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Effect of CO_2 concentration on algal growth: A review

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ABSTRACT

Natural changes in climate due to internal as well as external factors, like anthropogenic emission, fossil fuel combustion, transportation and heating which cause CO_2 emissions is one of the major issues which causes global warming (increasing concentrations of greenhouse gases). The production of algae is identified as one of the solutions of carbon sequestration along with production of renewable fuel solving the problem of food crisis to a certain extent. This review paper summarizes how CO_2 levels affected micro algal species. Several species of algae as *Scenedesmus obliquus*, *Botryococcus braunii*, *Chlorella vulgaris*, *Nannochloropsis oculata* have been reported to accumulate high concentration of lipid. These species are suitable for biofuel production as well as Carbon fixation.

Contents

1. Introduction

Direct emission of Carbon di oxide in the environment is a dangerous perspective. CO_2 is mainly responsible (60% to 63%) for

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the change in net irradiance between different layers of the atmosphere since 1979 to 2004 [1] and hence global warming could become a major global environmental problem during the 21st century. Various natural and man-made sources are responsible to the CO_2 emission. During 2010, CO_2 produced was about 84% of the U.S. greenhouse gas emissions from Industrial revolution and human activities (combustion of fossil fuels). Many strategies have been formulated to reduce CO_2 emissions from residential as well as commercial establishments, industries and minimize the effects caused by this environmental problem. The Kyoto- protocol was organized on 11 December 1997 in Kyoto, Japan to reduce the emission of gases. *Chlorella vulgaris* a green micro alga was grown under the 0.036% to 20% concentration of CO_2 [2,3] from 37 industrialized countries. We are familiar with conventional forms of renewable energy like Solar, wind, ethanol, biodiesel, wood or hydrogen. CO_2 fixation by algae is another such form; i.e. sunlight being used to reduce CO_2 to carbon. Capturing CO_2 from flue gases [4] is the precautionary principle which needs preventive action, at both national and international levels to minimize this potential action. But the transportation and storage of CO_2 becomes a very expensive process.

Air pollution, water pollution and depletion of fossil fuel are presently the three biggest challenges for humanity. Some investigators have recommended establishing waste water treatment plants but these plants emit lot of green house gases, second to make first generation biofuel, which are not sustainable. To sort out all these problems algal growth is found to be the best option. Various technologies that have been developed for enhancing biological carbon fixation (capture CO_2 from large emission source points) have assisted in safeguarding the environment. Carbon negative renewable energy technologies are very important and cost effective tool based on carbon sequestration concepts and produce C-rich products such as fuels and fertilizers. The 'drop-in' of renewable energy is achieved in the terms of various forms of renewable energy [73]. The capturing of power plant CO_2, recycling it and converting it into biomass/fossil fuel with the help of suitable means would be very interesting. Capturing of carbon dioxide is a method for greenhouse gas mitigation by algal growth [5]. Microalgae can fix CO_2 from three different sources, CO_2 from the atmosphere, CO_2 in discharge gases from industries, and CO_2 from soluble carbonates [6].

2. Algae—General description

Algae are eukaryotic organisms. Presence of chlorophyll and other pigments help in carrying out photosynthesis. The true roots, stems or leaves are absent. Algae can be multicellular or unicellular. Mostly they are *photoautotrophic* and carry on photosynthesis, some of these are *chemo heterotrophic* and obtain energy from chemical reactions as well as nutrients from preformed organic matter. Microalgae can fix CO_2 using solar energy with efficiency ten times greater than terrestrial plants [7]. Many species of algae are present such as; green, red and brown algae which belong to the group of Chlorophyta, Rhodophyta and Phaeophyta, respectively. Algae belong to a wide range of habitat like fresh water, marine water, in deep oceans and in rocky shores. The Plank tonic and benthic algae can become important constituents of soil flora and can exist even in such extreme conditions as in snow, sands/desert or in hot springs (temperatures above 80 °C).

Various physical and chemical parameters affect algal growth directly or indirectly, such as; light/irradiance/temperature, Carbon-di-oxide, pH, mixing /aeration, Salinity etc. Efforts are being made worldwide to reduce CO_2 emissions to meet the energy demands. The algae production to some extent may provide an opportunity to deal with both the problems. Earlier it was considered that microalgae were responsive to high level of CO_2 concentrations. But some microalgae are now reported to grow rapidly even at very high level of CO_2 concentrations. *Nannochloropsis species* not inhibited at an aeration of 2800 μL CO_2/L [8,9].

Carbon capture and sequestration is a safer technology to reduce the environmental carbon dioxide. The robust interest in CO_2 to algae results from its implicated photosynthesis conversion efficiency of as much as 12%. Most current research on oil extraction is focused on microalgae to produce biodiesel from algal oil [10]. Photosynthesis–fermentation model with double CO_2 fixation in both photosynthesis and fermentation stages, has enhanced carbon conversion ratio of sugar to oil and thus provided an efficient approach for the production of algal lipid [11]. The US Department of Energy's Aquatic Species Program has analyzed about 3000 different micro algal species for biofuel production [12]. This paper attempts to review the impact of various concentrations of CO_2 applied on algae lipid accumulation and to reduce the environmental problem as well as produce a valuable product [13].

2.1. Growth of algae

Algal growth is found in a wide range of habitats, like open and closed ponds, photo bioreactors, sewage and wastewater, desert, marine and sea water as well as CO_2 emitting industries etc. Generally they are found in damp places or water bodies and are common in terrestrial as well as aquatic environments. *Synechococcus lividus* is unicellular cyanobacterium. It loses all its chlorophyll as well as C-phycocyanin and becomes yellow in colour after 120 h of CO_2 deprivation condition; but when the media is aerated again with CO_2, it rapidly gets synthesized with its chlorophyll-*a* and C-phycocyanin pigments [14]. Light is a very important source for the growth of microalgae and it is the primary limiting factor [Photoperiod] at 3240 lx (300 ft candle). Total effective photoperiod of greater than 6 h a day is required to produce algae at a concentration level above 500 mg/L. Low temperatures increase the solubility of CO_2 and high concentration of dissolved CO_2 promotes high growth rate and yield [15]. Along with the light and CO_2 other variables also affected the growth of algal species.

2.2. Importance of algae

Algae is used as a source of food, fuel (oil, biodiesel, bioethanol, biohydrogen, and biogas), stabilizing agent (carrageen), fertilizer, chemical and in waste water treatment as well as in power plants to reduce CO_2 emissions and more. Algae provide much higher yields of biomass and fuels. Certain species of algae accumulated up to 60% intracellular lipid of their total biomass, it increases their heat of combustion and fuel value. Microalgae contain lipids and fatty acids are membrane components, storage products and as a sources of energy. More than 70,000 species of algae have been identified but all of them are not fit for human requirement. Algae can be grown under conditions which are unsuitable for conventional crop production like soybean and others. Algae has the capability of fixing CO_2 in atmosphere, thus facilitating the reduction of increasing atmospheric CO_2 levels, which are now considered as global problems. Algae contains 50% of their weight is oil. The biofuel from Algae is non-toxic, contains no sulfur and is highly biodegradable. Fifty percent of the photosynthesis process takes place on Earth by algae [16]. It removes inorganic carbon from the environment. Genetic engineering methods are improved microalgal photosynthetic rate to enhance CO_2 fixation and gain higher quantity of biomass to produce biodiesel and other important alternatives [17]. Some other investigators also observed that algae. Some algal species are significantly more economic. Algae have been various biological roles in ecosystem. Microalgae can produce 1 g of biomass to utilize 1.83 g CO_2. 1 kg of dry algal biomass can utilize up to 1.7 kg CO_2. Most of the investigators have been conducted experiments to ascertain the role of organic and inorganic carbon as a limiting source to the growth of microalgae belong to waste water treatment systems and laboratories. They have also tried to assess the role of carbon in eutrophication and amount of carbon consumed by microalgae [18].

3. Effect of CO_2 on microalgal species

Some micro algal species are discussed here which are having high CO_2 capturing efficiency.

3.1. Effect of CO_2 on Chlorella species

Some green algae are reported to easily grown at very high CO_2 concentration. *Chlorella species* is very common to be used as carbon sequestration. It is fresh water, single cell organism containing chlorophyll *a* and *b* and has high photosynthetic efficiency to convert CO_2 to O_2. *Chlorella species* belong to the Phylum Chlorophyta. *C. vulgaris ARC1* strain was studied under ambient CO_2 concentration (0.036%) and elevated CO_2 concentration (20%) and temperature 30 °C, 40 °C, 50 °C. At the 2nd day of incubation, *C. vulgaris ARC1* showed increase in biomass at the elevated CO_2 concentration (6%) and the temperature was 30 °C. No growth obtained at 50 °C and ambient CO_2 level or elevated CO_2 level. *C. vulgaris ARC1* could fix 18.3 mg and 38.4 mg CO_2L/day at ambient (0.036%) and elevated CO_2 (6%), respectively under 47 μmol/m^2/s photon density[3]. Another investigation showed that CO_2 fixation rate of *C. vulgaris* is 251.64 mg/L/day and 86.68% biomass was produced [43]. Highest chlorophyll concentration and biomass of *C. vulgaris ARC1* was produced 11 μg/mL and 210 μg/mL respectively, which were 60 and 20 times more than that of *C. vulgaris* at ambient CO_2 (0.036%), were recorded at 6% CO_2 level [3]. *ChlorellaKR-1* species showed maximum growth at 10% CO_2 and good growth rate up to 50% CO_2 and no CO_2 fixation at 70%CO_2 concentration. *Chlorella* is also a popular food supplement which provides all essential amino acids. *ChlorellaKR-1* has good growth at 30% CO_2, with a wide pH range and temperatures up to 40 °C [19]. The 0.029 gm dry cell weight/L/day was obtained by using TL5 lamps (florescent light source) with a light intensity of 9 W/m^2 and the source of carbon in the form of sodium bicarbonate concentration of 1000 mg/L was found to be optimal for the growth of strain ESP-31 in terms of both biomass production and carbon source utilization [20]. *Chlorella* biomass contained 25–30% protein, 6–10% carbohydrate, and 30–40% lipid. In biological CO_2 sequestration *Chlorella species* and *Spirulina platensis* showed 46% and 39% mean CO_2 fixation efficiency respectively, at input CO_2 concentration of 10%. Calcite deposition coupled CO_2 fixation is a commercially utilizable biomass producer, which is effective to sequestration of CO_2 [21]. *Chlorella species* are not limited by nitrogen or phosphorus but most likely by lowly dissolved organic carbon availability [22]. *C. vulgaris* could grow on autotrophic, mixotrophic and Heterotrophic medium. mixotrophic cells comparatively produced more biomass. In autotrophic culture *Chlorella protothecoides* accumulate 18–25% lipid. With the addition of organic carbons, lipid content increased 55.2% dry cell biomass [23].

About 26% CO_2 was recovered when *C. vulgaris* grown under a mass transfer coefficient of 0.0094 s^{-1} and CO_2 partial pressure of 0.0012 atm [24]. Effect of CO_2 on lipid metabolism was observed and found that higher unsaturation levels in low-CO_2 cells, promotes the desaturation of pre-existing fatty acids, rather than up-regulation of desaturation activity. The contents of eukaryotic lipids were higher at the expense of prokaryotic lipids in low-CO_2 cells than in high-CO_2 cells [25]. Direct injection of CO_2 in the growth medium of *C. vulgaris* with 0.0012 atm (1200 ppm CO_2 by volume) inlet, the partial pressure was sufficient to overcome any mass transfer limitations. Under these operating conditions, there was an increase of CO_2 recovery by 26%. Increase of CO_2 above 0.0012 atm, caused significant decrease in CO_2 recovery, with 9.7% and 2.1% at partial pressures of 0.00325 atm and 0.0145 atm, respectively [26].

Some investigator observed direct CO_2 fixation by *ChlorellaKR-1* which was successfully done using actual flue gases (SO_x and NO_x) from a liquified natural gas (LNG)—or diesel-fueled boiler and the results have indicated that *ChlorellaKR-1* may be applied for direct CO_2 fixation from actual flue gas [27]. The effects of CO_2 concentration and growth phase on pyrenoid and stroma starch in *Chlorella*. The air in which cells were grown contained 3% CO_2 (high-CO_2 containing cells) at the log phase, stroma starch was accumulated as a primary component but when these high-CO_2 cells were transferred to low-CO_2 conditions (air level, 0.04% CO_2), pyrenoid starch started to develop after several hours. After 12 h, the amount of starch per cell had increased to about 2.5 times of that in the high-CO_2 cells and the size of starch granules also drastically increased (about 2.5-fold in diameter) [28]. Hetrotrophic cells of *C. protothecoides* produced 57.9% Bio-oil which was 3.4 times more than autotrophic cells by fast pyrolysis (450 °C) [29]. *C. protothecoides* was grown autotrophically for CO_2 fixation and then metabolized heterotrophically for oil accumulation. Results showed that 61.5% less CO_2 was released compared to typical heterotrophic metabolism and the photosynthesis–fermentation model with double CO_2 fixation in both photosynthesis and fermentation stages, enhanced carbon conversion ratio of sugar to oil and thus provided an efficient approach for the production of algal lipid [11]. The gene encoded photo system I (due to the nuclear mutation) of the green alga *Chlamydomonas reinhardtii* was found that CO_2 fixation does not occur in the absence of photo system I [30]. The optimized conditions for higher biomass yield of *C. vulgaris* at 4% CO_2, carbon fixation rate, lipid content and calorific value of *C. vulgaris* was 6.17 mg/L/h, 21% and 17.44 kJ/g, respectively [31].

3.2. Effect of CO_2 on Zygnema species

Zygnema is a genus contains 140 species. *Zygnema species* are fresh water, filamentous algae (without branching), belongs to genera *Zygnemataceae contains* two star shaped chloroplast. *Zygnema* species are found in ponds, streams, ditches and similar type of water bodies. *Zygnema* species contains high quantity of biomass; approximately 18–58 g dry wt/m^2 was produced during summer (July and August). In CO_2 enriched medium 1.9–38 times more biomass was produced than in low CO_2 concentration [32]. *Spirogyra* and *Mougeotia* are related genera.

3.3. Effect of CO_2 on Scenedesmus species

Scenedesmus species is ubiquitous organism. *Scenedesmus species* is commonly found in fresh water lakes and rarely in brackish water. They belong to the family Scenedesmaceae, colonies of 2, 4 or 8 cells are arranged linearly or slightly in a zigzag manner. CO_2 biofixation and lipid production observed under different CO_2 levels (0.03% to 50% v/v) of *Scenedesmus obliquus* SJTU-3 and *Chlorella pyrenoidosa* SJTU-2 [33]. With the increased CO_2 concentration biomass also increased. Maximum biomass obtained from *S. obliquus* was 2.3 g/L at 15% CO_2 concentration [34].

Effect of anthraquinone (ANTQ) and phenanthrenequinone (PHEQ) on two *Scenedesmus armatus* strains (B1-76 and 276-4d) grown in a batch culture system aerated with CO_2 at a low (0.1%) or elevated (2%) concentration was observed. The toxic effect of ANTQ on this strain was more pronounced in high-CO_2 cells, where not only growth but also photosynthesis, respiration and SOD activity were significantly inhibited [35]. The toxicity of cadmium chloride ($CdCl_2$) at a concentration of 93 μM ($EC_{50/24}$) to green microalgae *S. armatus*, cultured at low (0.1%) and elevated (2%) concentration of CO_2. Algal growth inhibited at 0.1% CO_2 and in the presence of high-CO_2 grown cells. Cell viability was not affected. Algal growth was inhibited by cadmium in both types of culture. Algae living in elevated CO_2 conditions were better protected against cadmium [36]. *S. obliquus* is green algae, contains highest productivity of biomass, lipid and carbohydrate was 840.57 mg/L/day, 140.35 mg/L/day. The highest lipid and carbohydrate content was 22.4% (5-day *N*-starvation) and 46.65% (1-day *N*-starvation), respectively. The optimal CO_2 consumption rate was 1420.6 mg/L/day [37].

3.4. Effect of CO_2 on Hizikia fusiforme

H. Fusiforme (brown seaweed) is used as a food in Japan. *Hizikia species* is rich in dietary fibers, as well as minerals and in the presence of high CO_2 concentration the mean relative growth rate of *H. Fusiforme* increased. In the presence of light and CO_2, mean nitrate uptake rate and the activity of nitrate reductase (nitrogen assimilation) also increased [38].

3.5. Effect of CO_2 on Chaetoceros species

The major influence of high CO_2 was on diatom community structure, by favoring the large centric diatom *Chaetoceros lineola* over the small pennate species *Cylindrotheca closterium,* shifts in light, iron as well as CO_2 and mutual interactions of *C. lineola* colonies all played an important role in controlling Ross Sea plankton community structure. The major influence of high CO_2 was on diatom community structure, by favoring the large centric diatom *C. lineola* over the small pennate species *C. closterium* [39]. *Chaetoceros* cf. *wighamii (marine diatom)* was investigated for its potential use as food in mariculture. Temperature (20 °C, 25 °C, and 30 °C), salinity (25 and 35) and carbon dioxide addition (air and air+CO_2) effects on growth and biochemical composition of *C.* cf. *wighamii,* investigated under laboratory conditions. Addition of Carbon dioxide increased protein and lowered carbohydrates, but had no effect on lipid content [40].

3.6. Effect of CO_2 on Microcystis aeruginosa

M. aeruginosa cells consumed CO_2 in their growth medium and released O_2 due to photosynthesis and in the presence of high CO_2 level maximum O_2 was released, but the total inorganic carbon concentration of the medium and O_2 production have been in the inverse relationship. Photosystem II of *Microcystis species* was involved in photoinhibition and that free CO_2 may have played a protective role by reactivation of the system [41]. pH value was affected with the aeration of carbon dioxide (CO_2) on the growth of two species of blue–green algae, *M. aeruginosa* and *Anabaena spiroides*. Three conditions (pH 5.5, 6.0 and 6.5) were found to have significant inhibitory effects on the growth of the two algae species when acidification treatment was conducted during the logarithmic phase. *M. aeruginosa* was inhibited significantly, but was not dead at pH 6.5, whereas death occurred at pH 5.5 and 6.0. At pH 6.5 no inhibitory effect was found and maximum inhibitory effect occurred at pH 5.5 [42].

3.7. Effect of CO_2 on Botryococcus braunii

B. braunii was cultivated with flue gas (containing high CO_2) for biofuel production. Highest CO_2 fixation rate (496.98 mg/L/day) was observed in *B. braunii*and 87.96% biomass was produced [43]. Another investigation CO_2 fixation rate of *B. Braunii* was 1100 mg CO_2/L/day reported. *B. Braunii* 765 growth was observed at 2–20% CO_2 aeration, the results showed that strain could grow well under all tested CO_2 concentrations with an aeration rate of 0.2 vvm, when the culture pH ranged from 6.0 to 8.0. The maximum biomass was 2.31 g/L on 25th day at 20% CO_2, hydrocarbon content as well as algal colony size increased with the increase of CO_2 concentration [44]. 2.0% (v/v) of CO_2 level enhanced the growth and a two-fold increase in biomass and carotenoid contents in several species of *B. braunii* [45].

3.8. Effect of CO_2 in Nannochloropsis species

CO_2 concentration affected biomass production and lipid accumulation of *Nannochloropsis oculata* NCTU-3 in semicontinuous culture. Lipid accumulation increased from logarithmic to stationary growth phase. *N. oculata* NCTU-3 with 2% CO_2 was cultured in a semicontinuous system with high cell density of inoculums in the system aerated with higher CO_2 concentration (5–15% CO_2). Increased biomass production and lipid accumulation would not be followed as the cultures were aerated with higher CO_2[46]. A model was developed to predict biomass density (algal concentration) in semi-continuous mode under sparging (bubbled through a liquid) with carbon dioxide-enriched air using two species *Nannochloropsis salina* (flow rates of 800 and 1200 mL/min and CO_2 enrichments of 0.5, 1, and 2%) and *Scenedesmus species* (gas flow rate of 800 mL/min and CO_2 enrichments of 3 and 4%). Overall goodness of fit between the measured and predicted biomass densities under different sparging rates and CO_2-enrichments averaged 0.888, $p < 0.001$ [34]. Excess CO_2 increased the photosynthetic activity and phototropic biomass production. Two species (*N. salina* and *C. protothecoides*) with high biomass productivity were used and found that excess CO_2 stimulated photosynthesis but blocked the metabolization of the organic substrate. By cultivating microalgae under day–night cycle, organic substrate supported growth during the night, but only when CO_2 supply was not provided. Thus this represents a possible method for CO_2 stimulation of photosynthesis with mixotrophy [47].

3.9. Effect of CO_2 in Ulvarigida

Growth of Ulvarigida observed under normal (350 ppm) and high (10,000 ppm) CO_2 levels as well as in nitrate saturated and nitrogen limited conditions. Triglycerides accumulated at high CO_2 and under nitrogen limitation, while chloroplast-related lipids showed an inverse response. Under normal, non-enriched CO_2 levels, total lipids increased 30%, while under high CO_2, it decreased by 14% [48].

3.10. Effect of CO_2 in Chlorococcum species

Green alga *Chlorococcum littorale* (high CO_2 tolerance species) was investigated in the presence of inorganic carbon and nitrate at 295 K and a light intensity of 170 μmol-photon/m^2/s. Bubbled CO_2 concentration was adjusted by mixing pure gas components of CO_2 and N_2 to avoid photorespiration and β-oxidation of fatty acids under O_2 atmospheric conditions. Fatty acid content was almost constant at CO_2 concentrations (5% to 50%). The logarithmic growth phase was obtained under nitrate-rich conditions and after nitrate depletion, the content drastically increased with a decrease in CO_2 concentration. Maximum fatty acid content (34 wt

%) was obtained at 5% CO_2 concentration and it was comparable with other land plant seed oils [49]. The biomass concentration and lipid content of *Chlorococcum species* were influenced by different concentrations of salt, CO_2 and nitrate. The lipid productivity ranged from 2 to 90.8 mg/L/day in different mediums. The highest biomass concentration and total lipid content achieved were 1.75 g/L and 56% of dry weight, respectively [50].

3.11. Effect of CO_2 in Spirulina species

Spirulina is a small spiral coil shaped blue green algae. *Spirulina species* naturally grows in mineral rich water. *S. platensis* generally 80.40% biomass was produced at the 318.16 mg/L/day CO_2 fixation rate [43,74]. 60% higher productivity achieved with approximates 1% CO_2 added to *Arthrospira platensis* [51]. Mechanism of CO_2 and O_2 exchange between atmosphere and an algal mini-pond was examined the photosynthetic activity of a blue–green alga (*S. platensis*) mini-pond was found to be influenced by CO_2 concentration in the growth medium [52]. In an investigation CO_2 fixation rate of *S. platensis*413 mg CO_2/L/day was observed [8].

3.12. Effect of CO_2 in Prorocentrum minimum

Prorocentrum minimum (Dinoflagellate) is mostly found in brackish water and estuaries of temperate and tropical areas, a salinity range of 5-37 PSU and a temperature range of 4–31 °C [53]. CO_2 availability and temperature had pronounced effects on cellular quotas of CandNinHeterosigma, but not in *Prorocentrum*. Ratios of C: P and N: P increased with elevated carbon dioxide in Heterosigma but not in Prorocentrum [54].

3.13. Effect of CO_2 in Mytilusedulis

Mytilusedulis is a medium-sized edible marinebivalvemollusc. *Mytilusedulis* live in intertidal areas (littoral zone). Due to increased CO_2 concentrations in sea water, the pH value decreased several times. CO_2 induced reduction of pH value affecting the shell growth ofbluemussel*Mytilusedulis* negatively. Results shows that no growth at pH=6.7 and reduced growth at pH=7.1. [55].

4. CO_2 fixation with wastewater treatment

CO_2 mitigation by Microalgae production in waste water is a beneficial technology to produce nutriceuticals, specifically beta-carotene, extracted from *Dunaliella* and *Spirulina* biomass [56]. At the 272.40 mg/L/day CO_2 fixation rate,70.42% biomass was produced by *Dunaliella tertiolecta* [43]. Wastewater treatments of high rate algal ponds (HRAPs) are presently the most cost effective means to produce algal biomass for conversion to biofuels with minimum environmental impact. Some investigator developed the prevailing technologies to elevate microalgal CO_2 fixation with wastewater treatment and produced value added products like biofuels [57]. Nutrient removal from primary treatment sewage indicated that the efficiency of reducing wastewater-borne nutrients by an algal system was directly related to the physiological activity and growth of the Chlorella cells which in turn were affected by the initial inoculum size. This suggests that the removal of (chemical oxygen demand) COD and (Total organic nitrogen) TON was mainly due to the metabolism of indigenous bacteria. Under the open system, interaction between algal cells was found to be significant which could enhance the simultaneous removal of N, P and organic matter from primary settled sewage [58]. Intermittent CO_2 enrichment during nutrient deprivation of immobilized microalgal cells in a water-saturated air stream may accelerate tertiary wastewater treatment. Chlorophyll-*a* content was observed with 1000 ppm and 1500 ppm CO_2 [59]. The CO_2 sparging period and interval affected growth and lipid accumulation of microalgae cultivated in domestic wastewater under mixotrophic microenvironment and the presence of Chl-*b* supporting higher lipid productivity. With sparging period of 4 h (120 s), maximum biomass growth (GP, 3.4 mg/mL), lipid productivity (SP, 27.3%) was reported, while with intervals of 4 h (120 s) condition showed maximum biomass (3.2 mg/mL) and lipid productivity (27.8%) [60]. Lipid production of *C. vulgaris* with wastewater treatment was observed. The highest lipid content of *C. vulgaris* was 42% and Lipid productivity is 147 mg/L/day [61].

5. Photo bioreactor

A suitable hybrid type of photo bioreactor was developed for the growth of algae and cyanobacteria which affected various parameters like CO_2, availability of light (temperature), pH and O_2 removal [62]. Kumar et al. 2010 however used the bioreactor to get maximum yield and maximum energy efficiency [57]. Mixotrophy can be exploited to support algal growth over night or in dark-zones of a photo bioreactor [47]. A New concept applied photo bioreactor to the removal of carbon dioxide (CO_2) from flue gases of algal growth. The bioreactor contained fiber-optic-based solar concentrating systems and the two essential criteria to design a lighting system for algal photo bioreactors: Electrical energy efficiency and Lighting distribution efficiency. The 45% solar concentrating system efficiency was improved in recent years and a hybrid-solar-and-electric-lighting scheme has been found for uniform light distribution in algal photo bioreactors [63]. The carbon cycle is affected due to presence of algal species which causes carbon sequestration. High rate ponds (HRP) work as continuous stirred tank photo bioreactors and maintain environmental conditions for algal growth, where CO_2 is the main carbon source, the amount of nitrogen is decided by its pH value. So it is evident that HRP could be a potential ecological engineering alternative [64]. 420 mg/L of algae (dry

Table 1
CO_2 fixation rate and amount of CO_2 used in Biomass generation.

S. no	Algae	CO_2 fixation rate (mg/L/day)	% to Biomass	References
1.	*Dunaliella tertiolecta*	272.4	70.42	Eduardo B Sydney et al. [74]
2.	*Chlorella vulgaris*	251.64	86.68	Eduardo B Sydney et al. [74]
3.	*Spirulina platensis*	318.61	80.40	Eduardo B Sydney et al. [74]
4.	*Botryococcus braunii*	496.98	87.96	Eduardo B Sydney et al. [74]
5.	*Chlorella vulgaris*	865	N/A*	Hirata et al. [75]
6.	*Chlorella vulgaris*	624	N/A*	Yeoung-Sang Yun et al. [72]
7.	*Botryococcus braunii*	1100	N/A*	Marukami and Ikenouochi [76]
8.	*Spirulina platensis*	413	N/A*	De Morais and Costa [8]
9.	*Dunaliella tertiolecta*	313	N/A*	Kishimoto et al. [77]
10.	*Chlorella sp. UK001*	31.8	4.3	Hirata et al. [75]
11.	*Synechocystis aquatilis*	1500	N/A*	Marukami and Ikenouochi [76]

N/A=biomass produced at particular CO_2 fixation rate was not mentioned by these investigators.

Table 2
Biomass produced by microalgae species at particular CO_2 concentration.

S. no.	Algae	Amount of CO_2 supply (% CO_2)	Biomass produced (gm/L/day)	References
1.	*Chlorella vulgaris*	6	0.21	Chinnasamy et al. [3]
2.	*Chlorococum littorale*	N/A	9.2	Hu et al. [78]
3.	*Chlorella kessleri*	6	0.087	De Morais and Costa [8]
4.	*Scenedesmus obliquus*	12	1.14	De Morais and Costa [8]
5.	*Chlorella KR-1*	70	0.71 (Given at 5th day)	Ki Don Sung et al. [19]
6.	*Chlorella KR-1*	10	0.667	Ki Don Sung et al. [19]
7.	*Spirulina platensis*	10	2.91	Rishiram et al. [21]
8.	*Chlorella sp.*	10	2.25	Rishiram et al. [21]
9.	*Scenedesmus obliquus*	5	1.7	Pakawadee et al. [34]
10.	*Scenedesmus obliquus*	15	2.3	Pakawadee et al. [34]
11.	*Chlorella vulgaris*	0.03	0.226	Bhola et al. [31]
12.	*Chlorella vulgaris*	4	1.222	Bhola et al. [31]
13.	*Scenedesmus obliquus*	15	0.145	Pakawadee et al. [34]
14.	*Nannochloropsis oculata*	2	0.480	Sheng-Yi Chiu et al. [46]
15.	*Nannochloropsis oculata*	5	0.441	Sheng-Yi Chiu et al. [46]
16.	*Nannochloropsis oculata*	10	0.398	Sheng-Yi Chiu et al. [46]
17.	*Nannochloropsis oculata*	15	0.372	Sheng-Yi Chiu et al. [46]

cell weight) was produced from the sediment of microbial fuel cell (SMFC) when the current density reached 48.5 mA/m^2. Sediment microbial fuel cell (SMFC) generated CO_2 by the oxidation of organics [65]. The exchange of O_2 and CO_2 across the water surface from measurements of O_2, total CO_2, pH and chlorophyll-*a* in an experimental pond. It was found that the total amount of O_2 decreased during the production period and increased during the decomposition period. During decomposition period, 80% of consumed O_2 was supplied and 35% of produced TCO_2 was lost [66]. Growth rate of *Thalassiosira pseudonana* did not increase after the CO_2 concentration was elevated above 16.0 μmol/L [67]. Bulk carbon concentration and bulk pH were both important aspects of inorganic carbon limitation [68]. The increase of atmospheric pCO_2 leads to a decrease of pH that is countered by the phytoplankton carbon assimilation. The phytoplankton presence limits the decrease of pH due to the increase of atmospheric pCO_2 [69]. With the use of genetic engineering it is possible to modify the algal gene and increase the efficiency of CO_2 capture. By capturing solar energy more valuable products like proteins, carbohydrates, lipids and pigment can be produced. On the basis of investigations that have been carried out it can be concluded that microalgae are definitely going to be economical and a powerful tool for CO_2 mitigation. The effect of CO_2 level on the growth of microalgae varies between strain to strain [70,71]. CO_2 Fixation rate of *C. vulgaris* was 624 mg CO_2/L/day. CO_2 fixation rate of *C. vulgaris* is 26·0 gm CO_2/m^3/h in wastewater at 15% (v/v) CO_2 [72]. Maximum CO_2 fixation algal strains tolerate highest CO_2 *Synechocystis aquatilis*can fix 1500 mg CO_2/L/day Tables 1 and 2.

6. Conclusion

This review summarizes the algal growth and maximum biomass produced at a particular CO_2 concentration. Increase in CO_2 concentration in microalgal species increases the quantity of biomass and lipids was reported by investigators, but the optimum concentration of CO_2 for the species were not reported to get maximum biomass. Only one species *C. vulgaris* ARC 1 was experimentally optimized for 6% CO_2 concentration for maximum biomass. The highest CO_2 concentration fixed by *S. aquatilis, B. braunii, C. vulgaris and Synechococcus* species in decreasing order. Whereas *N. oculata, B. braunii, C. vulgaris* and *C. Littorale* produced more biomass concentration in decreasing orders. *N. salina* is able to tolerate a wide range of salinity (0–36 ppm) and CO_2 concentration. Further studies also require for optimize CO_2 concentration for maximum biomass production and growth rate of certain algal species.

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