011). CO_2 concentrations of more than 5% (v/v) are considered to be lethal to the development of certain microalgae species (Lee et al., 2000).

2.2. Pathways employed by microalgae

Microalgae are the principal oxygen-evolving photosynthetic microorganisms on Earth, accounting for over half of worldwide CO_2 fixation. Some microalgae species, on the other hand, have heterotrophic metabolism and can survive in dark environments. Some algae strains can grow mixotrophically under particular conditions. The capacity of microalgae to grow under auto-phototrophic heterotrophic or mixotrophic conditions is essential because it allows microalgae to sequester organic carbon in wastewater, which would otherwise be released into the atmosphere. The processes of CO_2 sequestration are explained in detail in this section and summarised in Fig. 1.

2.2.1. Auto-phototrophic metabolism

Microalgae could absorb dissolved inorganic carbon (DIC) from the aquatic surroundings in the forms of H_2CO_3, HCO_3^-, CO_2, and CO_3^{2-}. Terrestrial plants, on the other hand, have a significantly narrower range of DIC assimilation. The DIC forms vary widely depending on pH, mixing speeds, microalgae concentrations, and so forth. (Coleman and Environment, 1991; Li and Canvin, 1998; Miller et al., 1990). Different microalgae strains may prefer different DIC types. *Chlorella miniata, Monodus subterraneus*, and *Chlorella vulgaris*, for example, can only take up CO_2 (which uniquely shows the ease of permeability to many membranes), whereas marine eustigmatophyte algae such as *Nannochloropsis oculata* and *Nannochloropsis gaditana* can only actively transport HCO_3^- (Coleman and Environment, 1991; Giordano et al., 2005). Some species, on the other hand, such as *Chlorococcum littorale, Dunaliella terteolacta, Chlamydomonas reinhardtii, Chlorella pyrenoidosa,* and *Scenedesmus obliquus* have an external carbonic anhydrase (CA) and can use both HCO_3^- and CO_2. Certain strains such as *Chlorella kesslerii* and *Chlorella ellipsoidea* lack external CA but can still utilise both HCO_3 and CO_2 (Calvin, 1989; Miyachi et al., 1983; Satoh et al., 2001). The concentration and placement of CA in microalgae are dependent on strain, and this can influence the types of DIC that can be assimilated.

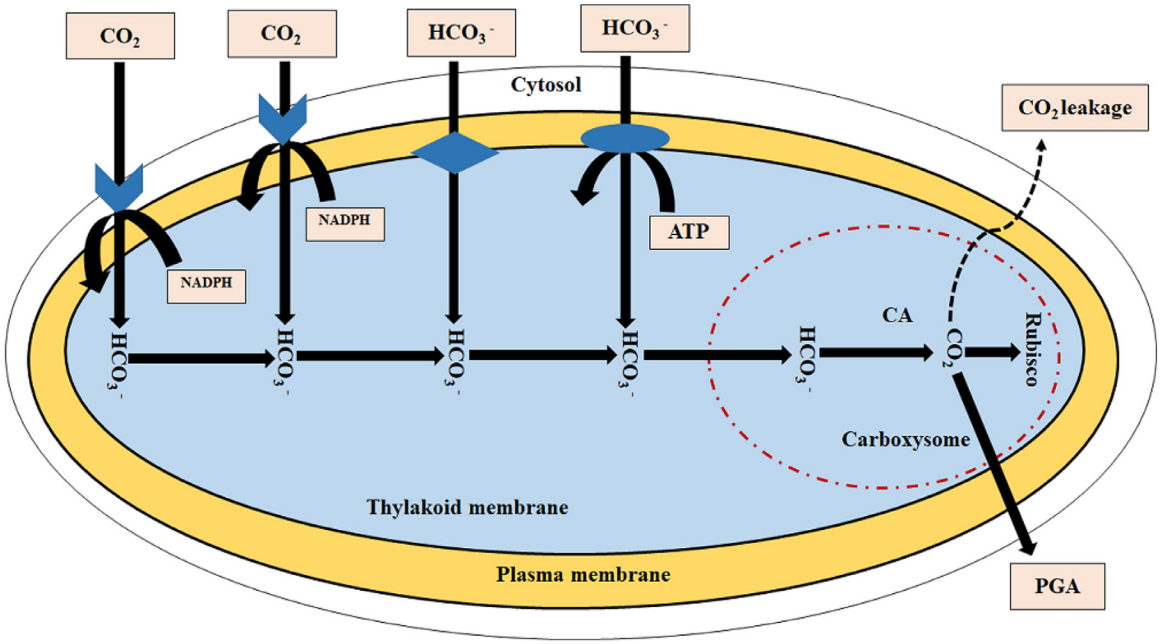

Fig. 1. CO_2 sequestration in microalgae species: Calvin cycle.

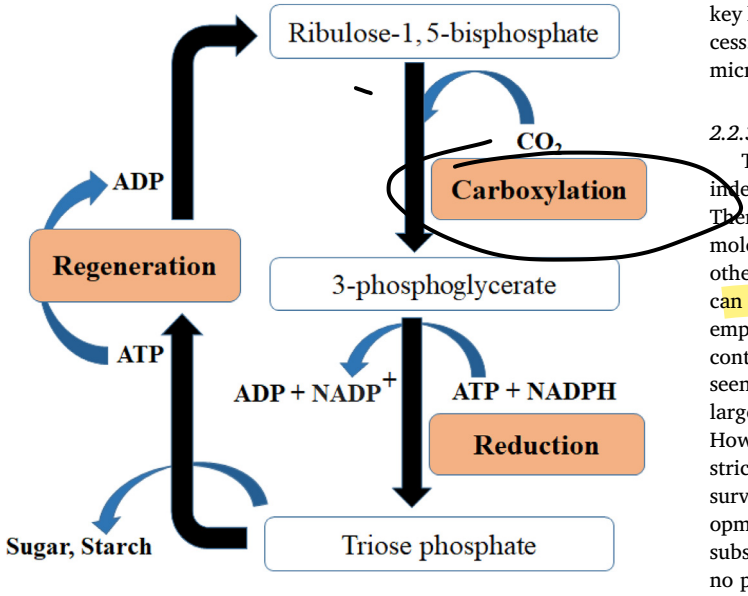

Fig. 2. Summary of auto-phototrophic assimilation of CO_2.

2.2.2. *Auto-phototrophic assimilation of CO_2*

Photosynthesis produces a large amount of ATP and NADPH, both of which are required for microalgal CO_2 fixation (Calvin, 1989). Calvin cycle describes the absorption of CO_2, which is done via three stages: carboxylation, reduction, and regeneration (in this sequence). CO_2 is absorbed by 5-bisphosphate carboxylase (RuBisCo), ribulose-1 into ribulose-1 and 5-bisphosphate (RuBP) during the carboxylation phase. This generates two molecules of 3-phosphoglycerate (3-PGA). The 3-PGA is then phosphorylated to glyceraldehyde 3-phosphate (G-3-P) via 3-phosphoglycerate kinase and glyceraldehyde phosphate dehydrogenase via chemical reduction, respectively. RuBP is replenished by a series of chemical reactions, and the fixation cycle advances to a subsequent stage. CO_2 is transferred to RuBisCo via the sequence of the cell wall, cell membrane, cytoplasm, chloroplast membrane, stroma, and extracellular boundary layer. CO_2 transit resistance and diffusion are the key limiting variables affecting CO_2 fixation throughout the transfer process. However, CO_2 can be produced by carbonic anhydrase in some microalgae strains when they consume HCO_3^- (Zhou et al., 2017).

2.2.3. *Heterotrophic metabolism*

To obtain energy and carbons, this metabolism often relies on light-independent absorption of organic complexes present in the medium. There is the pentose phosphate pathway (PPP), which allows organic molecules to flow through cell walls and be transformed into lipids and other metabolites through respiration (Sharkey, 2021). Some strains can exhibit heterotrophy in the presence of light. A mechanism that employs light as an energy source is known as photoheterotrophy. In contrast to autophototrophs, heterotrophs bypass the light constraint seen in autophototrophic development, allowing for quicker growth to larger biomass, lipid, and protein output, along with simpler operations. However, the variety of strains with a high heterotrophic capacity is restricted, and bacterial activities may have an adverse effect on culture survival. Glucose is the most employed organic carbon in the development of heterotrophic microalgae. As a result, feedstock costs are a substantial limiting factor in the synthesis of target metabolites, with no practical consequences for carbon sequestration. Organic molecules in wastewater, on the other hand, are a low-cost carbon source as well as a significant carbon sequestration target (Colman et al., 2002; Giordano et al., 2005; Zhou et al., 2017).

2.2.4. *Mixotrophic metabolism*

Mixotrophic metabolism follows autotrophic photosynthesis and heterotrophic assimilation. Because both CO_2 and organic carbon are required, this metabolism is a descendant of heterotrophic metabolism. Mixotrophic metabolism combined respiration and photosynthesis to produce the most glucose. As a result, mixotrophic metabolism may utilise both organic and inorganic carbon, resulting in a high biomass yield. Aerobic respiration collects organic carbon, whereas photosynthesis absorbs inorganic carbon (Yang et al., 2000). Microalgae grown in a mixotrophic culture produce more cells per unit of energy input than culture types (Mohan and Devi, 2014; Wang et al., 2014). A lower energy-conversion efficiency is experienced in mixotrophic metabolism compared to heterotrophic metabolism. However, when exposed to sunlight, each of these systems retains the necessary pigments and

photosynthetic carotenoids. Mixotrophic cultivation has certain advantages over photoautotrophic cultivation, such as greater growth rates, shorter growth cycles, lower biomass loss in the dark, and higher overall biomass output (Kong et al., 2012; Park et al., 2012). Mixotrophic metabolisms, on the other hand, have their own limitations, such as being somewhat expensive because of the high demand for organic carbon sources and being susceptible to invading heterotrophic bacteria in bare pond configurations. As a result, the mixotrophic mechanism has still another challenge in balancing two types of metabolisms (Patel et al., 2020).

2.3. Carbon Concentration Mechanism (CCM) in microalgae

As detailed in the previous discussions, the basic photosynthetic carbon metabolic route in algae is the Calvin–Benson cycle (C3 cycle). CO_2 is one of the aquatic system's limiting substrates (Durall and Lindblad, 2015). Bicarbonate is the most prevalent form of CO_2 in water at pH 7 and 30°C. The bicarbonate form of carbon is used in aquatic carbon capture, which is also required for algal growth and biomass production. Aquatic photosynthetic organisms are constantly subjected to variable degrees of physicochemical stress, which are influenced by the water matrix, the amount of dissolved inorganic carbon (Ci, CO_2, and/or HCO_3), and the environmental circumstances. As a result, aquatic photosynthetic organisms (of which microalgae is a part), have evolved carbon concentration mechanisms (CCM) as an adaptation mechanism to enhance photosynthetic efficiency in the presence of low CO_2 or inorganic carbon availability (Singh et al., 2014). Temperature, pH, alkalinity, and other environmental conditions all have an impact on the rate of inorganic carbon delivery to phytoplankton. Due to the slower diffusion rate of CO_2 in water, the water might become CO_2 deficient at times, resulting in a lesser availability of HCO_3 in the aquatic environment. To deal with the low ambient CO_2 concentration and high demand for inorganic carbon by diverse microalgae, mechanisms have been devised that utilise energy to enhance CO_2 concentrations in the area of RuBisCo. These are known as CO_2 concentrating mechanisms (CCMs) (Badger et al., 2002; Boatman et al., 2018).

The CCM of cyanobacterial species is mostly dependent on HCO_3 or CO_2 transport at the thylakoid or plasma membrane. Irrespective of the DIC species retrieved from the periplasm, the different transporters deliver HCO_3 to the cytosol. Carboxysomes, which contain cytosolic single carbonic anhydrase (CA) activity, absorb the HCO_3. When compared to the bulk medium, the CO_2 produced by CA increases the steady-state concentration in carboxysomes, resulting in RuBisCo's carboxylase activity being stronger than its oxygenase activity. (Omata et al., 1999; Raven and Beardall, 2003; Ritchie et al., 1996). As a result, CCM is composed principally of (i) active bicarbonate transporters, (ii) a set of strategically positioned CA, and (iii) RuBisCo localisation. Ongoing research in this field indicates the availability of multiple CCM techniques in a wide range of algae(Mistry et al., 2019; Price et al., 2002). However, like with many other features of CCMs, measuring CO_2 deficit at both the intracellular and extracellular levels to understand the structure and biochemistry of CCMs or to identify the source of the signal required for CCM activation is yet to be investigated.

3. Performance evaluation and factors influencing the microalgae-based process for CO_2 sequestration

3.1. Performance of microalgae for CO_2 sequestration

Microalgae clearly have great potential for CO_2 capture to produce clean air while also producing biomass. This section summarises the performance of microalgae utilisation in CO_2 sequestration and the produced biomass from the process (Table 1). Analysing the provided data in Table 1, the CO_2 sequestration using microalgae had high reliable performance. The CO_2 capture ranges from 40% up to the highest of 93.7%. The CO_2 sequestration mechanism, also known as capture and storage, is done via bioconcentration during photosynthesis (Singh and Dhar, 2019). It was reported that aquatic photosynthetic organisms, including microalgae, are highly responsible for global CO_2 assimilation (Prasad et al., 2021). The CO_2 capture mostly occurred via photoautotrophic metabolism, in which inorganic carbons are processed into carbohydrates with the help of light, with the fixation of carbon mostly occurring via Calvin–Benson cycle (Matito-Martos et al., 2021). The high growth rate of algae results in high carbon sequestration, which is engineered as one of the green technologies for CO_2 assimilation (Miranda et al., 2021).

During the limited CO_2 condition for photosynthesis, microalgae can perform a carbon concentrating mechanism (CCM) to still be able to survive and grow (Wang et al., 2015). This mechanism allows microalgae to increase their photosynthesis performance by concentrating CO_2 at Rubisco (ribulose-1,5-bisphosphate carboxylase/oxygenase) while simultaneously increasing carbon fixation and decreasing the photorespiration mechanism (Wang et al., 2015). There are some pathways mentioned to contribute to this mechanism, including the *C4*+crassulacean acid metabolism (Sayre, 2010), carboxysomes metabolism (Sun, Y. et al., 2019a), and elevated carbon concentration around enzymes (Prasad et al., 2021).

Not only giving an option for the greenhouse gasses treatment, but this method also gives valuable by-products in terms of microalgae biomass (Daneshvar et al., 2020). The produced microalgae biomass yield is known to be higher than any other crop per cultivated area (Choi et al., 2020; Ray et al., 2022). Referring to Table 1, the yield of microalgae cultivation during the CO_2 sequestration reaching up to 2.12 g/L exhibited by *C. vulgaris* with 40% removal efficiency. In a continuous CO_2 sequestration reactor using *C. pyrenoidosa*, biomass yield reached 90.25 g/d with a removal efficiency of 92% (Yang et al., 2020).

Microalgae biomass contains many valuable compounds that can be converted into pharmaceutical materials, food products and also renewable energy (Kurniawan et al., 2021). Protein content can be converted to food and pharmaceuticals material (Tanna and Mishra, 2019), while lipid in microalgae can be used to produce biodiesel (Wang et al., 2021). *Chlorella* sp. is mentioned as one of the ingredients, is used in making some personal care products (Jha et al., 2017). *Ochromonas* sp. and *Prymnesium parvum* are mentioned to be important in producing phycotoxins that are useful in pharmaceutical applications (Khavari et al., 2021). *C. reinhardtii* also showed its potential utilisation as a human growth factor, protein, and fibronectin supplements (Jha et al., 2017; Khavari et al., 2021). Despite the specific utilisation, several species of *Chlorella* and *Spirulina* were also mentioned to be the key factor in the food and supplement industries (Araújo et al., 2021; Luo et al., 2019). Besides their importance as biomass, these microalgae can be used for CO_2 capture and wastewater treatment (Tangahu et al., 2018). Yang et al. (2020) used terephthalic acid wastewater as the microalgae culture medium during the CO_2 sequestration. Song et al. (2020) mentioned the utilisation of brewery wastewater with nitrogen removal of 75.96%, phosphorus removal of 95.71%, and COD removal of 73.66%. Similarly, Ding et al. (2020) mentioned the simultaneous phycoremediation of palm oil mill effluent and CO_2 sequestration with the removal of ammonia, nitrogen and phosphorus reaching 100%, 65%, and 56%, respectively. High uptake of nitrogen and phosphorus by microalgae was used to support their rapid cell growth, which then makes it feasible also to be used as a wastewater treatment agent (Lage et al., 2021).

3.2. Factors influencing the CO_2 sequestration by microalgae

Among several environmental factors, the CO_2 concentration, pH, illumination period, and temperature are mentioned to significantly affect the sequestration efficiency.

3.2.1. CO_2 concentration

High concentration of CO_2 gave positive results to the carbon metabolism by microalgae, resulting in the higher biomass and fatty

Table 1
Performance of microalgae in CO_2 sequestration.

Species	CO_2 capture efficiency	Biomass Yield	Product yield	Operational condition	Source
Chlamydomonas reinhardtii	113 mg/L.d	512 mg/L	Bioethanol 0.46-0.49 g/g	Tris acetate phosphate medium, light-dark cycles of 24/0, 20-35°C temperature, pH 6.5-7, 6 d	(Banerjee et al., 2021)
Chlorella pyrenoidosa	92%	90.25 g/d	-	Six-stage serial algal reactors, purified terephthalic acid wastewater, light-dark cycles of 12/12, 25°C temperature, pH 4.4-7.4, 2 d	(Yang et al., 2020)
Chlorella sorokiniana UTEX1602, *Chlorella* sp. L166, *Scenedesmus* sp. 336	52.21%	900.04 mg/L	Lipid 20.82 mg/L Protein 142.12 mg/L	Batch conical flask, light-dark cycles of 24/0, 25°C temperature, pH 6.8, 10 d	(Han et al., 2021)
Chlorella sorokiniana, Coelastrella sp., Chlorella pyrenoidosa	567 mg/L.d	1.1 g/L	-	Palm oil mill effluent wastewater, light-dark cycles of 24/0, 25°C temperature, pH 7, 7 d	(Ding et al., 2020)
Chlorella sp. L166	93.7%	-	Lipid 6.89 mg/L	Hybrid low temperature plasma system, BG11 medium, 30°C temperature, 10 d	(Song et al., 2021)
Chlorella sp. L166 *Chlorella* sp. UTEX1602 *Scenedesmus* sp. *336,* and *Spirulina* sp. FACHB-439	-	1.02 g/L	Lipid 38 mg/L	Artificial brewery wastewater, light-dark cycles of 24/0, room temperature, pH 6.8-7, 10 d	(Song et al., 2020)
Chlorella sp. L166, L38 and UTEX1602	85%	-	Protein 164 mg/L Lipid 710.6 mg/L	BG11 medium supplemented with $NaNO_3$, 30°C temperature, pH 8, 36 d	(Song et al., 2019b)
Chlorella sp. UTEX1602 and L38	76.8%	-	Lipid 15.9 mg/L	Batch feeding ammonia adsorption-microalgae hybrid system, BG11 medium, 30°C temperature, 27 d	(Song et al., 2019a)
Chlorella vulgaris	75%	1.28 g/L	-	Open race pond, 60 L, 4 cycles, 30°C temperature, pH 7-8, 30 d	(Yadav et al., 2020)
Chlorella vulgaris	40%	2.12 g/L	-	Belt conveyor reactor, 20:20:20 NPK media, 20-27°C temperature, pH 7.6, 18 d	(Al Haboubi, 2021)
Chlorella vulgaris (UTEX 2714)	182 mg/L.d	0.219 g/L.d	-	Batch photobioreactor, Bold's Basal Medium, light-dark cycles of 12/12, 20-40°C temperature, 8 d	(Hossain et al., 2022)
Desmodesmus sp.	210 mg/L.d	1.1 g/L	Lipid 419.57 mg/L	Batch photobioreactor, light-dark cycles of 12/12, pH 6.5-8, 8 d	(Premaratne et al., 2021)
Parachlorella kessleri	86.4%	65.8 mg/L.d	Lipid 11.25 mg.L Protein 13.68 mg/L	Polycarbonate bubble column photobioreactors, Bold's Basal Medium, light-dark cycles of 16/8, room temperature, pH 8.5, 14 d	(Beigbeder et al., 2021)
Spirulina platensis	-	9.1 g/m^3	-	BIOCOIL photobioreactor, liquid medium broth, 40 d	(Concas et al., 2010)
Spirulina platensis	178.46 mg/L/d	1.75 g/L	Lipid 58.42 mg/L	Hybrid adsorption and conversion system, Zarrouk medium, light-dark cycles of 24/0, pH 8.5-11, 18 d	(Li et al., 2020)

acid accumulation in the species of *Chlamydomonas reinhardtii*. This phenomenon was obtained due to the existence of *MDH3, FBA2, GAP1* and *GLYK* genes that are capable of handling the changes in carbon flux (Zhu et al., 2017). In contrast, it was also reported that the higher the concentration of CO_2, the more toxic effect exhibited to the microalgae due to the acidification (Solovchenko and Khozin-Goldberg, 2013). Lestari et al. (2019) confirmed that optimum CO_2 sequestration by *Nannochloropsis sp.* was obtained at 10% CO_2 concentration, other species like *Nannochloropsis salina* (Chen et al., 2016), *N. oculata* (Chiu et al., 2009), and *Dunaliella* (Kim et al., 2012) showed lower optimum CO_2 growth concentration of 2% - 6%, concluding that tolerability to the CO_2 concentration is highly dependent on the microalgae species.

3.2. 2 pH

Neutral pH (6.5 to 8) is suggested as a good condition for microalgae cultivation. CO_2 sequestration is not only related to the growth of microalgae biomass, but also highly related to the nutrient uptake, photosynthetic activity, and several enzymatic reactions (Prasad et al., 2021). Acidic pH has the benefit for CO_2 sequestration due to the increasing concentration of free-CO_2 (which is favourable for acid-tolerant species like *Scenedesmus* sp. (Wang, H. et al., 2018), and *C. sorokiniana* (Abiusi et al., 2022). Alkaline pH also gave an increase to the CO_2 solubility in the form of CO_3^{2-} ions (Prasad et al., 2021), this condition will be beneficiary for the high-CO_2 and alkaline tolerant species like *C. sorokiniana* str. SLA-04 (Vadlamani et al., 2017) and *Chlorella* sp. AT1 (Kuo et al., 2017).

3.2.3. Illumination period

The illumination period played an important role due to the light-dependent photoautotrophic metabolisms (Liang et al., 2018). Longer illumination period is needed for photoautothropic and mixoautothropic species (Morales-Sánchez et al., 2015). Light-dependent enzymatic reactions convert the photon into ATP and NADPH which are used to provide energy for fixation and sequestration by the presence of Rubisco in Calvin-Benson cycle (Liang et al., 2018). During the dark cycle, microalgae optimise the function of chlorophylls, while in the light cycle, the electron flow from QA- to QB- increased the charge recombinant promoting the formation of P680 to produce oxygen (Aro et al., 1993). For example, *C. vulgaris* prefer the longer light as compared to the dark cycle to produce more microalgal biomass (Bazdar et al., 2018), while in other research, a longer light cycle may cause light stress to the species of *N. salina* which resulted in lower lipid production by this species (Sforza et al., 2012).

3.2.4. Temperature

The optimum temperature effect is highly dependent on the microalgae species; for example, the *C. vulgaris* species has an optimum temperature of 30°C (Ördög et al., 2016), *N. oculata* at 20 °C (Ördög et al., 2016), *Scenedesmus sp.* at 25 °C (De Morais and Costa, 2007), and *S. obliquus* at also at 30 °C (Yoo et al., 2010). The temperature has opposite relation with the dissolution of CO_2 in the aqueous solution, thus affecting the overall removal (Prasad et al., 2021). Temperature affects the CO_2 sequestration by microalgae due to the change in the carboxylase and Rubisco enzymes activity (Prasad et al., 2021). As enzyme is a protein unit, low temperature gave changes to the amino structures while high temperature stretch and break the polypeptide chain (Yan et al., 2018), resulting in the disruption of the CO_2 sequestration.

4. Lifecycle analysis and cost considerations of the process

In recent years, the quest to minimise the likely shortage of land and fodder for producing biofuels shifted the focus to third-generation

feedstock, i.e., aquatic biomasses such as microalgae and seaweeds (Saranya and Ramachandra, 2020). Moreover, the inherent capacity of microalgae to convert CO_2, sunlight, and water to valuable compounds, including carbohydrates, lipids, and protein, and subsequently process them to produce bioenergy makes them potential feedstock candidates (Peter et al., 2022). Additionally, there is growing evidence that microalgae can curb CO_2 emissions (Kassim and Meng, 2017; Kuo et al., 2016; Li et al., 2021; Prasad et al., 2021; Sadeghizadeh et al., 2017). However, the microalgae CO_2 sequestration challenges include (but are not limited to) microalgae strain, CO_2 source composition, CO_2 tolerance capacity, and the cultivation system (Singh and Ahluwalia, 2013).

Among the factors militating against CO_2 sequestration, massive energy consumption and operating cost burden are enormous in the biomass cultivation phase (Slade and Bauen, 2013). As a result, scaling up microalgae cultivation for commercial biomass production is challenging and demands a feasibility test of a laboratory-scale culture process. Therefore, researchers have explored various cultivation systems for microalgal biomass production and tested them on laboratory and industrial scales (Ugwu et al., 2008). Yet, to date, only a few research works have conducted a lifecycle analysis and cost implications of the processes.

4.1. Lifecycle analysis of microalgae CO_2 sequestration

The lifecycle analysis (or lifecycle assessment, LCA) approach has become a powerful tool that evaluates the entire life cycle of processes or products and offers quantitative and holistic analyses of the associated environmental impacts and resource use (Li et al., 2021; Sun, C.-H. et al., 2019b). For example, regarding microalgae cultivation, a viable option for CO_2 sequestration, an LCA approach is instrumental in evaluating various configurations regarding the cultivation parameters for sustainable and economic development (Peter et al., 2022). To illustrate, an LCA has been used to assess microalgae cultivation, targeting the efficiency of pond systems and photobioreactors (PBRs) (Hossain et al., 2019). Another study applied LCA in reconciling questions regarding the economics, commercial-scale logistics, and lifecycle metrics of covered-raceway ponds cultivation systems and glass helical photobioreactors (Somers et al., 2021). It was also instrumental in comparing the eco-performance of different scenarios and the possible outcomes of microalgae farming (Peter et al., 2022).

Furthermore, an LCA has been effectively used to analyse and appraise the environmental impacts of algae food or feed (Ye et al., 2018), microalgae biodiesel production (Collet et al., 2014; Kushwaha et al., 2022), and microalgae biofuel production (Mu et al., 2020; Somers et al., 2021). More importantly, this section focuses on the LCA framework applied in the microalgae cultivation processes since microalgae culture significantly impacts CO_2 sequestration and downstream production. According to the International Standard Organisation (ISO), LCA is generally divided into four phases (ISO, 2006) as illustrated in Fig. 3. These are goal and scope definition, inventory analysis, lifecycle impact assessment, and results interpretation. Besides, the components that make up the phases (also indicated in Fig. 3) will help to guide the LCA comparison of the reviewed articles and enable the extraction of information and gaps necessary for the improvement of future assessments.

4.1.1. Goal and scope definition

The initial stage in an LCA is determining the research goals and scope for analysis. Although LCA can analyse a product, service, or process or compare various processes and products, we focus on the LCA studies that investigated the microalgae CO_2 sequestration process through cultivation. In this regard, we reviewed seven articles that centered on the lifecycle analysis of microalgae cultivation, without including the process of biomass application. This approach provides a basis for comparing and deciphering differences in the LCA processes of the articles that can influence performance and impact assessment. Furthermore, functional units, system boundaries (background and foreground processes), and allocation procedure are the choice aspects that are covered in this section, and these can impact the results of an LCA study.

The functional unit provides a reference that relates the input and output flows, which also depends on the study scope and product being analysed. Thus, the produced biomass weight (usually in kg) is the easily measured functional unit that is used in the articles. Moreover, the articles specified the nature of the biomasses, such as dry weight or moisture content, which is useful for comparison (Table 2). In addition, the goal of the various LCA was to provide a coherent comparison of the procedural options of cultivating microalgae for processing into a product. For instance, comparative LCA for cultivation systems, methods, frameworks, scenarios, system design options, and CO_2 sources was undertaken. In these examples, the aim was to use LCA to determine which option produces microalgal biomass at low cost with greater performance and minimal effect on the ecosystem. The uniformity of the functional unit adopted by the studies, although contingent on the intended product, makes the comparability of the investigated environmental impacts feasible. In addition, the articles' LCA focus remained unchanged despite cultivating the microalgae for various purposes such as bioenergy, food and feed, and cosmetics.

The system boundaries are made up of the foreground and background processes, relating to the stages that are typically influenced by the study and the processes that furnish materials and energy, respectively (Pérez-López et al., 2017). The scope of the LCA presented in the articles was instrumental in defining the system boundary, which followed a cradle-to-gate approach. Fig. 4 illustrates a system boundary that utilised the "cradle-to-gate" analysis, including the cultivation, harvesting, and processing phases. The system boundary shown here can be adapted to other LCA for microalgae cultivation. However, contingent upon the scope and goal of the analysis, microalgae nutrients, cultivation systems, and microalgae strains may change. Additionally, Table 2 presents the system boundaries (foreground processes) of the LCA defined in the reviewed articles. It is observed that in some studies that utilised PBR for microalgae cultivation, the process started with cleaning and sterilisation of the reactors. However, it was not clearly spelt out in the other studies (Table 2). Further, most of the studies reported 1 kg dry weight (DW) as their functional unit, signifying that the foreground processes might have involved a drying step. Yet, only a few studies, as shown in Table 2, enlisted the drying step. Likewise, more than half of the articles considered transportation in the boundary of the system, although a negligible contribution to impact assessment was reported (Porcelli et al., 2020). Moreover, the goal and scope of the other studies might have warranted the omission of transportation, which can also be supported by the attention to cradle-to-gate approach and the assumption of same location for all process facilities. Nevertheless, Bussa et al. (2019) suggested that a well-defined system boundary is vital to recognise appropriate processes and make accurate inferences from the results. Thus, providing every detail regarding the system boundary contributes to a modest comparison of LCA studies.

4.1.2. Lifecycle inventory analysis (LCI)

In LCI step, pertinent data that are based on the defined elements in Section 4.1.1 are collected. As shown in the system boundary (background processes), all primary input streams (nutrients, energy, water, gases) and all outputs (such as wastewater and gases) produced during the cultivation process make up the LCI. For example, in the study conducted by Yadav et al. (2020), the primary system inputs include electrical energy, flue gas CO_2, growth nutrient, and tap water. Similarly, Peter et al. (2022) considered water supply, CO_2, electricity source, and air input in analysing LCI. Table 3 clearly shows variation, especially, in the input flows of the various LCA reported for microalgae cultivation. Specifically, this distinction is mainly on nutrient as its requirement for microalgae growth is dependent on the microalgae species. Regardless, a significant number of the articles enlisted potassium, phosphorous, and nitrogen either in their elemental or compound forms, which make a significant input flow. Further, only about 28.6% of the articles did

Fig. 3. Phases and their components in lifecycle analysis.

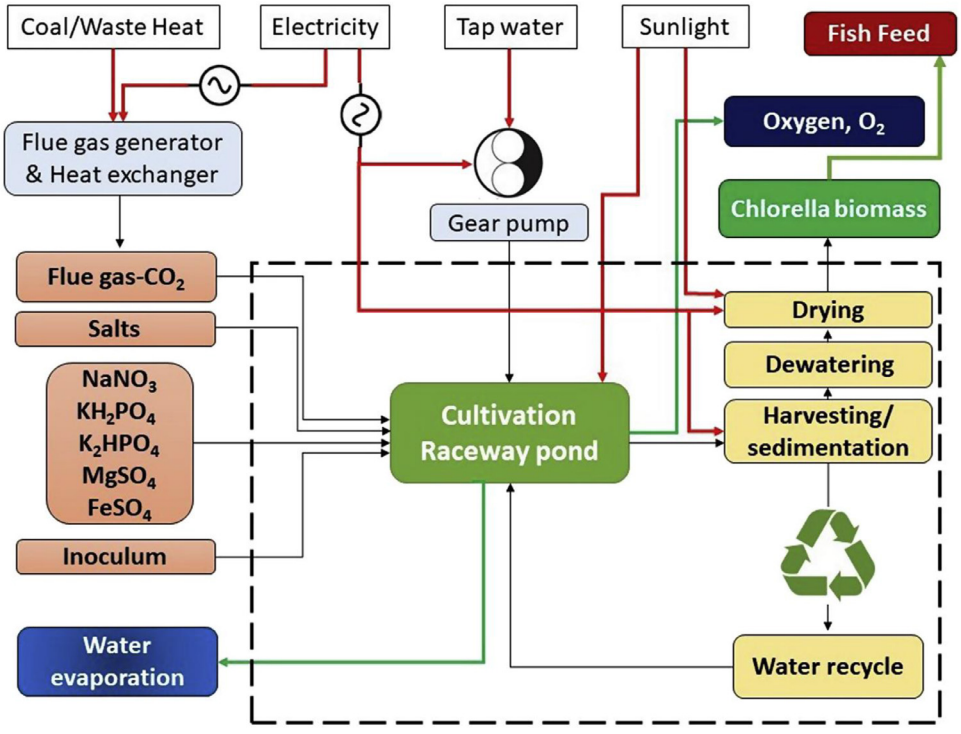

Fig. 4. The system boundary of "cradle-to-gate" microalgae cultivation for biomass production and CO_2 sequestration LCA (*Reprinted from* Yadav et al. (2020) *with permission from Elsevier*).

not explicitly include other trace elements, either in their elemental or compound sources. Often, trace amounts of these nutrients are required but not always included in microalgae growth as shown in Table 3.

One of the articles investigated the performance and impact of using a recycled nutrient medium for microalgae growth (Peter et al., 2022). Recycling nutrient medium results in minimising the amount of required nutrient input sourced externally with a concomitant reduction in the associated costs and impact due to production and transportation. Another input, which forms the basis of this literature is carbon dioxide. It is evident from Table 3 that all the articles enlisted CO_2, being a vital input flow for their LCA. It also bolsters the use of microalgae for CO_2 sequestration. Additionally, other listed inputs are disinfectants, hypochlorite,

Table 2
An overview of some LCA methodological characteristics.

LCA goal	Functional unit/ Microalgae strain	Suggested biomass purpose	Foreground processes	Production scale/ capacity	Facility location	References
Compare cultivation frameworks (inorganic medium (BG-11), BG-11 mixed with diary waste powder, and recycled option 2 medium)	1 kg biomass (DW)/ *Chlorella vulgaris*	Biofuel	Disinfection of reactor, formulation of growth medium, algae growth process, and biomass drying	Laboratory, large scale up/ 1 L PBR vs 2500 L PBR	Unspecified	(Peter et al., 2022)
Compare photobioreactor design options (PBR vs MUTL-PBR)	1 kg biomass (DW)/ *Acutodesmus obliquus*	Cosmetics	Supply of nutrient, cultivation, harvesting, and biomass stabilisation	Laboratory, pilot scale/ 250 L PBR vs 100 L MUTL-PBR	Nuthetal, Germany	(Sandmann et al., 2021)
Compare cultivation methods (heterotrophic, phototrophic, or combined)	1 Kg biomass (with 90% H2O, w/w)/ *Galdieria sulphuraria*	Functional/ sustainable food	Cultivation, flocculation & centrifugation, and water neutralisation	Uknown scale/ 12 L H-PBR vs 350 L P-PBR	Unspecified	(Thielemann et al., 2021)
Compare cultivation systems (Open pond vs PBR)	1 kg torrified biomass/ *Chlorella vulgaris*	Bioenergy	Cultivation, harvesting, drying, and torrefaction	Laboratory, pilot scale/ 1000 L open pond vs 1 L PBR	Unspecified	(Ubando et al., 2020)
Compare commercial and waste CO_2 sources	1 kg biomass (DW)/ *Phaeodactylum tricornutum*	Functional/ sustainable food	Cleaning & sterilisation, cultivation, harvesting, and freeze-drying	Semi-industrial scale/ 250 L PBR	Italy	(Porcelli et al., 2020)
Compare cultivation scenarios (RP-BA, RP-BFG, and RP-SBPPFG)	1 kg biomass (DW)/ *Chlorella vulgaris*	Fish feed	Cultivation, harvesting & sedimentattion, dewatering, and drying	Batch & semi-continuous pilot scale/ 60 L ORP	Kharagpur, India	(Yadav et al., 2020)
Compare production systems (Hor-PBR, Ver-PBR, and ORP) and weather conditions (Winter, Summer, and Fall)	1 kg biomass (in 22% DW slurry)/ *Nannochloropsis sp*	Unspecified	PBR Cleaning, culture medium preparation, cultivation, and biomass concentration	Pilot large scale/ 560 L Hor-PBR, 1060 Ver-PBR, and 4730 L ORP	Wageningen, Netherlands	(Pérez-López et al., 2017)

MUTL-PBR: mesh ultra-thin layer photobioreactor; PBR: photobioreactor; DW: dry weight; H-PBR: Heterotrophic PBR; P-PBR: Phototrophic PBR; ORP: open raceway pond; RP-BA: raceway pond-batch mode without flue gas; RP-BFG: RP with flue gas source; RP-SBPPFG: RP-semi-continuous mode with flue gas; Hor-PBR: horizontal PBR; Ver-PBR, vertical PBR.

acids, and peroxides, which were likely used in cleaning and sterilisation stage. Although, these were not captured in the foreground processes of some articles depicted in Table 2. Generally, LCI gathers all the inputs and outputs of unit processes, equipment, land use, labour, and energy and materials for production processes (Mu et al., 2020).

4.1.3. Lifecycle impact assessment (LCIA)

LCI results are transformed into specific impact indicators to appraise the potential environmental impacts in this stage. At first, the impact categories for the analysis are chosen, and then LCI results are assigned to the impact categories, followed by the probable impact indicators calculation (Mu et al., 2020). These selection, classification, and characterisation steps are mandatory for an LCIA. Thus, all the reviewed articles performed these critical LCIA steps except two articles with LCIA methods designated as “unspecified” in Table 3, which did not conduct an LCIA. It is noteworthy that an LCIA is an integral phase of an LCA, which seeks to evaluate the environmental impact attributable to the product being studied. Therefore, an LCA without this phase may be viewed as incomplete, irrespective of the objectives of the study. Furthermore, the remaining LCIA steps, including normalisation and weighing, were not considered in 57.1% of the articles either because they are optional in ISO standard and not essential to accomplish the objectives of the study (Porcelli et al., 2020) or were deemed irrelevant to furnish pertinent information for the study’s objectives (Pérez-López et al., 2017). Nevertheless, (Yadav et al., 2020) included the normalisation step to compare each impact category for the different production scenarios on the same graph, avoiding the maintenance of different suites of characterisation factors. In addition, the influential LCIA features are presented in Table 3.

The LCIA methods integrate characterising elements and models for various impact categories, which differ from one method to another. For instance, the ReCiPe method covers more impact categories compared to CML and IMPACT 2000+ (Bussa et al., 2019). Nevertheless, the reviewed articles employed various LCIA methods and in some cases, two or more methods were combined. About 42.9% of the articles used the CML method; one article applied the IMPACT 2000+ method, another used the ReCiPe method, whereas the remaining two articles did not conduct an LCIA; thus, no record of the methods (Table 3). Generally, the selected LCIA methods are congruent with the stated goals and scopes of the articles. They equally encompass an extensive set of impact categories that may be affected by the intended product. Moreover, as there is no all-encompassing set of impact categories delineated for bio-based products, literature recommends those covering water and land use and the effects of pesticides and nutrients used in the cultivation phase (Bussa et al., 2019).

To effectually perform an LCA of a microalgae product, actual data is germane for the cultivation phase, for example, because any assumption made may influence the general growth process. Likewise, the assumption that a considered algae species has a superior growth rate may present the species as suitable yet may not account for the required conditions or nutrients that are involved in achieving such a growth rate. Therefore, the quality of data used in an LCA cannot be downplayed. Incidentally, all the reviewed articles that conducted an LCIA used measured, calculated, or field data coupled with literature data for the robustness of the LCA. In addition, different software may yield varying outcomes in an LCA study. The discrepancy may be due to the structure of the software programmes in executing LCIA methods and variation in the nomenclature of the characterisation factors. All the same, all the articles indicated the software used, and more than half of the articles used the SimPro software, which seems to be the prevalent software for the assessments in the literature.

4.1.4. Results interpretation

In this final stage, the outcomes of the LCI and LCIA are classified, quantified, and evaluated to reach appropriate conclusions and recommendations. The LCA characterisation results of the reviewed articles are in line with the methodologies they applied to achieve the goals of their studies. In some cases, the contributions of the foreground and background processes to environmental burden were relatively evaluated. For instance, Pérez-López et al. (2017) charted the relative contributions of the subsystems (reactor cleaning, nutrient supply, cultivation, and concentration) and the production processes included in the

Table 3
Characteristic components of LCIA and LCI inputs for microalgae cultivation.

LCIA methods	Data sources	Software	LCA technique	Database	Input flows				Output flows	Ref.
					Nutrients	*Energy*	*Gases*	*Others/ materials*		
Unspecified	Actual lab data, literature	GaBi	Cradle-to-gate	GaBi ts education database	$MgCO_3$, $NaNO_3$, K_2HPO_4, $MgSO_4$, $CuSO_4.5H_2O$, $MgCO_3$, $Co(NO_3)_2{\cdot}6H_2O$, EDTA, $Na_2MoO_4{\cdot}2H_2O$, S, Na, P, Se, K, Cu, Fe, Mn, etc	Electricity	CO2, O2	Boric acid, citric acid	Unspecified	(Peter et al., 2022)
IMPACT 2002+	Experimental trial	SimaPro v.8.2.0.0	Unspecified	Ecoinvent v.3.1	Water, culture media	Electricity	CO_2	Cultivation time, H_2O_2, citirc acid, land	Unspecified	(Sandmann et al., 2021)
Unspecified	Literature	Umberto v.10	Unspecified	Ecoinvent v.3.6	N, P, glucose, water	Electricity, natural gas	CO_2, O_2	H_2SO_4	AWW, CO_2, O_2, CB	(Thielemann et al., 2021)
ReCiPe version 2016	Literature, measured data, calculated data, personal communication	SimaPro v.8.5.2	Cradle-to-gate	Ecoinvent	N, P, K, $MgSO_4$, $NaNO_3$, Water, EDTA, NaOH, $ZnSO_4.7H_2O$,	Electricity	CO_2	Citric acid, Cl, etc	Wet biomass	(Ubando et al., 2020)
CML 2001	Literature, calculated data	GaBi	Cradle-to-gate	Ecoinvent v.2.0	Water, NaClO, $FeCl_3$, EDTA, Na_2SiO_3, $ZnSO_4.7H_2O$, NaH_2PO_4, KNO_3	Electricity	CO_2	NaClO, HCl	Wastewater, CO_2, NaClO	(Porcelli et al., 2020)
CML, ReCiPe, IPCC, CED	Literature, actual field data	SimaPro v.8.0.3.14	Cradle-to-gate	Ecoinvent v.2.2	$NaNO_3$, $ZnSO_4.7H_2O$, KH_2PO_4, NaCl, $MgSO_4.7H_2O$, $CaCl_2.2H_2O$, $CuSO_4.5H_2O$, $FeSO_4.7H_2O$, KOH, H_3BO_3	Electricity	CO_2	Disinfectant, coal	Wastewater, CO_2	(Yadav et al., 2020)
CML 2001, CED	Measured data, calculated data	SimaPro v.8.0	Unspecified	Ecoinvent v.2.0	$NaNO_3$, $ZnSO_4.7H_2O$, KH_2PO_4, $MnCl_2.2H_2O$, $MgSO_4.7H_2O$, $CaCl_2.2H_2O$, $CuSO_4.5H_2O$, $FeSO_4.7H_2O$, $Na_2EDTA{\cdot}2H_2O$, $Co(NO_3)_2{\cdot}6H_2O$, $Na_2MoO_4{\cdot}2H_2O$, NaOH	Electricity	CO_2, air	Disinfectant, plastic beads, Cl solution, etc	Wastewater	(Pérez-López et al., 2017)

CED: cumulative energy demand; CML: centrum milieukunde lieden; IPCC: intergovernmental panel on climate change.

operation of the compared reactor configurations. They indicated that the cultivation stage contributed 80% or more impact in all the analysed categories, making it the major hot spot. Similarly, another study that utilised the characterisation results of the CML method to calculate subsystems analogous to those mentioned earlier but including flue gas compression, transport, and waste treatment reported a 75% impact or more (Yadav et al., 2020). Furthermore, in addition to cultivation, both drying and torrefaction contributed significantly to environmental burden in the scenarios studied by Ubando et al. (2020). For instance, drying dominated in all the impact categories in a laboratory scale open pond cultivation system scenario. More so, the elevated impact of torrefaction in the said scenario was due to the high electricity requirement for each kg of the torrefied microalgal biomass. Again, with the results of Porcelli et al. (2020) indicating that the main contribution, for majority of the impact categories, was derived from cultivation (approximately 50%) and freeze-drying (around 40%), it can be inferred that the cultivation phase significantly contributes to the impact categories of the production processes.

The assessment of the influence of energy use during microalgae production process is crucial, in that energy is involved in almost all the process subsystems; thus, contributing immensely to environmental load. As an instance, among the reviewed articles, only two (Pérez-López et al., 2017; Yadav et al., 2020) utilised the CED methodology to evaluate the overall energy consumption of the production process. The calculated averages of the total cumulative energy demand (CED) reported by Pérez-López et al. (2017), considering all the weather conditions, were 17854.7 and 37203 MJ for PBR and ORP production systems, respectively. Similarly, the consumption of 36943.3 MJ (converted from GJ reported in the article) from both non-renewable fossil energy (about 85% of total CED) and non-renewable nuclear energy (approximately 10% of total CED) was recorded by Yadav et al. (2020). The closeness and higher values of energy consumption in both studies (for ORP systems) may be attributed to aeration and mixing of the open raceway ponds. Conversely, the calculated average energy consumption (5323.4 MJ) for PBR systems in the work of Sandmann et al. (2021) (using IMPACT 2002+ LCIA method) supports prior observation and indicates that microalgal biomass production in ORP systems may consume more energy than in PBR systems, irrespective of location.

The use of energy, especially non-renewable sources, in microalgae production generates greenhouse gases (GHGs) that are directly linked to climate change. Thus, the GWP (kg CO_2 eq) impact is associated with the emissions of GHGs such as CO_2, N_2O, and CH_4. From the reviewed articles, the calculated average GWP impacts of producing 1 kg of biomass in photobioreactors were 1086.8 kg CO_2 eq (Pérez-López et al., 2017), 278 kg CO_2 eq (Porcelli et al., 2020), and 331.5 kg CO_2 eq (Sandmann et al., 2021), whereas 2256 kg CO_2 eq (Pérez-López et al., 2017) and 914.3 kg CO_2 eq (Yadav et al., 2020) were the GWP impacts for producing microalgal biomass in open raceway ponds. Undisputedly, during the microalgae cultivation phase in the ORP, CO_2 is sequestered, which should substantially minimise the GWP impact. Regardless, it should be recalled that ORP system consumes more energy that PBR due to the reason given above; therefore, the higher GWP value for ORP in Pérez-López et al. (2017) study might be attributable to huge electricity consumption. To further buttress, the comparison of ORP and PBR for producing microalgal biomass in four different scenarios showed negative GWPs for two ORP scenarios during cultivation process; but the energy used for drying contributed substantially to GWP value (Ubando et al., 2020). Conversely, both cultivation and drying processes in PBR scenarios consumed considerable amount of energy leading to a high GWP impact. Be that as it may, using solar energy, without GHGs emission, will absolutely minimise GWP effect on the environment, during microalgal biomass production in ORP systems.

Additionally, we found discrepancies in various reviewed articles for other impact categories, which are ascribed to the LCIA methodologies employed. In some cases, the units of the impact categories were different (e.g., CTUh and kg 1,4-DB eq for human toxicity potential). Nonetheless, we pinpointed a few articles that were useful in comparing the contribution of microalgal biomass production processes to some impact categories. For instance, the average contribution of microalgal biomass production in ORP systems to human toxicity potential was 445.6 kg 1,4-DB eq (Pérez-López et al., 2017) and 190.7 kg 1,4-DB eq (Yadav et al., 2020), while that for PBR was 236.4 kg 1,4-DB eq (Pérez-López et al., 2017). Also, for eutrophication potential, 3.83 kg PO_4^{3-} eq (Pérez-López et al., 2017) and 0.48 kg PO_4^{3-} eq (Yadav et al., 2020) were obtained for the ORP systems whereas 1.76 kg PO_4^{3-} eq (Pérez-López et al., 2017) was calculated for the PBR systems. In addition, the microalgal biomass production processes contributed to abiotic depletion potential in PBR systems: 8.39 kg Sb eq (Pérez-López et al., 2017); 1.2×10^{-3} kg Sb eq (Porcelli et al., 2020); and in ORP systems: 6.01 kg Sb eq (Yadav et al., 2020); 17.5 kg Sb eq (Pérez-López et al., 2017). From the foregoing, it appears that producing 1 kg of microalgal biomass through the open raceway pond, in contrast to the photobioreactors, portends a higher environmental burden regarding the enlisted impact categories. All the same, it may be an inaccurate deduction owing to the differences in the studies' goals, microalgae species, productivity levels, LCIA methodologies, and data sources. Therefore, more comparable studies (in terms of goals and methodologies) are required to make viable decisions regarding the prospects of producing microalgal biomass in an environmentally friendly manner.

4.2. Cost considerations of microalgae CO_2 sequestration

It is essential to investigate the impacts of producing microalgae and their features on the cost of microalgae. However, various variables, such as the cost of raw materials and instruments, may change due to market fluctuations and uncertainties (Peter et al., 2022). It is noteworthy that there is a cost attached to the input flows to every subsystem within the system boundary. For instance, the cost of land for construction, the cost of borosilicate glass for constructing PBRs, the cost of energy, water, and disinfectants for cleaning, the cost of water, energy, nutrients, and pesticides for cultivation, and the cost of energy for drying. Moreover, Schade and Meier (2021) indicated that for producing 1 kg dry weight of microalgal biomass, the cost of purchasing a glass tube system takes the highest toll on the investment cost (24 – 31%), followed by the cost for the drying system (21 – 24%), and then the cost of constructing buildings for cultivation, which is between 18 and 21% of the total investment costs (Fig. 5). On the operating costs, the fee for hiring labour covers as much as 39 to 42% of all the total operating costs (Schade and Meier, 2021).

In another study, the researchers stated that irrespective of the process options, the infrastructure for producing microalgae biomass in the plant stayed constant. The total capital cost for constructing a 14,000 L PBR was estimated at $ 451000 (Peter et al., 2022). Similarly, the LCA framework demonstrated that the three flow alternatives (1. a chemical-based BG-11; 2. a blend of biscuit waste with BG-11; and 3. re-using the culture medium residue from number 2, after harvesting) utilised identical electricity consumption of approximately 12325.34 kWh/day. Moreover, the total operating cost ranged from $138,000 to $ 3,780,000 for the three process flow alternatives (Peter et al., 2022).

Furthermore, recent techno-economic analyses of microalgal biomass production using open and closed systems are presented in Table 4. Results show that the production cost of closed systems is higher than the open systems, whereas the operating cost of the latter is higher. Also, the close cultivation system needs only a small plant capacity than the open system, while the microalgae productivity of the closed system is enormous compared to the open system. From Table 4, it could be deduced that the numerous advantages of the closed cultivation system, including easy control of operating conditions and adaptability, contribute to the cost-effectiveness of microalgal biomass cultivation and efficient CO_2 sequestration. However, other factors such as nutrient source and microalgae strains play a vital role in microalgae CO_2 capture.

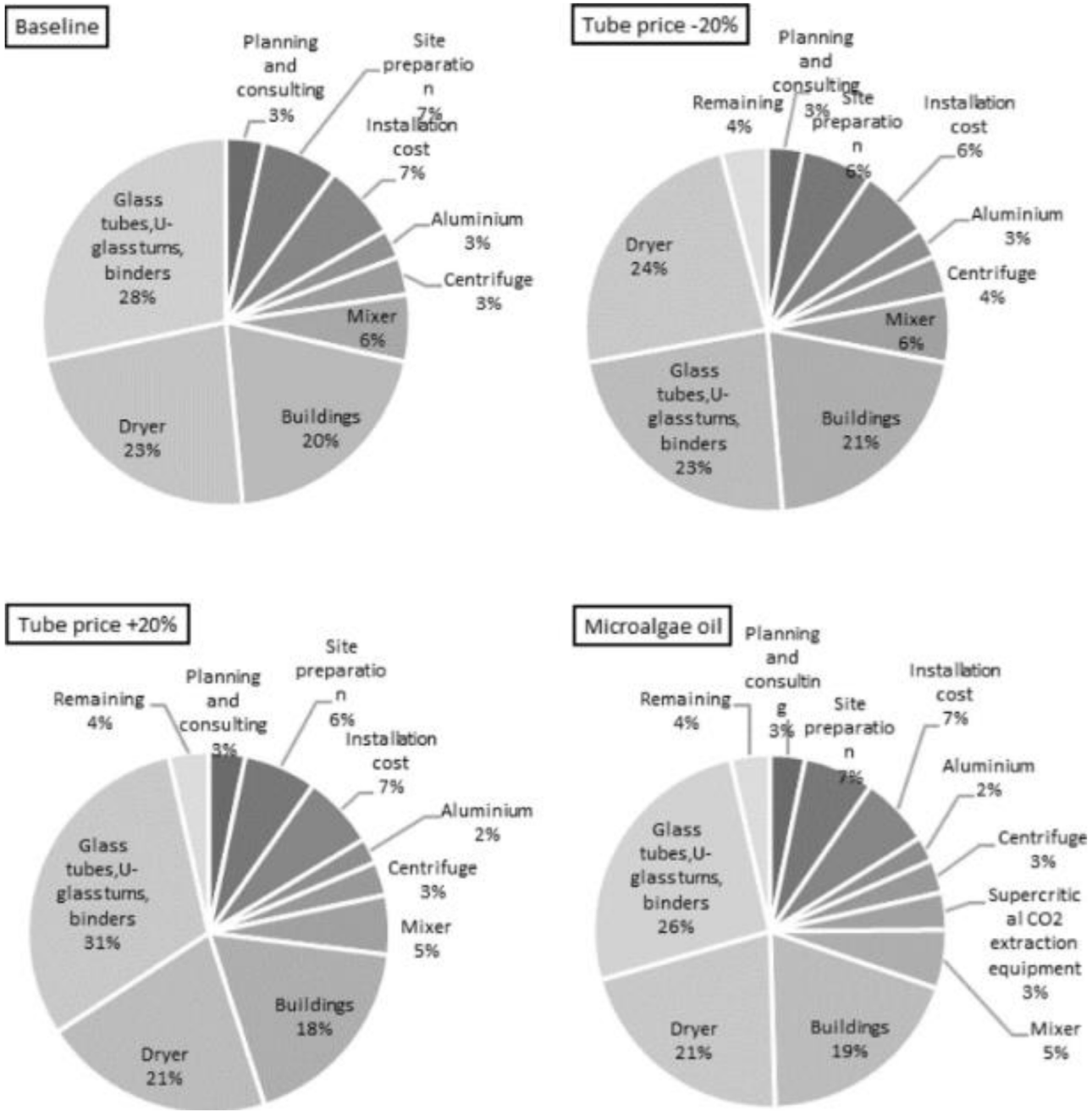

Fig. 5. Summary of component contribution to investment costs in microalgal biomass cultivation in PBRs. (*Reused from Schade and Meier (2021) with attribution to Springer under the Creative Commons licence (CC BY).*).

5. Energy and environmental implications of microalgae-based CO_2 sequestration

The use of microalgae for CO_2 sequestration is a promising technology to diminish the carbon in the atmosphere and also help in mitigating the trend toward global warming, as reported by researchers (Banerjee et al., 2020; Morales et al., 2018; Singh and Ahluwalia, 2013; Verma and Srivastava, 2018). However, its applicability and viability are a function of the energy and environmental implications of the process. This notion is important to conserve energy, protect our natural environment, humans, and ecological health while driving innovation and not compromising our life (Ighalo and Adeniyi, 2020). Several studies have reported the energy-environ effects of the use of microalgae for CO_2 sequestration. Xu et al. (2019a) studied the efficiency of microalgae's photosynthetic carbon fixation from a mechanistic perspective. They observed that inorganic carbon sources could be derived from flue gases from power plants and other industrial exhaust gas, and wastewater from the industrial and agricultural process can be used as nutrient sources to cultivate microalgae at low cost for CO_2 sequestration. Such an investigation is interesting as it shows how this technology can simultaneously influence the energy-environment nexus in a positive way. Through the photosynthesis process, the carbon absorbed by microalgae can be converted to carbohydrates, further processed to biodiesel and bioethanol, respectively (Lam et al., 2012). This is an eco-friendly application of energy, which is cleaner than fossil fuel sources. Cheah et al. (2015a) also reported that microalgae are the dominant

Table 4
Comparison of biomass production cost implication for open and close systems.

Location	Cultivation system	Production plant capacity (t/year)	Microalgae productivity (t/km^2/year)	Capital cost ($/year)	Operating cost ($/year)	Production cost ($/kg)	Reference
Albuquerque, New Mexico	Flat panel PBR	108	10,800	94,356	278,146	3.5	(Banerjee and Ramaswamy, 2019)
Albuquerque, New Mexico	Outdoor raceway pond	2.7	6,200	958,790,076	149,044,782	0.54	(Banerjee and Ramaswamy, 2017)
Michigan, USA	Photovoltaic powered PBR	14.6	NA	1,675	90,647	10	(Pavlik et al., 2017)
Anand district, Gurajat state	High volume V-shaped pond	504	62,146	1,200,000	100,000	0.48	(Kumar et al., 2020)
NA	Algal turf scrubber	500,000	7,300	338.83*	171.79*	0.51	(Hoffman et al., 2017)

NA means not available;
* values are in $/t.

biotics used in oxidation ponds for wastewater treatment plants and sewage treatment ponds. According to Zhao and Su (2020) to an average, annual 0.5393 $GtCO_2$ sequestration and 324.33 million tons of biomass including 64.87 million tons of biofuel could be benefitted from microalgae. Chen et al. (2018) reported that microalgae used to sequester CO_2 could capture about 9% solar energy via photosynthesis to produce about 280 tons of dry biomass ha^{-1} yr^{-1} whilst consuming about 513 tons of CO_2. Ono and Cuello (2003) revealed that using thermophilic microalgae species for CO_2 sequestration can help reduce thermal plants' cooling costs. Though not directly related to the energy-environment nexus, cost is also an important aspect of sustainability. Based on the reviewed literature, the energy and environmental results showed that microalgae for CO_2 sequestration are an environmentally sustainable and energy-efficient process.

6. Conclusion

The use of microalgae for CO_2 sequestration diminishes the carbon in the atmosphere and also helps in mitigating the increasing trend toward global warming. Several conclusions were derived from this review. Performance analysis revealed that the capture and sequestration of CO_2 by microalgae ranges between 40% and 93.7%. The CO_2 sequestration mechanism is done via bioconcentration during photosynthesis. Based on the review of energy and environmental implications of microalgae-based CO_2 sequestration, several knowledge gaps have been identified, leading to more opportunities for future studies in this area. Most of the literature reviewed has shown that microalgae are environmentally friendly and bio-energy producing media for CO_2 sequestration. However, the macro performance of microalgae in carbon emission reduction has not yet been fully understood. Such studies are needed into the suitability of microalgae species for CO_2 sequestration. The production cost of closed systems is higher than the open systems, whereas the operating cost of the latter is higher. Also, the close cultivation system needs only a small plant capacity than the open system, while the microalgae productivity of the closed system is enormous compared to the open system. The cost-effectiveness of the CO_2 sequestration technique for microalgae cultivation and harvesting still needs to be pursued based on recent economic realities. It is recommended that design and operation be focused on cost-effectiveness so the technology can compete favourably with existing technologies. In recent times, researchers have explored the selection and cultivation of microalgae species based on bench-scale domestication for CO_2 fixation. In the future, information on the selection and cultivation of microalgae species for large-scale CO_2 sequestration from actual combustion flue gas will be required.

Declaration of Competing Interest

The authors declare that there are no conflicts of interest.

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