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CO_2 capture by microalgae

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Dedication

This thesis is dedicated to my family, whose love and support have been a constant source of strength and inspiration. To my parents, for their unwavering belief in my potential and for always encouraging me to pursue my dreams. To my partner, for their endless patience, understanding, and encouragement throughout this journey. Your support has been my anchor and my motivation.

ABSTRACT

Fossil fuels, known as unsustainable energy sources, are being depleted due to rising fuel demands. Microalgae offer promise as renewable fuel sources due to their fast growth, ability to store lipids and carbohydrates for biofuel production, and the potential for cultivation in various systems using nutrients and CO_2 from sources like fossil fuel emissions. Researchers are exploring CO_2 capture through photosynthesis by microalgae to convert carbon into valuable products, reducing emissions and creating economic value.

In the cultivation of microalgae, the efficiency of CO_2 transfer from the gas phase to the liquid culture medium is a critical factor. During our work we used MATLAB to develop mathematical structures and create computer codes to simulate these processes. The present study researches the microalgal strains *Chlorella vulgaris* to capture CO_2, with 0.03 % (CO_2 concentration in air), and 2 % CO_2 supply. The concentration of CO_2 Transferred inside the medium was (6.88 Mol/L). The gas-liquid mass transfer coefficient $k_L a$ correspond to (0.015 Mol/L). the quantities of CO_2 fixed by *Chlorella vulgaris* in this case (1.05Mol/L).

ملخص

يتم استنفاد الوقود الأحفوري، المعروف باسم مصادر الطاقة غير المستدامة، بسبب ارتفاع الطلب على الوقود. تقدم الطحالب الدقيقة واعدة كمصادر وقود متجدد بسبب نموها السريع، وقدرتها على تخزين الدهون والكربوهيدرات لإنتاج الوقود الحيوي، وإمكانية الزراعة في أنظمة مختلفة باستخدام المغذيات وثاني أكسيد الكربون من مصادر مثل انبعاثات الوقود الأحفوري. يستكشف الباحثون التقاط ثاني أكسيد الكربون من خلال التمثيل الضوئي بواسطة الطحالب الدقيقة لتحويل الكربون إلى منتجات قيمة، وتقليل الانبعاثات وخلق قيمة اقتصادية.

في زراعة الطحالب الدقيقة، تعد كفاءة نقل ثاني أكسيد الكربون من مرحلة الغاز إلى وسط زراعة السائل عاملاً حاسماً. خلال عملنا استخدمنا MATLAB لتطوير الهياكل الرياضية وإنشاء رموز الكمبيوتر لمحاكاة هذه العمليات. تبحث هذه الدراسة في سلالات الألغال الدقيقة *Chlorella vulgaris* لالتقاط ثاني أكسيد الكربون، مع 0,03% (تركيز ثاني أكسيد الكربون في الهواء)، و 2٪ من إمدادات ثاني أكسيد الكربون. كان تركيز ثاني أكسيد الكربون المنقول داخل الوسط .(6,88 Mol/L) ويقابل معامل نقل الكتلة السائلة الغازية k_La (0.015 مول/لتر). كميات ثاني أكسيد الكربون التي حددتها *Chlorella vulgaris*في هذه الحالة.(1 .05Mol/L)

Résumé

Les combustibles fossiles, connus sous le nom de sources d'énergie non durables, sont épuisés en raison de la demande croissante de combustibles. Les microalgues sont prometteuses en tant que sources de carburants renouvelables en raison de leur croissance rapide, de leur capacité à stocker des lipides et des glucides pour la production de biocarburants et du potentiel de culture dans divers systèmes utilisant des nutriments et du CO_2 provenant de sources telles que les émissions de combustibles fossiles. Les chercheurs explorent la capture du CO_2 par photosynthèse par les microalgues pour convertir le carbone en produits précieux, réduire les émissions et créer de la valeur économique.

Dans la culture de microalgues, l'efficacité du transfert de CO_2 de la phase gazeuse au milieu de culture liquide est un facteur critique. Au cours de notre travail, nous avons utilisé MATLAB pour développer des structures mathématiques et créer des codes informatiques pour simuler ces processus. La présente étude étudie les souches de microalgues *Chlorella vulgaris* pour capturer le CO_2, avec 0,03 % (concentration de CO_2 dans l'air) et 2 % d'apport de CO_2. La concentration de CO_2 transféré à l'intérieur du milieu était de (6,88 Mol/L). Le coefficient de transfert de masse gaz-liquide k_La correspond à (0,015 Mol/L). les quantités de CO2 fixées par *Chlorella vulgaris* dans ce cas (1,05Mol/L).

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Nomenclature

CO_2 Carbon dioxide

(NAD(P)H) Nicotinamide adenine dinucleotide phosphat

$[CO_2]$ concentration of CO_2 dissolved in the liquid (mol. L^{-1}) ; $[CO_2]^*$ maximum concentration of that can dissolve in the liquid (mol. L^{-1}),corresponding to the equilibrium with the gas phase; k_{La} transfer volume coefficient relative to the liquid phase (j^{-1}), k_L where is the transfer coefficient and to the interfacial area per unit column volume ; V volume of liquid (L) ;

k_{HA} is a constant related to the Henry's law constant ;

d_h is the hydraulic diameter ;

ε is the porosity of the packing ;

a is the specific surface area of the packing ;

v_l are the liquid and gas velocities, respectively ;

D_l are the diffusion coefficients for the liquid and gas phases, respectively ;

C_L are empirical constants ;

ϑ_g is the kinematic viscosity of the gas ;

g is the gravitational acceleration. ;

η_l is the dynamic viscosity of the liquid ;

ρ_l is the density of the liquid ;

General Introduction

INTRODUCTION

With the global population increase and improved living conditions, the worldwide demand for energy is constantly rising. Historically, fossil fuels have been the primary energy source. However, the inevitable reduction of fossil fuel reserves and the simultaneous increase in energy demands necessitate the development of alternative sources. Various biomass feedstocks, including terrestrial plants and aquatic algae, have emerged as renewable fuel sources (Bahadar and Khan, 2013). Aquatic microalgae, with their rapid growth, high biomass yields, diverse product range, and ease of harvest from ponds or closed bioreactor systems, present an ideal option for producing liquid fuels that could potentially serve as sustainable, environmentally friendly, carbon-neutral fuel sources (Gao et al., 2012; Singh et al., 2013).

Microalgae, particularly *Chlorella vulgaris*, are aquatic microorganisms that utilize photosynthesis, similar to higher plants (Hanelt et al., 2007). They have the unique ability to fix carbon dioxide (CO_2), converting this greenhouse gas into biomass usable for the production of biofuels, dietary supplements, and bioactive compounds (Spolaore et al., 2006; Milledge, 2011; Razzak et al., 2013). This capability makes microalgae cultivation particularly interesting for CO_2 sequestration, especially from fossil fuel power plant emissions (Yun et al., 1997).

In the cultivation of microalgae, the efficiency of CO_2 transfer from the gas phase to the liquid culture medium is a critical factor. The volumetric mass transfer coefficient (K_{La}) is a key parameter in determining the rate at which CO_2 dissolves into the culture medium and becomes available for uptake by the microalgae. A higher K_{La} indicates more efficient CO_2 transfer, which can enhance microalgal growth and biomass productivity (Chisti, 2007). Therefore, understanding and optimizing K_{La} is essential for improving the efficiency of photobioreactors used for microalgae cultivation.

This master's thesis explores the sequestration of CO_2 by *Chlorella vulgaris* using a bubble column photobioreactor under autotrophic conditions with air enriched with 2% CO_2. Our main objective is to model and simulate the dissolution of CO_2 in the culture medium and its consumption by the microalgae. We used MATLAB to develop mathematical structures and create computer codes to simulate these processes. Special attention was given to the volumetric mass transfer coefficient (K_{La}) and its relationship with the dissolved CO_2 concentration, ultimately quantifying the CO_2 ingested by the microalgae in terms of molar concentration (mol/L).

This focus on K_{La} and CO_2 transfer is driven by the need to enhance the efficiency of CO_2 utilization in microalgae cultivation systems. Improved CO_2 transfer rates can lead to higher biomass yields and more effective CO_2 sequestration, making the overall process more viable and cost-effective for large-scale applications. Computer simulation allows for the prediction of performance and optimization of the operational conditions of the photobioreactor, offering promising perspectives for the development of sustainable and economically viable large-scale solutions .

Background and Motivation

Global Energy Demand: The world's energy demand is escalating due to population growth and enhanced living standards, leading to an urgent need for sustainable energy solutions.

Fossil Fuel Challenges: Reliance on fossil fuels poses significant challenges, including limited reserves and severe environmental impacts, such as greenhouse gas emissions contributing to climate change.

Renewable Energy Sources: Among renewable energy sources, biomass feedstocks, encompassing terrestrial plants and aquatic algae, offer promising alternatives.

Importance of Microalgae

Microalgae, particularly species like *Chlorella vulgaris*, present numerous advantages for biofuel production and environmental sustainability. Microalgae exhibit rapid growth rates, high biomass yields, and the ability to produce a diverse range of products, from biofuels to bioplastics. *Chlorella vulgaris* is noted for its exceptional photosynthetic efficiency and CO_2 fixation capabilities, which not only make it an ideal candidate for biofuel production but also for CO_2 sequestration, addressing both energy and environmental challenges.

CO_2 Sequestration and Cultivation Efficiency

The volumetric mass transfer coefficient (K_{La}) is a critical parameter in the context of CO_2 transfer efficiency in photobioreactors. Optimizing K_{La} is essential to enhance the growth and biomass productivity of microalgae, ensuring that these systems can meet the high demands for sustainable energy production while effectively sequestering CO_2.

Objectives of the Study

Primary Objective: Model and simulate CO_2 dissolution and consumption by *Chlorella vulgaris* in a bubble column photobioreactor.

Specific Goals:

- Develop mathematical models using MATLAB.
- Simulate CO_2 transfer and uptake.
- Quantify CO_2 ingestion in molar concentration (mol/L).
- Optimize KLa for enhanced efficiency.

This these is composed of four chapters:

- *Chapter I :* contains a bibliographical study of Microalgae ;
- *Chapter II :* presents some equations of determination of the gas-liquid mass transfer coefficient k_{la} and Equilibrium Concentration of CO_2 in the Gas Phase ;
- *Chapter III :* contains the Materials and methods *;*
- *Chapter IV* : contains the results to determine the gas-liquid mass transfer coefficient k_{la} ;

Chapter one :

Bibliographical study on Microalgaes

1. Introduction

Microalgae are microscopic, photosynthetic organisms that are found in various aquatic environments. They are a diverse group of eukaryotic cells, containing chlorophyll and other pigments, which allow them to carry out photosynthesis. Microalgae are composed of proteins, carbohydrates, and lipids, and their biomass can be utilized for a variety of applications, including biofuel production, food supplements, and CO_2 sequestration. This chapter delves into the intricacies of microalgae species, their cellular compositions, cultivation techniques, and the role they play in capturing CO_2 through photosynthesis.

2. MICROALGAE SPECIES AND THEIR COMPOSITIONS

Microalgae are made up of eukaryotic cells. Microalgae cells consist of cell wall, plasmatic membrane, cytoplasm, nucleus and organelles, such as mitochrondria, lysosomes and golgi (Taher et al., 2011). Microalgae also have plastids, the bodies with chlorophyll that carry out photosynthesis. However, various strains of microalgae have different combinations of chlorophyll molecules - some have only Chlorophyll A, some A and B, while other strain, A and C (Um and Kim, 2009). The biomass of microalgae contains three main components : proteins, carbohydrates and lipids. The biomass composition of various algae is shown in Table 1. To achieve the maximum benefits from microalgae cultivation, it is essential to pay attention to the selection of suitable species. Microalgae cultivation is composed of a single specific strain that is precisely selected for producing the desired product and the most beneficial outcome of the cultivation process. The cultivation conditions, including (1) water media with adequate pH and temperature, (2) necessary contained nutrients and (3) CO_2 dosed in a controlled manner in the presence of sunlight, are also required for microalgae cultivation. The nitrogen source (e.g., ammonia and nitrates), other minerals and vitamins are the nutrients that must be provided sufficiently to ensure the proper growth of microalgae.

3. CULTIVATION TECHNIQUES

A diverse array of microalgae cultivation methodologies has been documented in the literature (Wang et al., 2008; Suali and Sarbatly, 2012; Bahadar and Khan, 2013; Zhao and Su, 2014). These techniques vary depending on factors such as (1) investment cost, (2) targeted products, (3) nutrient sources, and (4) CO_2 capture methods.Microalgae cultivation systems can be broadly classified into open and closed systems. Open systems typically encompass outdoor

setups like ponds, lagoons, deep channels, shallow circulating units, among others. Conversely, closed systems consist of vessels or tubes constructed from transparent materials and are positioned outdoors, exposed to either natural sunlight or artificial irradiation (Razzak et al., 2013).

3.1. Open System

Historically, open ponds have been the preferred choice for large-scale microalgae cultivation due to their straightforward construction and easy operation. These cultivation systems fall into two main categories: natural water bodies like lakes, lagoons, and ponds, and artificial water systems such as ponds, tanks, and containers. The design, dimensions, and types (e.g., agitated, inclined) of open systems vary depending on their intended applications.

Several types of ponds exist, including unstirred, raceway, and circular ponds. Among these, unstirred ponds (depicted in Fig. 1(a)) are particularly favored for their economic viability, attributed to their simple management and construction. Commercial unstirred ponds are typically constructed within natural water bodies with depths of less than half a meter. They find extensive commercial application in cultivating certain microalgae species like Dunaliella salina (Borowitzka and Borowitzka, 1990). However, their utility is constrained by the limited range of conditions under which microalgae can thrive, facing challenges from unfavorable growth conditions and competition with contaminating protozoa, bacteria, and viruses (Chaumont, 1993).

Raceway ponds, also referred to as stirred paddle wheel open ponds, represent the most widely employed open system in current practice (see Figure I. 1(b)). Typically shallow, with depths ranging from 15 to 25 cm, these ponds are typically constructed either as single channels or interconnected groups of channels. According to Razzak et al. (2013), the productivity of biomass within raceway ponds averages between 60 and 100 mg dry weight/L/day. Primarily utilized for the commercial cultivation of four microalgae species—Chlorella sp., Spirulina platensis, Haematococcus sp., and Dunaliella salina (as noted by Moheimani and Borowitzka, 2006)—the circulation of the cultivation media in these ponds is induced by paddles. Ensuring optimal circulation velocity is essential to facilitate water flow without sedimentation deposition or cell aggregation (as discussed by Brindley et al., 2002). Nevertheless, addressing issues such as solid deposition in stagnant areas presents significant challenges.Circular ponds, known as central pivot ponds (Figure I. 1(c)), stand as the earliest large-scale open ponds for algae cultivation. These ponds typically maintain a depth of approximately 25–30 cm and are

usually constructed from concrete, with diameters reaching up to 45 m. Lee (2001) highlights that agitation within these ponds is achieved through rotating paddles, ensuring exposure of a 20-to-30-cm-thick layer of inorganic nutrient solution with algae to sunlight and CO_2 bubbles under continuous movement. Despite the numerous advantages of open systems, including those mentioned above, they are not without limitations. These limitations, as noted by Razzak et al. (2013), include poor light consumption by cells, evaporative losses, diffusion limitation of CO_2 from the atmosphere, extensive land area requirements, and susceptibility to contamination by unwanted algae, mold, and bacteria. While these limitations can be partially mitigated through the use of translucent plastic covers or greenhouses over open ponds, such measures fail to fully address contamination issues and are hindered by high capital costs, maintenance requirements, and concerns regarding overheating, particularly given the significant land area required for covered ponds.

Table I. 1. Compositions of microalgae based on dry matter (Um and Kim, 2009 ; Sydney et al. 2010 ; Singh et al., 2012).

Microalgae specie	Protein (%)	Carbohydrate (%)	Lipid (%)
Anabaena cylindrical	43–56	25–30	4–7
Aphanizomenon flos-aquae	62	23	3
Arthrospira maxima	60–71	13–16	6–7
Botryococus braunii	8–17	8–20	21
Chlamydomonas rheinhardii	48	17	21
Chlorella pyrenoidosa	57	26	2
Chlorella vulgaris	51–58	12–17	14–22
Dunaliella bioculata	49	4	8
Dunaliella salina	57	32	6
Euglena gracilis	39–61	14–18	14–20
Isochrysis sp.	31–51	11–14	20–22
Neochloris oleoabundans	20–60	20–60	35–54
Porphyridium cruentum	28–39	40–57	9–14
Prymnesium parvum	28–45	25–33	22–38
Scenedesmus obliquus	50–56	10–17	12–14
Spirogyra sp.	6–20	33–64	11–21
Spirulina maxima	60–71	13–16	6–7
Spirulina platensis	46–63	8–14	4–9
Synechococcus sp.	63	15	11
Tetraselmis maculata	52	15	3

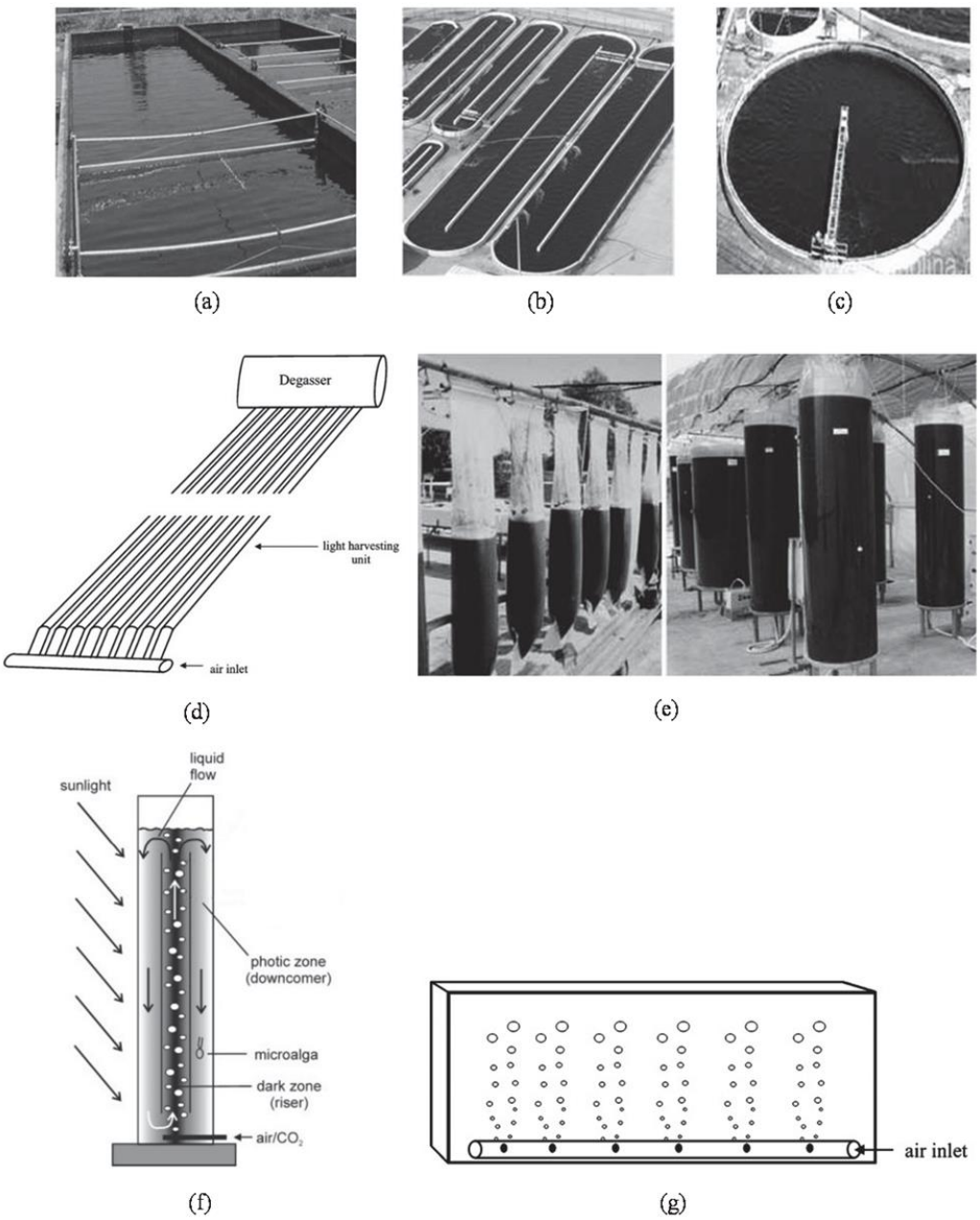

Figure I. 1. Cultivation systems : (a) unstirred pond, (b) raceway pond, (c) circular pond (Chen *et al.*, 2009), (d) tubular photobioreactor (Carvalho *et al.*, 2006), (e) plastic bag photobioreactor (Richmond, 2008), (f) air-lift loop reactor (Barbosa*et al.*, 2003) and (g) flat plate photobioreactor (Carvalho *et al.*, 2006).

3.2. Closed System

losed systems for microalgae cultivation offer numerous advantages over open systems, such as better control over environmental parameters like light, CO_2 concentration, and temperature. Photobioreactors, a type of closed system, are particularly effective in minimizing contamination risks and optimizing growth conditions. They can mitigate issues such as unwanted algae, mold, and bacteria, control temperature, minimize water evaporation, and prevent carbon dioxide losses.

However, despite these benefits, it's important to acknowledge that photobioreactors have limitations. While they significantly reduce the growth of competitive algal weeds, they may not entirely eliminate contaminants. Additionally, constructing and operating photobioreactors can be challenging and costly, posing as significant disadvantages. Various designs of photobioreactors exist, including flat plate and tubular configurations, each with its own set of advantages and drawbacks (Borowitzka, 2007).

Tubular photobioreactors (depicted in Fig. 2(d)) are constructed from transparent materials and are typically positioned in outdoor settings to utilize sunlight irradiation. These reactors are equipped with gas exchange vessels for supplying CO_2, air, and nutrients, as well as for removing O2, which are interconnected with the main reactor (Richmond, 2004; Chisti, 2007). To optimize the exposure of microalgae to sunlight, these cultivation vessels require a large surface area per unit volume. Typically, the tubes have diameters of less than 10 cm to ensure sunlight permeability.

In a standard tubular microalgae cultivation system, the culture medium is circulated through the tubes, where it undergoes photosynthesis in the presence of sunlight. Subsequently, the medium is recirculated back to a reservoir using either a mechanical pump or an airlift pump. This pumping mechanism also serves to maintain a highly turbulent flow within the reactor, preventing the aggregation of microalgal biomass (Chisti, 2007). A portion of the microalgae is typically harvested after circulating through the solar collector tube, enabling continuous system operation.

However, while tubular photobioreactors are extensively researched at the laboratory scale, their practicality is still limited. In some designs, the tubes are arranged in a coiled spiral configuration, forming helical-tubular photobioreactors. These reactors are particularly suitable for cultivating microalgal species under sunlight exposure. Occasionally, artificial lighting is employed to supplement natural sunlight and enhance microalgae growth. Nevertheless, the

adoption of artificial light increases investment costs, making helical-tubular photobioreactors viable primarily for producing high-value added products (Morita et al., 2001; Briassoulis et al., 2010).

Microalgae cultivation can be facilitated using transparent polyethylene bags, known as plastic bag photobioreactors (illustrated in Fig. 2(e)). These bags are either suspended or placed within a cage to expose them to sunlight, while aeration is provided by mixing air at the bottom of the bags (Razzak et al., 2013 ; Xia et al., 2013). To prevent settling of cells, transparent polyethylene sleeves sealed at the bottom in a conical shape are utilized.

Airlift photobioreactors (depicted in Figur I. 1(f)) offer a straightforward and cost-effective approach for mass cultivating various microalgae species. These reactors are typically constructed from acrylic glass due to its affordability and accessibility. Airlift photobioreactors comprise two distinct zones : a dark region known as the "rinser" and an irradiated area. They are considered to fulfill the desired criteria for next-generation photobioreactors, offering high light penetration, biomass production, ease of maintenance, and minimal contamination (Barbosa et al., 2003). However, scaling up airlift photobioreactors can be challenging due to their intricate flow patterns (Mirón et al., 2000).

Vertical bubble columns and airlift cylinders can significantly enhance radial fluid movement, facilitating efficient cycling of medium between irradiated and dark zones. These units boast several advantages, including high mass transfer, low shear stress mixing, low energy consumption, ease of operation under sterile conditions, suitability for algae immobilization on moving particles, and reduced photoinhibition and oxidation. Nonetheless, they are associated with limitations such as high manufacturing and maintenance costs, reduced irradiation per unit surface area, the necessity for sophisticated construction materials, increased shear stress on microalgal cultures, and the requirement for a larger number of units to construct a commercial-scale plant (Razzak et al., 2013).

Flat plate photobioreactors (depicted in Figure I. 1(g)) represent a highly efficient method for cultivating microalgae biomass. These photobioreactors offer an elevated surface area to volume ratio, facilitating optimal illumination, and feature a convenient modular design that enables straightforward scale-up (Barbosa et al., 2005). Enhanced mixing rates in flat plate photobioreactors result in rapid increases in microalgae biomass productivity, ensuring proper CO_2 supply to the cultivation while eliminating excess oxygen and promoting the flashing effect.

Suitable for both outdoor and indoor cultivation, flat plate photobioreactors excel in algae immobilization and are comparatively inexpensive and easy to maintain (Ugwu et al., 2008). Vertical flat plates can be accommodated within units ranging from 1000 to 2000 L in volume capacity, demonstrating successful long-term operation. Consequently, these photobioreactor units are fully scalable (Richmond, 2004). The ideal strain, as well as the advantages and disadvantages of each photobioreactor used for microalgae cultivation, are summarized in Table 2.

4. CO_2 CAPTURE VIA MICROALGAE

Biotechnological approaches for CO_2 capture aim to diminish CO_2 emissions.

These methods involve reactor utilization to initiate photosynthetic reactions, with microalgae acting as biocatalysts, catalyzing a series of biochemical reactions that convert CO_2 into photosynthetic metabolic compounds (Jacob-Lopes et al., 2010).

Microalgal biomass typically contains about 50% carbon by dry weight, predominantly sourced from CO_2. Approximately, 100 tons of microalgal biomass fixes 183 tons of CO_2 (Huang and Tan, 2014).

Microalgae employ three distinct inorganic carbon assimilation pathways: (1) direct CO_2 assimilation through the plasma membrane; (2) utilization of bicarbonate by inducing the enzyme carbonic anhydrase, which converts HCO3– to CO_2; and (3) direct transport of bicarbonate via the plasma membrane.

Continuous CO_2 supply is essential throughout daylight hours. Regulating CO_2 feeding is assessed through pH measurements to minimize CO_2 loss. Consequently, CO_2 fixation employing microalgae can curtail CO_2 emissions from power plants, yielding positive environmental impacts (Inoue et al., 1995; Yun et al., 1997; Abu-Khader, 2006; Brennan and Owende, 2010).

Table I.2. Cultivation of microalgae species in closed photobioreactor systems.(Klinthong et al., Aerosol and Air Quality Research, 15: 712–742, 2015)

Type of photobioreactor	Strain	Capacity (L)	Biomass concentration	Advantage	Disadvantage	Reference
Tubular	*Phaeodactylum tricornutum*	200	1.19 g/L	1. Very effective light use,	Fouling with some growth along walls.	Acien Fernández *et al.*, 2001.
	Phaeodactylum tricornutum	75	1.38 g/L	2. Excellent temperature control,		Hall *et al.*, 2003.
	Porphyridium cruentum	6000	35 g/m^2/d			Sakai *et al.*, 1995.
	Spirulina sp.	10000	25 g/m^3/d	3. Reasonable scale up.		Torzillo *et al.*, 1986.
	Spirulina platesnsis	5.5	0.62 g/L			Huntley and Redalje, 2007.
	Spirulina platensis	65	32.5 g/m^2/d			Negoro *et al.*, 1993.
	Spirulina sp.	100	0.01 g/L/g			Chiu *et al.*, 2008.
Airlift	*Botryococcus branuii*	3	2.31 g/m^3/d	1. Good light use,	1. Low hydrodynamic stress on algae, 2. Difficult to scale up.	Avila *et al.*, 2001.
	Chaetoceros sp.	170	0.80 g/L	2. High temperature control,		Krichnavaruk *et al.*, 2007.
	Chlorella sp.	n/a	109–264			James and Al-Khars, 1990.
	Chlorella vugaris	2	0.28-0.89 g/L/d	3. High mass transfer coefficient		Hanagata *et al.*, 1992.
	Haematococcus pluvialis	3	4.09 g/L			Kaewpintong *et al.*, 2007.
	Nannochloropsis sp.	n/a	32.5–95.3 g/m^3/d			James and Al-Khars, 1990.
Bubble column	*Aphanothece microscopica*	3	0.77 g/L/d	1. Scalable; homogeneous culture environment, 2. Low cooling requirement, 3. Effective light use.	Increased shear stress by pumps limiting biomass productivity.	Jacob-Lopes *et al.*, 2009.
	Chaetoceceros sp.	170	3.31 g/L			Krichnavaruk *et al.*, 2007.
	Chlorella vulgaris	1.8	1.41 g/L			de Morais and Costa, 2007b.
	Cyanobium sp.	1.8	0.071 g/L			Henrard *et al.*, 2011.
	Phaeoductylum sp.	1.9	n/a			Brindley *et al.*, 2002.
	Isochrysis aff. Galbana	5	n/a			Mandalm and Palsson, 1998.
	Monodus sp.	64	0.03–0.20 g/L			Bosma *et al.*, 2007.
	Monoraphidium sp.	4.5	23 g/m^3/d			Miyamoto *et al.*, 1988.
	Scenedesmus obliquus	1.8	2.12 g/L			de Morais and Costa, 2007b.
	Spirulina sp.	3.5	4.13 g/L			de Morais and Costa, 2007b.
Flat plate	*Chlorella vulgaris*	1.5–3.0	0.027–0.045 g/L/h	1. Excellent light use and temperature control, 2. Low cooling requirement, 3. High gas transfer coefficient.	Difficult to scale up.	Satoh *et al.*, 2001.
	Dunaliella sp.	3.4	1.5 g/L			Barbosa *et al.*, 2005.
	Dunaliella tertiolecta	30	3.42 g/d			Chang and Yang, 2003.
	Nannochloropsis sp.	200	0.225 g/L			Richmond and Wu, 2001.
	Namnochloropsis sp.	440	0.27 g/L			Richmond and Wu, 2001.
	Phaeodactylum sp.	5	1.38 g/L			Meiser *et al.*, 2004.
Plastic bag	*Tetraselmis* sp.	50	20–30 g/m^3/d	-	-	Trotta, 1981.

4.1. Photosynthesis :

Biological processes through photosynthesis offer a promising route for capturing CO_2 in the form of microalgal biomass. In microalgae, photosynthesis, known as "oxygenic photosynthesis," releases oxygen. This process converts CO_2 into lipids and other hydrocarbons, earning the label "CO_2 fixation process." Water serves as the electron donor in oxygenic photosynthesis, with oxygen being released post-hydrolysis.

4.2. CO_2 Source

Microalgae rely on CO_2 as their primary carbon source, essential for their growth. Without a sufficient supply of CO_2, these organisms cannot thrive, often leading to a limitation in productivity. Hence, the reduction of atmospheric CO_2 through microalgal photosynthesis is regarded as both safe and beneficial for the human ecosystem (Mukherjee and Moroney, 2011).

4.3. Biology of microalgae

Microalgae are single-celled eukaryotic organisms, meaning they have a nucleus. They come in various shapes and sizes, ranging from a few micrometers to several tens of micrometers (Cadoret and Bernard, 2008). Found in diverse environments including saline, freshwater, and arid regions, microalgae constitute the majority of marine plankton and are responsible for producing most of the Earth's atmospheric oxygen (Berberoglu et al., 2009). The estimated number of species ranges from 200,000 to 1,000,000, indicating significant potential and diversity compared to the approximately 250,000 recognized plant species (Cadoret and Bernard, 2008 ; Pulz and Gross, 2004). Among this vast number of estimated microalgal species, only about 10,000 are known, and despite increasing interest from industries since the mid-20th century, only a few dozen microalgae are cultivated on an industrial scale (Degen et al., 2001 ; Spolaore et al., 2006). Most microalgae thrive at temperatures of 25-35°C and a neutral pH (Zeng et al., 2011). Microalgae are classified into families based on shared characteristics:

Diatoms or Bacillariophyceae: this is the most significant group of photosynthetic eukaryotes as they are the primary CO_2 fixers in aquatic environments. There are 265 genera of diatoms comprising nearly 10,000 species, distributed equally between freshwater and marine habitats. Diatoms constitute 80% of the biomass (marine plankton) consumed by fish and account for

20% of oceanic carbon production (Cadoret and Bernard, 2008). They are characterized by being encased in a silica shell called a frustule.

Green algae or Chlorophyceae: widely distributed, they are rich in a green pigment giving them their color: chlorophyll.

Brown algae or Phaeophyceae.

Red algae or Rhodophyceae: these algae contain a red pigment, phycoerythrin. They are found in both freshwater and marine environments.

Cyanobacteria: Cyanobacteria are not strictly microalgae because they are photosynthetic prokaryotes (lacking a nucleus), but they are often classified as such and sometimes referred to as blue-green algae.

Microalgae are microorganisms. Like all microorganisms, microalgae have a growth curve divided into four phases. This curve is characteristic of microalgae growth in non-renewable environments, i.e., in natural environments or batch culture mode.

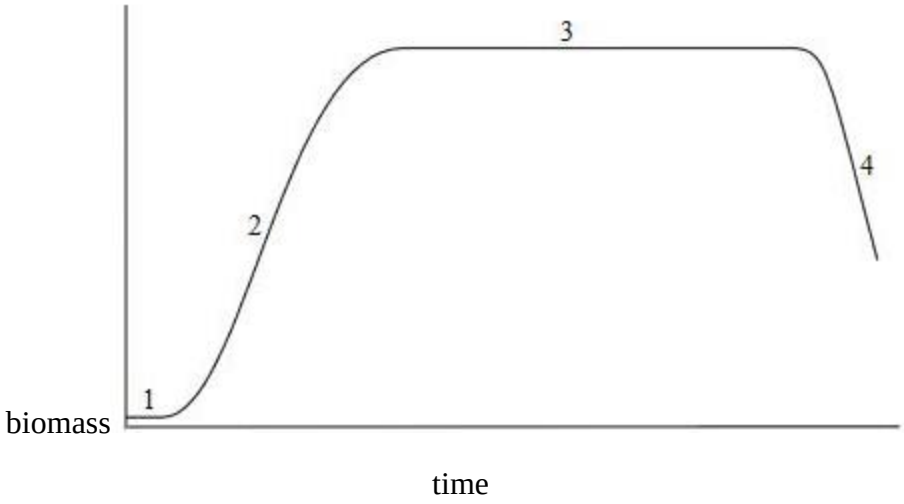

Figure I.2. Growth phases of microorganisms (According to FAO, 1996)

- Latency Phase: The latency phase is the period during which the microorganism adapts to the environment, and the growth rate during this period is almost negligible.
- Exponential Phase: This phase is characterized by maximum and constant growth rate. Microorganisms multiply rapidly, and mortality is low.
- Stationary Phase: During this phase, the carrying capacity of the environment is reached, resulting in zero growth where the reproduction rate equals the mortality rate.
- Decline Phase: In this phase, microorganisms die off and cease reproduction.

Microalgae are photoautotrophic organisms, meaning their energy source is light, and their carbon source is inorganic carbon such as carbon dioxide. However, some microalgae can grow without light ; they are termed heterotrophic. Their carbon source can be various organic compounds like glucose (Cadoret and Bernard, 2008). Certain algae can develop by combining both modes, known as mixotrophic organisms.

Compared to other biomass, microalgae exhibit a growth rate 50 times higher than terrestrial plants (Suali and Sarbatly, 2012). They produce 20 times more oils than terrestrial oilseed crops (Park et al., 2011). Microalgae also demonstrate greater photosynthetic efficiency, thus fixing more carbon dioxide than terrestrial plants (Suali and Sarbatly, 2012 ; Langley et al., 2012). In terms of water requirements, fixing one kilogram of carbon requires 140 to 200 kilograms of water, which is relatively low compared to trees (requiring 550 kilograms of water) (Berberoglu et al., 2009).

5. Factors influencing the algal culture

The cultivation of microalgae is influenced by various environmental, physical, and biological parameters that depend on the intrinsic characteristics of the algal species and the geometry of the production system. These parameters affect not only photosynthetic activity and biomass productivity but also the physiological and metabolic behavior of microalgae in culture (Richmond, 2004). Key factors include light, temperature, pH, salinity, nutrients, dissolved oxygen concentration, and the presence of toxic elements (Kumar et al., 2010). Additionally, parameters related to the hydrodynamic functioning of the reactor, such as residence time, gas transfer rate, and the degree of medium homogeneity, can impact the availability of nutrients and light energy (Kumar et al., 2010).

5.1. Light

Algal growth depends on the availability and efficient use of light energy (Smith, 1983; Lindström, 1984). It is important to note the significance of light path, cell concentration (which, if too high, causes self-shading), and the pigment characteristics of algal cells (Malone, 1982). Insufficient light can limit productivity and growth, even if other parameters are at optimal levels (Richmond, 1999).

Microalgae exhibit various behaviors depending on the level of illumination (see Figure A1.1):

- ✓ Respiration phase (in the absence of light): metabolic reactions involving the consumption of oxygen and the release of carbon dioxide.
- ✓ Limitation phase: occurs due to insufficient light energy (low light intensity, high light path, unfavorable reactor geometry) or mutual cellular shading caused by high cell concentration (Kumar et al., 2011).
- ✓ Saturation phase: characterized by maximum photosynthetic efficiency.
- ✓ Inhibition phase: defined by a loss of photosynthetic activity due to excessive light intensity (Vonshak et al., 1988).

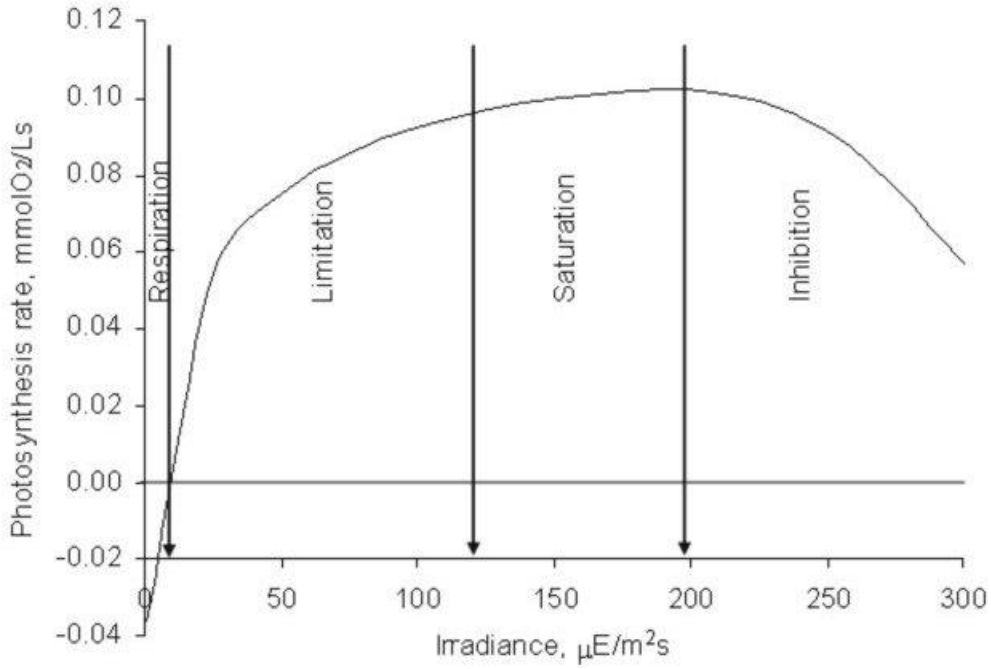

Figure I.3. Photosynthetic yield as a function of incident light intensity.(F. G. Acién Fernández, J. M. Fernández Sevilla, and J. A. Sánchez Pérez Universidad de Almería, Spain).

5.2. Temperature

The growth kinetics of algae are influenced by temperature (Richmond et al., 1990; Torzillo et al., 1991), with growth rates generally increasing with higher temperatures. This parameter regulates the cellular, physiological, and morphological responses of microalgae (Kumar et al., 2010). Temperature can cause changes in cellular structure, particularly in cell volume (Richmond, 2004). For instance, a temperature above the optimal value leads to an increase in

cell volume (Harris, 1988). Microalgae typically tolerate a temperature range of 15 to 26°C, with optimal cell concentration at 23°C (Kumar et al., 2010). Extreme temperatures, above 35°C, can be lethal for some algal species (Alcaine, 2010). Additionally, increased temperature affects the CO_2 fixation metabolism in microalgae (Kumar et al., 2011).

5.3. PH

This parameter largely depends on the concentration of dissolved CO_2 in the culture medium, governed by the chemical equilibrium among the different forms of carbon in water (CO_2, H2CO3, HCO3-, and CO32-). A high influx of CO_2 can lead to acidification of the medium, which may inhibit the growth of microalgae. Similarly, the presence of sulfur monoxide, a toxic element, causes significant acidification of the medium, thereby limiting growth (Kumar et al., 2011). Therefore, pH control of cultures is necessary to promote the growth of specific species with particular environmental requirements (Kumar et al., 2011). Generally, algal growth is favored at a pH close to neutrality, although some species can tolerate extreme pH values.

6. Conclusion

This chapter has provided an in-depth analysis of microalgae species, their cellular structures, and the importance of selecting the right species for cultivation to maximize benefits. It has discussed the various cultivation techniques, comparing open and closed systems, and highlighted the advantages and disadvantages of each. The chapter has also emphasized the role of microalgae in CO_2 capture and the environmental benefits associated with their cultivation. By understanding the factors that influence microalgae growth, such as light, temperature, pH levels, and nutrient availability, researchers and industry professionals can optimize cultivation processes to enhance productivity and efficiency. The chapter concludes by underscoring the potential of microalgae as a sustainable resource for bioenergy and as a tool for mitigating climate change through CO_2 fixation.

Chapter two :

Mathematical models

1. Modeling

1.1. Introduction

In the course of the present study, we opted for a non-structured, low-complexity growth model derived from the work of Nouals (2000). This model, previously presented in section 2.3, allows us to highlight the limiting effect of two parameters: light and the concentration of total inorganic carbon. The modeling of the culture in the photobioreactor involves mass balances that describe the evolution of each system variable over time using the algal growth kinetics, a gas-liquid transfer model for CO_2, and a model to estimate the light energy received by the culture.

Following the validation of the perfectly mixed nature of the flow in the photobioreactor , the overall behavior of the biological process is defined through mass balances.

2. Experimental determination of the gas-liquid mass transfer coefficient $k_L a$

Additionally, k_L depends on the turbulence of the mixture, which decreases as the viscosity and density of the mixture increase for the same agitation energy. This could be the case when algae are present. The dispersion of gas into fine bubbles is also less efficient, leading to an increase in the volumetric fraction of large-diameter bubbles, which results in a reduction in the interfacial area value (Kantarci et al., 2005).

$$\mathrm{V d[CO_2]} = \mathrm{k_L a}\left[[\mathrm{CO_2}]^* - [\mathrm{CO_2}]\right]\mathrm{V dt} \quad (1)$$

$$\frac{d[CO2]}{dt} = k_L a\left[[\mathrm{CO_2}]^* - [\mathrm{CO_2}]\right] \quad (2)$$

With:
$[\mathrm{CO_2}]$: concentration of $\mathrm{CO_2}$ dissolved in the liquid (mol. $\mathrm{L^{-1}}$) ;
$[\mathrm{CO_2}]^*$ maximum concentration of that can dissolve in the liquid (mol. $\mathrm{L^{-1}}$),corresponding to the equilibrium with the gas phase;
$k_L a$: transfer volume coefficient relative to the liquid phase ($\mathrm{j^{-1}}$), $\mathrm{k_L}$ where is the transfer coefficient and to the interfacial area per unit column volume ;
V : volume of liquid (L);

Assuming that the content of the gas remains constant and equal to its input content (the dissolved quantity is negligible), is therefore constant and given by Henry's law under the

conditions of the experiment. And integrating equation II.3, we obtain the following relationship:

$$\ln\left[[\mathrm{CO_2}]^* - [\mathrm{CO_2}]\right] = k_L a(t - t_0) + \ln\left[[\mathrm{CO_2}]^* - [\mathrm{CO_2}]_0\right] \quad (3)$$

$$\ln\left(\frac{[\mathrm{CO_2}]^* - [\mathrm{CO_2}])}{[\mathrm{CO_2}]^* - [\mathrm{CO_2}]_0)}\right) = k_L a \cdot t \quad (4)$$

3. Equilibrium Concentration of CO_2 in the Gas Phase

When studying mass transfer models and equations for CO_2 absorption in a system involving the microalgae *Chlorella vulgaris*, it is crucial to consider factors such as the diffusion of CO_2 in the liquid phase, CO_2 solubility in the liquid phase, mass transfer resistance in the gas-liquid interface, and the biological uptake of CO_2 by *Chlorella vulgaris*.

Key considerations may include the use of models like the film theory for mass transfer at the gas-liquid interface, the Henry's law for CO_2 solubility, and possibly kinetic models to describe the biological absorption of CO_2 by *Chlorella vulgaris*.

Experimental data on the mass transfer coefficients, CO_2 solubility, and biological uptake rates specific to *Chlorella vulgaris* will be essential for developing accurate models and equations for CO_2 absorption in this system. Collaborating with experts in bioprocess engineering, biotechnology, and algal cultivation can provide valuable insights for this research endeavor.

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The molar flow of carbon dioxide in equilibrium is given by (Bozonc et al,2022):

$$C_{CO_2,g}^{eq} = k_{HA} \times CO_2, l \quad (5)$$

Here, $k_{HA}$is a constant related to the Henry's law constant.

4. Partial Mass-Transfer Coefficients

For the liquid and gas phases, the partial mass-transfer coefficients are calculated using Billet and Schultes (1999) correlations for unstructured packing columns :

Liquid-side Mass-Transfer Coefficient (k_l):

$$k_l = C_L \times 12^{1/6} \times v_l^{1/2} \times (\frac{D_l}{dh})^{1/2} \quad (6)$$

Gas-side Mass-Transfer Coefficient (k_g):

$$k_g = c_v \times \frac{1}{(\varepsilon - h_l)^{1/2}} \times (\frac{a}{d_h})^{1/2} \times D_g \times (\frac{v_g}{a \times \vartheta_g})^{3/4} \quad (7)$$

Where :

- ✓ $d_h = \frac{\varepsilon}{a}$ is the hydraulic diameter.
- ✓ ε is the porosity of the packing.
- ✓ a is the specific surface area of the packing.
- ✓ v_l and v_g are the liquid and gas velocities, respectively.
- ✓ D_l and D_g are the diffusion coefficients for the liquid and gas phases, respectively.
- ✓ C_L and c_v are empirical constants.
- ✓ ϑ_g is the kinematic viscosity of the gas.

Liquid Holdup

The liquid holdup is the fraction of the packing volume occupied by the liquid :

$$h_l = (12 \times \frac{1}{g} \times \frac{\eta_l}{\rho_l} \times v_l \times a^2)^{1/3} \quad (8)$$

- ✓ g is the gravitational acceleration.
- ✓ η_l is the dynamic viscosity of the liquid.
- ✓ ρ_l is the density of the liquid.

5. Effective Mass-Transfer Area

The effective mass-transfer area depends on the Reynolds number (R_{el})(Billet, Reinhard, and Michael ,1999) :

$$R_{el} = (\frac{v_l \times \rho_l}{a \times \eta_l}) \quad (9)$$

For $R_{el} < 5$

$$a_e = a \times C_h \times (\frac{v_l \times \rho_l}{a \times \eta_l})^{0.15} \times (\frac{v_l^2 \times a}{g})^{0.1} \quad (10)$$

For $R_{el} \geq 5$

$$a_e = a \times C_h \times 0.85 \times (\frac{v_l \times \rho_l}{a \times \eta_l})^{0.25} \times (\frac{v_l^2 \times a}{g})^{0.1} \quad (11)$$

4. Enhancement Factor (E)

For the absorption of CO_2 in a microalgae culture, the enhancement factor (E) is given by the Hatta number (H_a) (Atrozi et al,2023)

$$E = \frac{H_a}{tanh H_a} \quad (12)$$

5. Global Mass Transfer Coefficients

The global mass transfer coefficients for carbon dioxide in the gas and liquid phases are :

$$K_g = \frac{1}{\frac{1}{K_g} + \frac{k_{HA}}{E.k_l}} \quad (13)$$

$$K_l = \frac{1}{\frac{1}{K_{HA}} + \frac{1}{E.k_l}} \quad (14)$$

Conclusion

Modeling the capture of CO_2 by microalgae, focusing on the rate constant k_{La} and the equilibrium concentration of CO_2, is essential for optimizing carbon sequestration bioprocesses. A thorough understanding of these parameters allows for improving the efficiency of microalgae culture systems and maximizing their CO_2 capture potential, thereby contributing to sustainable solutions for reducing greenhouse gas emissions.

Chapter three :

Materials and methods

1. Introduction

Aquaculture, particularly, is a critical component of global food security, yet it faces challenges such as high bait costs and environmental concerns due to reliance on low-quality imported baits. Microalgae, with their high nutritional value and efficiency in photosynthesis, offer a sustainable solution for aquaculture by enhancing fish growth, immunity, and water quality. They also provide a superior alternative to traditional fish meals and contribute to water purification and microbial balance regulation.

2. Microalgae culture modes The Photobioreactor

Aquaculture production in Asia constitutes approximately 92% of global output, with China alone contributing over 60% of this. While aquaculture significantly supports global food security, high bait costs and the reliance on low-quality, imported baits create economic and environmental challenges. Microalgae, rich in nutrients and highly efficient in photosynthesis, offer a promising solution as they enhance growth, immunity, and water quality in aquaculture. They provide superior nutrition compared to traditional fish meals and help purify water and regulate microbial balance (Wang et al., 2020; Britsch et al., 2021; Zhang et al., 2021).

2.1. photoautotrophy culture mode

Photosynthesis in microalgae involves the fixation of CO_2 through the absorption of light, electron transport, photosynthetic phosphorylation, and carbon assimilation, ultimately converting light energy into usable forms such as reduced coenzyme II (NAD(P)H) and ATP (Sun et al., 2016). The growth of photoautotrophic microalgae is primarily influenced by CO_2 levels and light conditions, including both the duration and intensity of light exposure. This light energy is then transformed into cellular components (Butti and Mohan, 2018).

In aquaculture, utilizing photoautotrophic microalgae offers significant economic benefits. Notably, it avoids the need for carbonate addition, preventing potential issues with excessive alkalinity in the water (Hwang et al., 2014). However, this mode of cultivation presents challenges for certain microalgae species. It heavily relies on external factors, meaning growth may be limited when solar energy is insufficient, either due to shorter daylight periods or significant intervals between light exposure (Hwang et al., 2014). Insufficient solar energy can decrease microalgal density, creating conditions favorable for bacterial proliferation (Yu and Kim, 2017).

Moreover, in photoautotrophic cultures, many algal cells metabolize internally stored nutrients like polysaccharides, lipids, and proteins for survival. This results in lower biomass compared to other cultivation methods (Simal-Gandara et al., 2022).

3. Culture of *Chlorella vulgaris*

3.1. The Photobioreactor (using)

In the cultivation of *Chlorella vulgaris*, a bubble column type photobioreactor is employed, featuring dimensions of 5 cm in outer diameter and 50 cm in height for the central portion. The working volume amounts to 0,3 liters with an illuminated surface area of 0.1096 m².

The strain used is *Chlorella vulgaris*.

Known for lipid production was grown in photobioreactors bubble collum containing 300 mL of mineral medium, situated in a water bath (30°C) under continuous illumination with incident light intensity 100 µE/m2/s and feeding of air enriched with 2% CO_2 (v/v) at 15 L.h-1 per tube. The growth was followed by optical density at 750 nm and N° of cells/mL*107 was also determined through a calibration curve performed by gravimetry. The inoculum of *Chlorella vulgaris* used was 10%(v/v).

Figure III.1: Batch cultivation of *C. vulgaris* in lab-scale photobioreactor (Ghobrini, 2022).

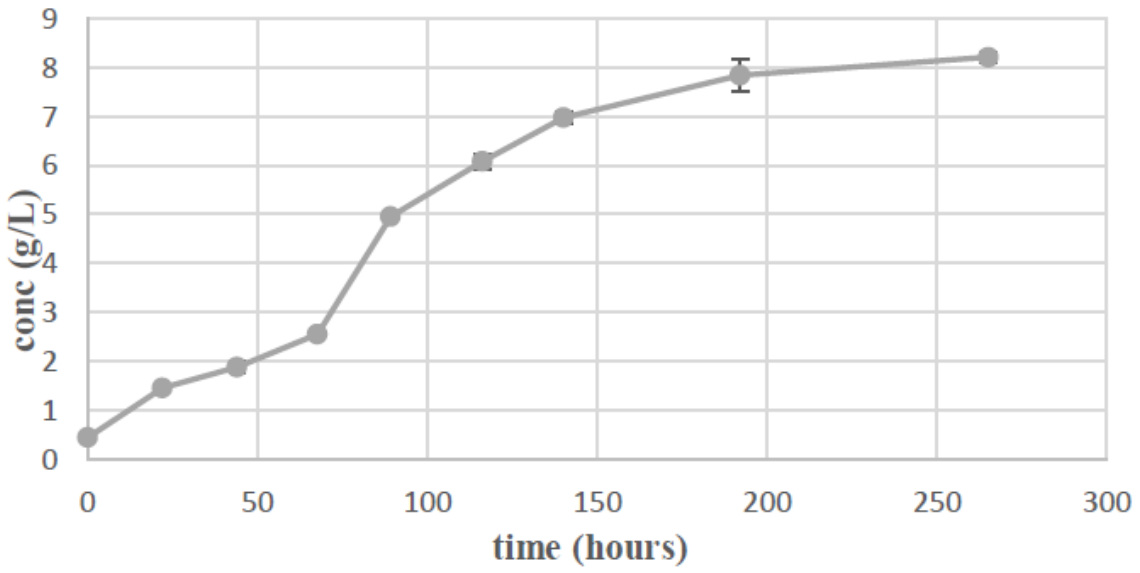

Figure III.2.*Chlorella vulgaris* growth curve (Ghobrini, 2022).

The photobioreactor is designed with a double jacket system where distilled water circulates to regulate the temperature via a cryostat, maintaining a temperature of 30°C throughout the *Chlorella vulgaris* cultivation process.

Gas injection occurs at the reactor's base with a flow rate of 250 $mL \cdot min^{-1}$ at 1 atm and 30°C. Prior to entering the reactor through a fritted glass disc, the gas passes through a sterile filter (Millipore, 0.2 µm). Gas flow rate and composition are monitored by two mass flow meters, one controlling air supply and the other managing CO_2 supply. The gas inlet serves for mixing and CO_2 delivery to the culture, with gas exiting at the reactor's top through another sterile filter (Millipore, 0.2 µm). Flow rate consistency is ensured by monitoring at both the inlet and outlet during cultivation.

Illumination of the photobioreactor is achieved through fluorescent lamps on two sides, comprising four white fluorescent lamps (Biolux L36W/965) and four pink fluorescent lamps (Fluora L36W/77). The Biolux lamps emit wavelengths akin to natural light, while the Fluora lamps predominantly emit red and blue wavelengths, ideal for stimulating photosynthetic pigments in *Chlorella vulgaris*. The combination of these lamp types enhances the photosynthesis process during cell culture in the photobioreactor.

A photometer (LI 250A, LI-COR, USA) is employed to measure incident and outgoing light intensities, oriented towards the fluorescent lamps for incident light measurement and towards the reactor for outgoing light intensity assessment.

Three outlets situated at the top of the reactor enable sampling during cultivation activities and facilitate continuous pH monitoring.

The reactor and the culture medium are sterilized using autoclave treatment (121°C, 20 minutes) before any use. Sampling and inoculation of the reactor are performed under flame control to maintain the sterility of the setup and the culture.

3.2. Batch Cultures (using)

During batch cultivation, the liquid phase is introduced at the beginning of the experiment in a discontinuous mode, while the gas phase is continuously introduced throughout the experiment. Figure III.2 illustrates the setup of the photobioreactor during a batch culture of *Chlorella vulgaris*.

Gas flow rate and composition are controlled using two VSO® model flow meters from Pneutronics (Parker, USA). In this cultivation, the CO_2 concentration is gradually increased to the desired value to prevent inhibition of cell growth due to excessive CO_2 concentration when the cell concentration is low. Similarly, light intensity is gradually increased to avoid inhibition of cell growth caused by excessive light intensity when the cell concentration is too low (Chisti, 2007).

During the cultivation of *Chlorella vulgaris* with a light intensity of 180 μmol.m-2.s-1, the reactor was illuminated on three sides, as dictated by the arrangement of fluorescent lamps to achieve the desired light intensity.

pH measurement is performed using a Consort C864 pH probe (Biopoint, England) after sampling the culture from the reactor.

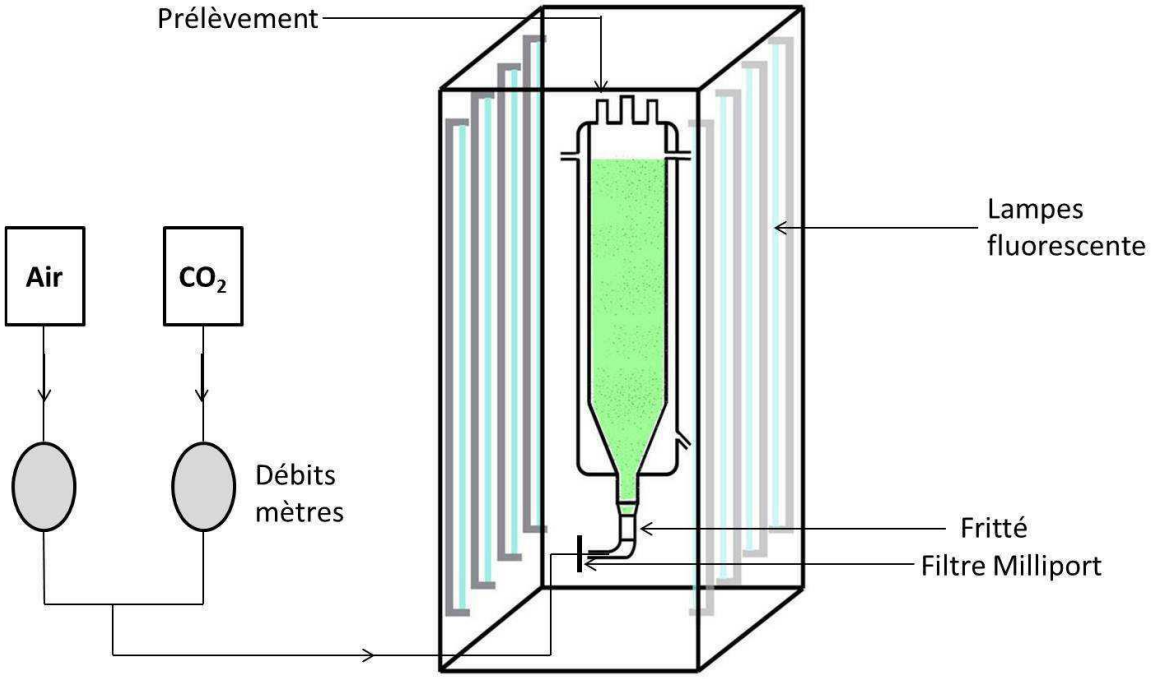

Figure III.3. Assembly of the photobioreactor for the cultivation in batch mode.(Barbara Clement-Larosière. Etude de la croissance *de Chlorella vulgaris* en photobioréacteur batch et continu, en présence de concentrations élevées de CO_2,. Autre. Ecole Centrale Paris, 2012).

3.3. Culture medium

The cultivation of *Chlorella vulgaris* is carried out in modified Bristol 3N culture medium, the composition of which is detailed in Appendix I. This medium consists of a mixture of three solutions. These solutions are prepared in advance and stored at 4°C, with renewal every two months.

Once the Bristol medium solution is prepared, it is autoclaved for 20 minutes at 120°C and then stored at 4°C. The Bristol medium solution is prepared just before starting a culture to avoid any bacterial contamination during storage.

4. Conclusion:

The cultivation of microalgae, specifically *Chlorella vulgaris*, in a photobioreactor presents a promising approach to address the challenges in aquaculture. The study demonstrates the optimal conditions for microalgae growth, including the importance of light, CO_2 levels, and temperature regulation. By utilizing a bubble column type photobioreactor, the culture of

Chlorella vulgaris can be effectively managed to maximize its benefits in aquaculture. The use of microalgae not only supports the industry economically by reducing the need for expensive bait but also mitigates environmental issues associated with aquaculture practices. As such, the integration of microalgae culture in aquaculture systems represents a significant step towards sustainable food production and environmental stewardship.

Chapter four :

Results

Introduction

This study delves into the intricate dynamics of gas-liquid mass transfer and CO_2 sequestration in microalgae cultures using a mathematical modeling approach. By employing partial differential equations discretized into ordinary differential equations and integrated into MATLAB/Simulink 2007, the research aims to elucidate the underlying processes affecting gas flow rate, CO_2 concentration, and temperature changes over time. The analysis focuses on the behavior of a system where these parameters exhibit distinct trends, indicating a controlled reaction or process.

A key aspect of the investigation is the impact of algae and extracellular compounds on the mass transfer performance, particularly the volumetric mass transfer coefficient (k_{La}). Through detailed simulations and experimental validations, the study evaluates the evolution of dissolved CO_2 concentrations in various scenarios, including the presence of *Chlorella vulgaris*, a microalga known for its CO_2 absorption capabilities. The findings reveal a comprehensive understanding of the factors influencing the efficiency of CO_2 capture, highlighting the potential for optimizing operational parameters to enhance sequestration efficiency.

By presenting a series of figures and analyses, the research provides insights into the temporal changes in gas flow rate, CO_2 concentration, and temperature, and their interdependencies. The results underscore the importance of system dynamics in achieving a stable state of CO_2 dissolution and absorption, offering valuable guidance for future advancements in sustainable CO_2 capture technologies.

The mathematical model's partial differential equations underwent numerical discretization to become ordinary differential equations, which were then integrated into Matlab/Simulink.2007

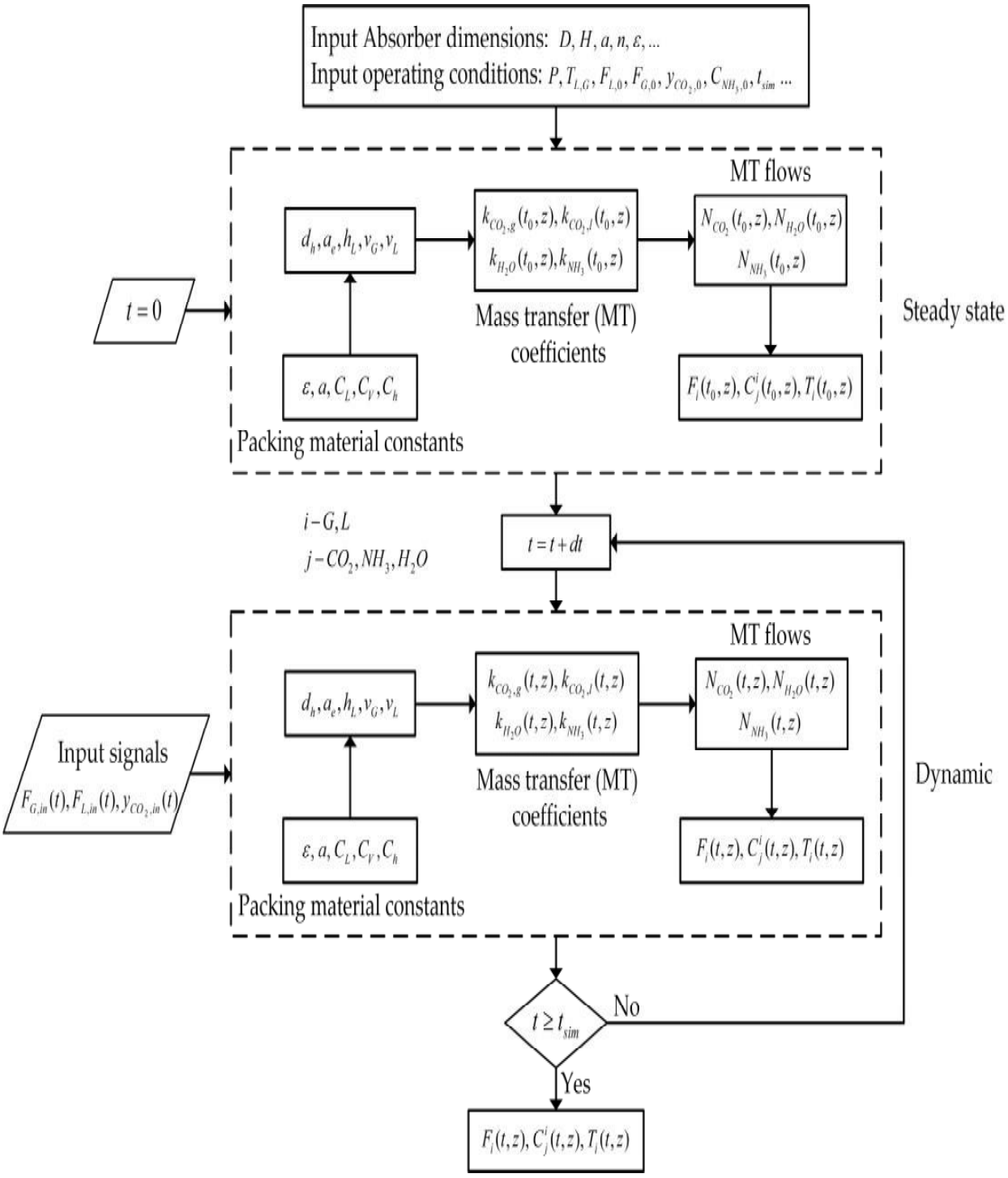

Figure V. Diagram of the algorithm used.

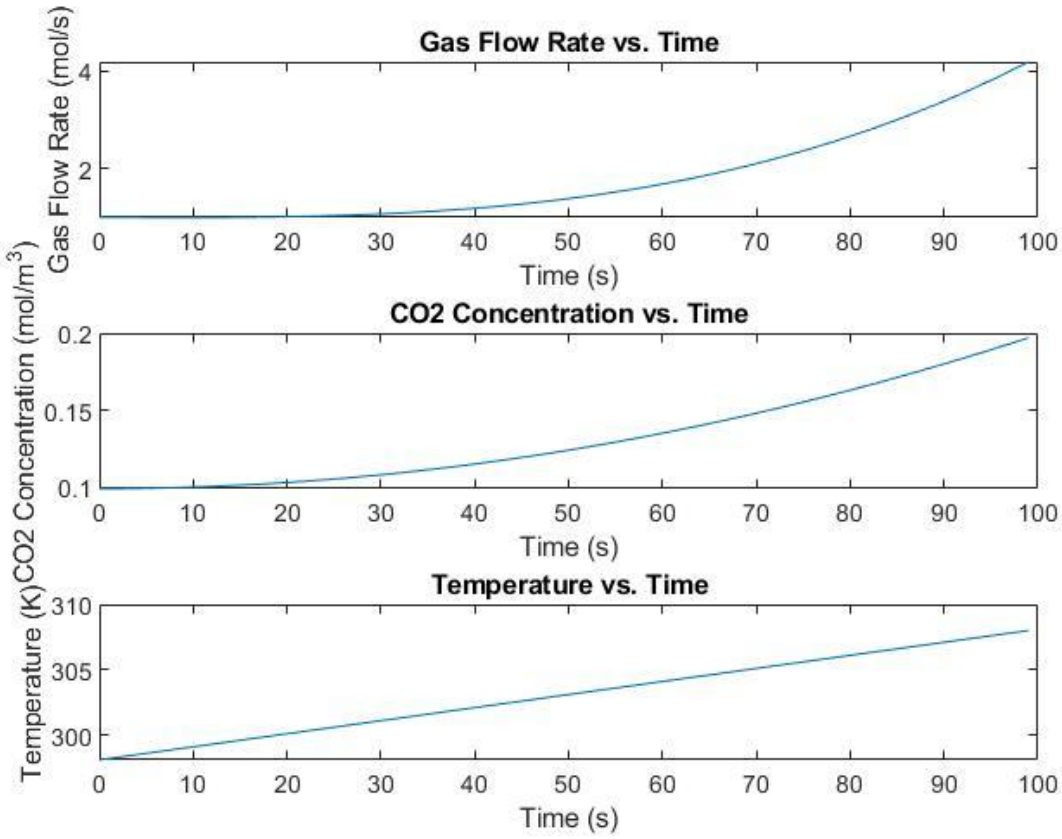

Figure V 1. Gas Flow Rate, CO_2 Concentration, and Temperature Changes Over Time.

1. Gas Flow Rate vs. Time

Description: This graph shows the gas flow rate (in mol/s) on the y-axis versus time (in seconds) on the x-axis.

Analysis:

The curve starts at a low flow rate and increases gradually over time.

Initially, the flow rate increases very slowly, indicating a period of low flow rate.

Around the midpoint (50 seconds), the flow rate begins to increase more noticeably.

By the end of the time period (100 seconds), the flow rate reaches its highest value, indicating an accelerating trend.

Comment:

The increasing trend suggests that the gas flow rate is not constant and is accelerating as time progresses. This could be due to a variety of factors such as increased pressure, temperature, or changes in the system's dynamics controlling the gas flow.

2. CO_2 Concentration vs. Time

Description:

This graph shows the concentration of CO_2 (in mol/m³) on the y-axis versus time (in seconds) on the x-axis.

Analysis:

The CO_2 concentration starts at a low value and gradually increases over time.

The increase is relatively linear, indicating a steady rise in CO_2 concentration.

There are no sharp changes or inflections in the curve, suggesting a stable and controlled increase.

Comment:

The steady increase in CO_2 concentration over time could be due to the continuous addition or production of CO_2 in the system. The linear nature of the increase suggests that the rate of CO_2 addition or production is constant.

3. Temperature vs. Time

Description: This graph shows the temperature (in Kelvin) on the y-axis versus time (in seconds) on the x-axis.

Analysis:

The temperature starts at just above 290 K and increases steadily over time.

Similar to the CO_2 concentration graph, the temperature increase is linear.

The rate of temperature increase appears to be consistent throughout the time period.

Comment:

The steady increase in temperature might be due to a controlled heating process or an exothermic reaction taking place within the system. The linear trend indicates a uniform input of heat or a consistent rate of heat generation.

Overall Comment

The three graphs together suggest a system where gas flow rate, CO_2 concentration, and temperature are all increasing over time. The gas flow rate increases more exponentially, while CO_2 concentration and temperature increase linearly. This could imply a scenario where the system's dynamics are gradually ramping up, possibly due to a controlled reaction or process that is being progressively intensified. Understanding the interdependencies between these variables would require further contextual information about the system being analyzed.

4. Results

For a total flow rate of 250 ml/min of a mixture of air and 2% CO_2, the dissolved gas concentration and mass transfer dynamics will be influenced by the factors mentioned above. The reduction of turbulence and increase in medium viscosity in the presence of algae and extracellular compounds will be determining factors for the gas-liquid mass transfer performance and thus the value of $k_L a$.

In summary, the presence of algae and extracellular compounds in the medium can reduce the value of $k_L a$ a by decreasing turbulence, increasing bubble size, and changing the viscosity of the medium, affecting the transfer of dissolved CO_2 in the reactor.

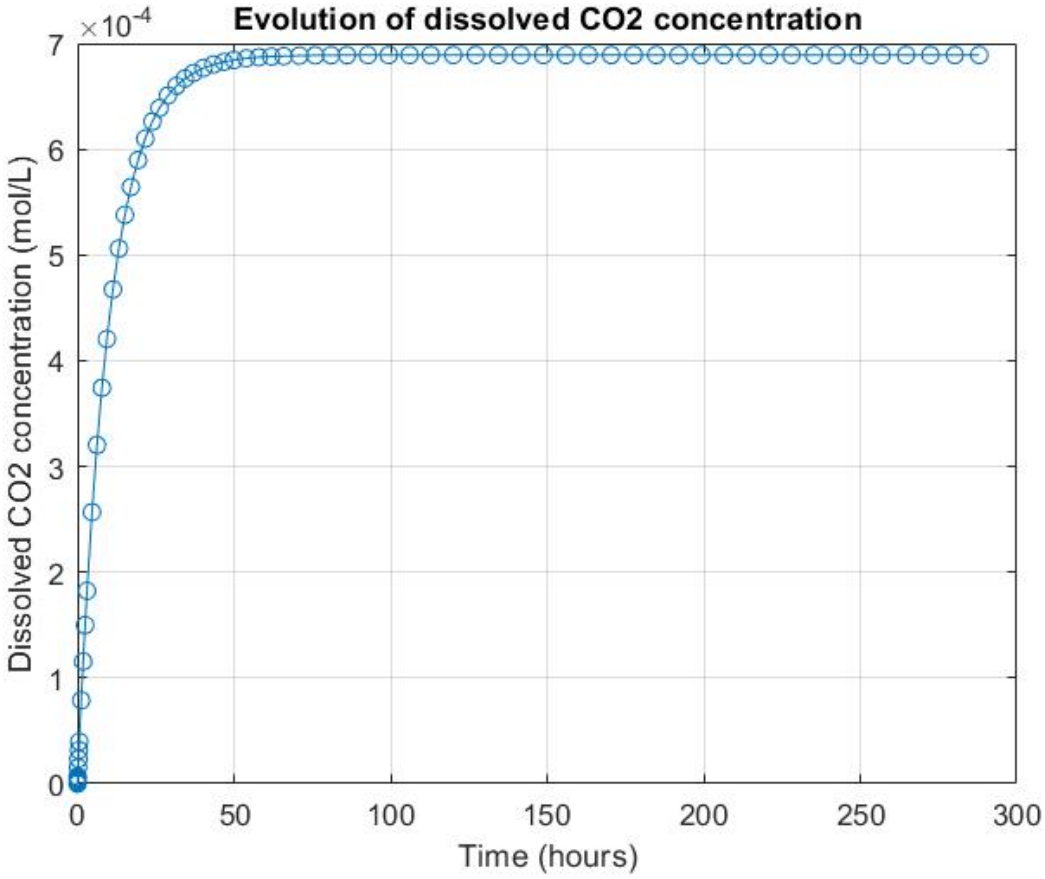

Figure V.2. Evolution of the concentration of dissolved CO_2 in the presence of a gas flow rate.

This graph illustrates the evolution of dissolved CO_2 concentration (mol/L) over time (hours). The data points, marked by circles, show a rapid increase in CO_2 concentration within the first 25 hours, reaching a plateau around 7×10^-4 mol/L. Beyond this point, the concentration

remains relatively stable, indicating that the system has reached equilibrium. The steady state is maintained for the remainder of the observed period, up to 300 hours. This behavior suggests that the dissolution process of CO_2 into the solution occurs quickly and stabilizes thereafter.

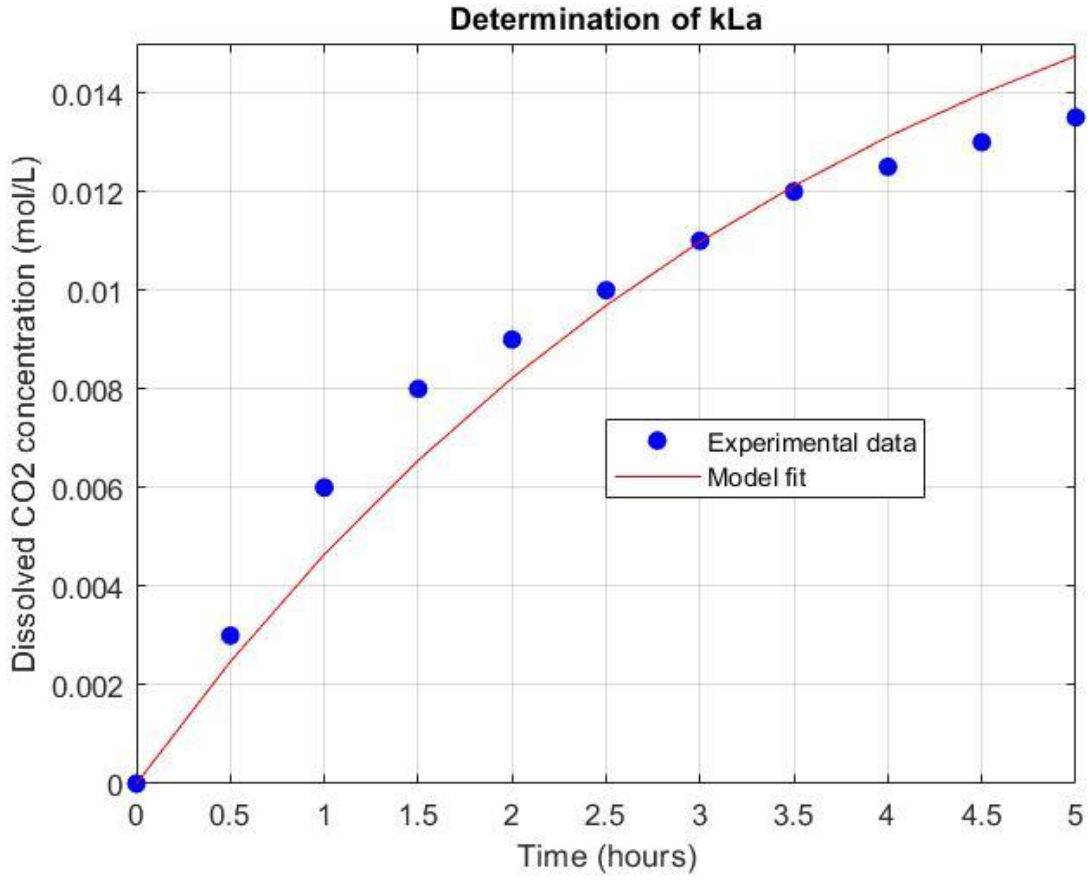

Figure V.3. Determination of $k_L a$.

This graph depicts the determination of the volumetric mass transfer coefficient (k_{La}) by plotting the dissolved CO_2 concentration (mol/L) against time (hours). The blue dots represent the experimental data points, showing an increase in CO_2 concentration over a period of 5 hours. The red line represents the model fit to the experimental data, indicating that the model accurately describes the observed trend. The increasing trend suggests a continuous increase in dissolved CO_2 concentration over time, which is well-captured by the model. The close alignment between the experimental data and the model fit demonstrates the reliability of the model in predicting the CO_2 dissolution process.

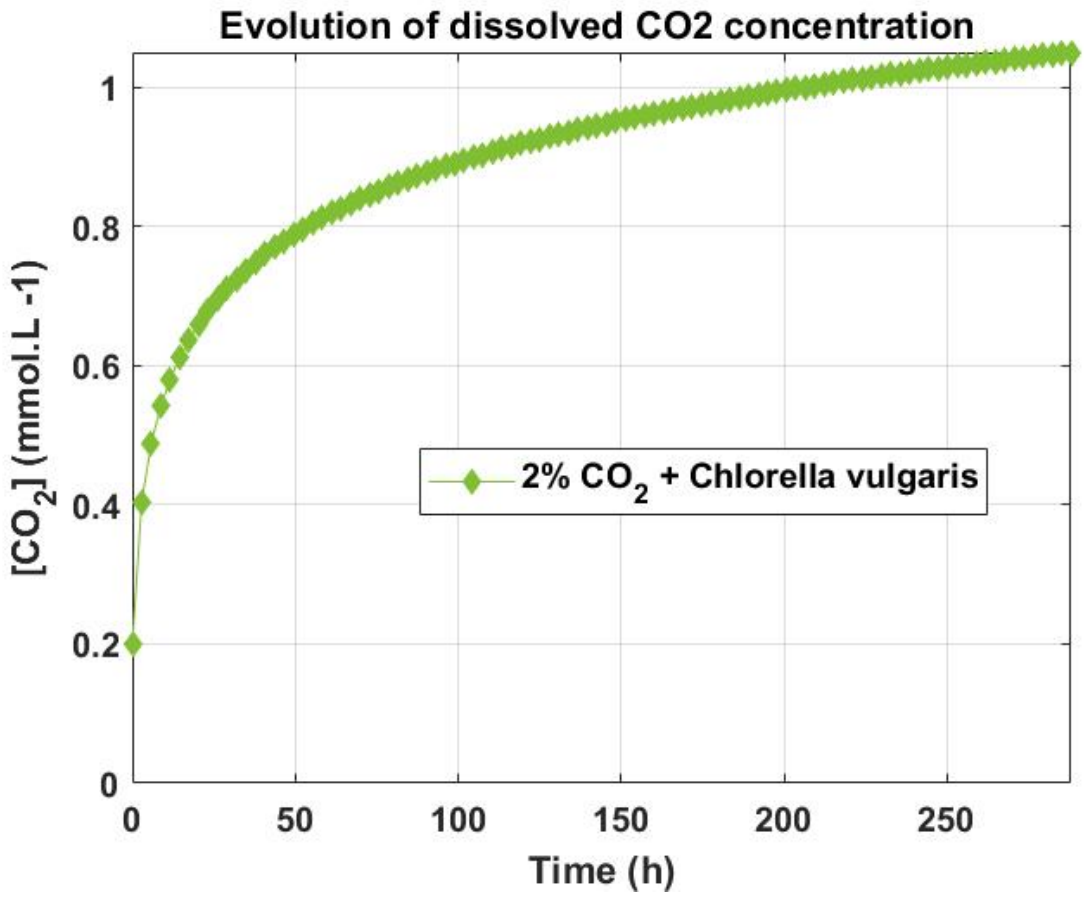

Figure V.4. Change in the concentration of dissolved CO_2 for a *Chlorella vulgaris* culture during the stationary growth phase. The CO_2 concentration in the feed gas is 2% (v/v).

This graph illustrates the evolution of dissolved CO_2 concentration over time, measured in hours, in a system containing 2% CO_2 and *Chlorella vulgaris*. The concentration of dissolved CO_2, indicated in mmol.L^{-1}, shows a rapid initial increase, reaching approximately 0.5 mmol.L^{-1} within the first 50 hours. Beyond this point, the rate of increase slows down, approaching a plateau near 1 mmol.L^{-1} as time progresses. This suggests that the system reaches an equilibrium state where the dissolved CO_2 concentration stabilizes. The data highlights the dynamic interaction between CO_2 dissolution and *Chlorella vulgaris* over an extended period.

5. Yield

The total concentration of CO_2 transferred onto the medium is 6.88 Mol/L)

The total concentration of absorbed CO_2 from *Chlorella vulgaris* is (1.05 Mol/L)

$$\text{Yield} = \frac{\text{The total concentration of absorbed co2}}{\text{total concentration of co2 transferred}} \quad (15)$$

$$\eta = \left(\frac{1.05}{6.88}\right)*100 = 15.26\% \quad (16)$$

Conclusion

In this chapter we used the MATLAB-based analysis of CO_2 capture by microalgae has yielded valuable insights into the gas-liquid mass transfer dynamics and the equilibrium concentration of CO_2. The findings underscore the critical role of optimizing operational parameters to enhance the efficiency of CO_2 sequestration processes. The total concentration of CO_2 transferred onto the medium is 6.88 Mol/L) .The total concentration of absorbed CO_2 from *Chlorella vulgaris* is (1.05 Mol/L) . Yield = 15.26% which is considered an acceptable result .

General Conclusion

Conclusion :

Throughout this study, we focused on the efficiency of CO_2 transfer in microalgae cultivation, utilizing MATLAB to develop mathematical models and computer codes to simulate these processes. Specifically, our research centered on the microalgal strain *Chlorella vulgaris* for CO_2 capture, examining two scenarios with CO_2 concentrations of 0.03% and 2% in the air supply. The results demonstrated significant CO_2 capture, with a concentration of 6.88 Mol/L transferred into the culture medium. Additionally, the gas-liquid mass transfer coefficient (KLa) was determined to be 0.015 Mol/L, indicating efficient CO_2 transfer. Notably, *Chlorella vulgaris* fixed 1.05 Mol/L of CO_2 under these conditions, highlighting its potential for CO_2 sequestration and biomass production.

This study underscores the importance of optimizing CO_2 transfer efficiency in microalgae cultivation for enhanced CO_2 capture and biofuel production. By further refining cultivation techniques and utilizing advanced simulation tools, we can unlock the full potential of microalgae as a sustainable and economically viable solution for meeting future energy demands while mitigating climate change.

For future perspectives, consider exploring new strains of microalgae, optimizing cultivation techniques, evaluating the economics and environmental implications, transferring findings to industrial applications, and contributing to the development of new technologies for more efficient and sustainable production.

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Faculté des sciences et Technologies
Département d'automatique et d'électromécanique

غرداية في : 2024/09/18

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الإذن بطباعة النسخة النهائية لمذكرة ماستر الموسومة بعنوان

.....Carbon dioxide capture by microalgae .....

إمضاء رئيس القسم
مساعد رئيس قسم الآلية والكهروميكانيك
مكلف بما بعد التدرج و البحث العلمي
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