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Algae-based bioenergy production aligns with the Paris agreement goals as a carbon mitigation technology

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Abstract

Strategies to mitigate climate change have been developing and applying in the productive sector. Carbon capture and storage technologies might decrease the impact of CO_2 emissions on the environment. Biological technologies are an important tool to mitigate CO_2 emissions and microalgae cultivation emerges as a promising alternative, due to the important role of these organisms on the environment, the capacity of growing in different conditions, and the possibility of converting the microalgae biomass into a wide range of value-added products and biofuels. This study evaluated the potential algae-based CO_2 mitigation by coupling industrial flue gas of a Brazilian cement plant to a microalgae cultivation system. The biodiesel production from microalgae biomass is also investigated to replace fossil fuels. The microalgae plant facility was projected to occupy a reminiscent area of 3.8 ha in the cement plant boundary. Two different mitigation scenarios were analyzed and the results showed that by using 15% of intermittent CO_2 input from the cement industry in the microalgae cultivation system it is possible to mitigate 1268 tCO_2 $year^{-1}$ and to produce 2317 L $year^{-1}$ of biodiesel. This study provides support information to decision-making to implement carbon capture strategies in the future carbon market to mitigate the environmental impacts of climate change.

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Keywords: *Chlorella sp*; Climate change; CO_2 biofixation; CO_2 mitigation; Microalgae cultivation

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1. Introduction

The use of non-renewable energy sources over the last decades has been causing environmental concerns. The development of sustainable technologies and products emerges as an alternative to overcome the depletion of natural resources, contributing to a carbon-neutral economy transition.

Parties of the United Nations Framework Convention on Climate Change (UNFCCC) extended a landmark agreement to combat and mitigate climate change at COP 21, realized in Paris in 2015. The Paris Agreement aims to strengthen the global effort to keep the global temperature below 2 °C compared to pre-industrial levels and to limit the temperature increase even further to 1.5 °C. Additionally, the agreement also aims to implement financial mechanisms to increase the ability of countries to deal with the transition to a low carbon economy through decreasing greenhouse gases (GHG) emissions and implementing climate-resilient pathways [1].

The Nationally Determined Contribution (NDC) under the Paris Agreement is a document that embodies each Party country to communicate how it will reduce the national emissions aiming to achieve the long-term goals to mitigate climate changes. Brazil's NDC extended the signed commitments of the former Kyoto protocol and reaffirms the country's commitment to reduce total net greenhouse gases (GHG) by 37% in 2025 and the total Brazilian emissions by 43% in 2030 [2].

The Brazilian industrial sector was responsible for emitting 70.7 Mton of CO_{2eq} in 2020, which corresponds to 17.8% of emissions. Among them, the transport sector was responsible for 45.1% of the total emissions against the total of 32.2% of other sectors' emissions, such as agriculture, energy services, electricity, and fugitive emissions [3]. The remaining 4.9% are emissions from the residential sector. However, Brazil is a developing economy increasing its industrial park and the adoption of sustainable practices should be a priority.

One of the major contributors to the release of anthropogenic CO_2 into the atmosphere is cement manufacturing. The cement industry is highly energy consuming and GHG emitter. Almost 70% of CO_2 emissions in a cement industry occur during clinker production, resulting from the decarbonatation of raw material during the calcination process. The remaining emissions result from the combustion of fossil fuels to power the manufacturing, indirect emissions from electricity consumption, and those related to the transport of raw materials [4]. The transport mode in Brazil favors a higher CO_2 emission since 96% of cement is transported in diesel trucks [5]. Currently, the Brazilian cement industrial park is composed of 100 cement plants, totalizing an installed production capacity in the order of 100 million tons per year [6]. Considering that the specific emission in Brazil is 565 kg CO_2 ton^{-1} of produced cement [5], the potential annual emission is around 57 million tons of CO_2 in one year. Therefore, it is essential to focus on the development of new strategies to reduce carbon emissions and to increase the production of bioenergy to replace fossil fuels.

Some strategies for carbon capture and storage have been developed over the years to mitigate environmental damage caused by CO_2 emissions. Among biological technologies, microalgae cultivation emerged as an attractive alternative to carbon capture [7].

Microalgae are eukaryotic or prokaryotic organisms, with high biomass productivity, compared with traditional crops. They can grow in different kinds of resources, from freshwater, seawater, and wastewater, using non-arable lands for their cultivation, promoting the remediation and valorization of different types of streams [8]. In addition, microalgae can be grown throughout the year, and their biomass production provides the mitigation of GHG, due to the high photosynthetic rates and the potential of coupling the cultivation system with industrial flue gas emissions [9]. Furthermore, microalgae have arisen as a very promising alternative for producing a wide range of high-value compounds and bioenergy, and some studies have shown the potential of these organisms for biodiesel production [10].

In this context, this work aims to analyze the algae-based carbon capture strategy from the cement industry, by coupling the microalgae cultivation system to the flue gas emissions and ultimately using the microalgae biomass as feedstock for biodiesel production.

2. Methods

2.1. Biomass production

A strain of freshwater microalgae represented by a *Chlorella vulgaris* was selected to be cultivated for biomass production due to its high growth rate, production of large amounts of lipids and valuable compounds [11] and to its ability to tolerate high concentrations of NOx and SOx, that composes the cement flue gases [12,13].

To simulate the microalgae growth, it was applied a derived Monod growth model [14], using different CO_2 concentrations in a tubular photobioreactor designed for this study. The model was simulated using the MATLAB/Simulink software®. According to He et al. [14], the kinetic model used has the following assumptions: (1) biomass was produced in a homogeneous system; (2) CO_2 concentration and light intensity were the limiting factors that influenced the growth of microalgae; (3) the relationship between the partial pressure of CO_2 and its equilibrium concentration in the liquid phase was modeled by Henry's Law. The Eqs. (1)–(3) summarize the kinetic assumptions of the model.

$$\frac{dX}{dt} = \frac{S}{S + K_s + S^2/K_I} \times \frac{I}{I + K} \times \mu_{max} \times X \tag{1}$$

$$I = \frac{I_a}{A.X}\left(1 - e^{-A.X}\right) \tag{2}$$

$$\frac{dX}{dt} = K_{LA}\left(P/H - S\right) - Y_{S/X} \times \frac{S}{S + K_s + S^2/K_I} \times \frac{I}{I + K} \times \mu_{max} \times X \tag{3}$$

where, X is the microalgal biomass concentration (kg m^{-3}); S is the dissolved CO_2 concentration (mol m^{-3}); I is the average light intensity (mmol m^{-2} s^{-1}); I_0 is the surface light intensity (mmol m^{-2} s^{-1}); A is the coefficient (m^3 kg^{-1}); P is the CO_2 partial pressure in the gas phase (Pa); μ_{max} is the maximum specific growth rate of microalgae (h^{-1}); K_s is the Michaelis–Menten constant of CO_2 (mol m^{-3}); K_I is the inhibition constant of flue gas (mol m^{-3}); H is Henry's constant of CO_2 (Pa m^{-3} mol^{-1}); K_{La} is the mass transfer rate (h^{-1}); K is the Michaelis–Menten constant of light intensity; and $Y_{S/X}$ is the yield coefficient (mol CO_2 kg biomass^{-1}).

The kinetic parameters used for the simulation of microalgae growth are summarized in Table 1.

Table 1. Kinetic parameters used in microalgae growth simulation.

Parameter	Description	Value	Units
μmax	Specific maximum growth rate	0.07	h^{-1}
Kd	Mortality rate	0.028	h^{-1}
Ks	Michaelis–Menten constant for or CO_2	0.00021	mol m^{-3}
KI	CO_2 inhibition constant	10	mol m^{-3}
K	Michaelis–Menten for luminous intensity	14	μmol m^{-2} s^{-1}
KLA	Mass CO_2 throughput	17	h^{-1}
H	CO_2 Henry Constant	3,202	Pa m^3 mol^{-1}
YS/X	Growth coefficient	100	(mol CO_2) (kg biomass)$^{-1}$
A	Constant	14.7	m^3 kg^{-1}
I0	Light intensity	41,085	μmol photons m^{-2} s^{-1}
CO_2 (A)	Atmospheric CO_2 concentration	0.0004	Volumetric fraction
CO_2 (G)	CO_2 concentration in effluent gases	0.15	Volumetric fraction
X(0)	Initial biomass concentration	0.1	kg m^{-3}
S(0)	Initial concentration of dissolved CO_2	0.013	mol m^{-3}

To overcome the microalgae growth inhibition caused by medium acidification due to continuous exposure to flue gas, the model considers an on-off flue gas input mode, in which flue gas was modeled to pulse into the photobioreactors at a specific frequency of 1 min gas-on (15% CO_2), and 29 min gas-off (0.04% atmospheric CO_2) [14].

2.2. Carbon capture case study

In this work, it was designed a carbon capture system based on microalgae cultivation coupling to flue gases from a cement industrial plant located in the city of Cubatão, São Paulo, Brazil. Dataset was obtained from the public "Project Design Document" sent to the UNFCCC and the Brazilian Interministerial Commission on Global Climate Change (National Authority Designated Brazilian Government) for the approval of projects under the Clean Development Mechanism (CDM) of the former Kyoto Protocol to obtain carbon credits. This document and data were chosen as a base to obtain insights about future prospection and implementation of carbon mitigation mechanisms to achieve the Paris Agreement goals. The CDM project sent to UNFCCC aimed to replace fossil fuel with natural gas in the blast-oven slag dryer used in the manufacture of cement, thus reducing carbon dioxide emissions. The project started in 2004, with an expected operating lifetime of about 30 years.

In this study, two different scenarios described in the CDM project sent to the UNFCCC were used to calculate the amount of CO_2 mitigated by microalgae cultivation in the cement industry:

1. The base scenario, that corresponds to the emission of about 22,461 tCO_2 per year, using fossil fuel;
2. The CDM scenario, that corresponds to the emission of about 12,000 tCO_2 per year, using natural gas.

2.3. Microalgae downstream process

The downstream process considered biomass harvesting, drying, cell disruption, lipid extraction, oil refining, and transesterification process. The production of biodiesel was estimated according to the adapted methodology published by Branco-Vieira et al. [15]. Briefly, the dried biomass was milled in a ball mill machine to release all cellular components and total oil content was recovered by using a supercritical CO_2 method, assuming that only triglycerides are obtained from the biomass, with an efficiency of 95% of extraction. In terms of microalgae oil content, it was considered an amount of 22% of total lipids in *C. vulgaris* cells [16]. The lipids were converted into fatty acid methyl esters (FAME) or biodiesel, via an alkali-catalyzed transesterification reaction.

3. Results and discussion

3.1. Biomass production

The microalgae growth was simulated according to the model during 12 days of cultivation, using two different CO_2 concentrations. The microalgae biomass production using atmospheric CO_2 concentration (0.04% of CO_2) showed a yield of 0.408 kg m^{-3} of biomass on the 12th day of cultivation, and an average productivity of 0.254 kg m^{-3} d^{-1} (Fig. 1). On the other hand, the production of microalgae biomass fed with 15% of CO_2 from cement plant flue gases was around 1.44 kg m^{-3}, which corresponds to the average productivity of 0.681 kg m^{-3} d^{-1} (Fig. 1). The values achieved using flue gas correspond to an increase of 28.33% on the microalgae growth rate and 37.30% on microalgae daily productivity.

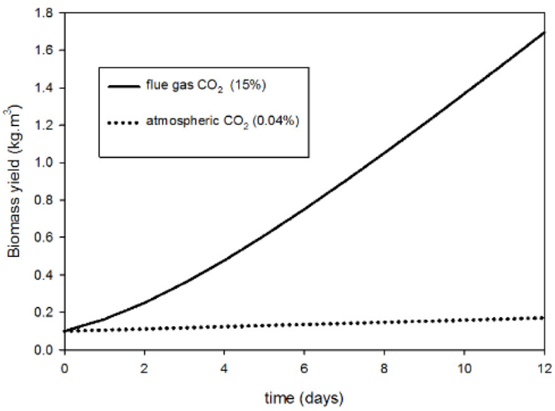

Fig. 1. Microalgae biomass yield during 12 days of cultivation.

An experimental study conducted by Kumar et al. [9] to verify the growth of *Chlorella* sp. using different kind of wastewater and 6% of industrial CO_2 emissions has shown average biomass productivity of 0.6 g/L, similar to that found in this study. Although the simulated parameters have not considered the presence of other potentially toxic gases to microalgal growth, some studies in the literature have verified that a couple of microalgae strains support certain concentrations of these gases and sustain considerable growth. In the same study conducted by Kumar et al. [9], a concentration of 180 ppm of SOx and 250 ppm of NOx was considered, and the microalgae cultivation has achieved a reasonably high biomass yield.

On the other hand, Kumar et al. [17], have studied the growth of *Chlorella sorokiniana* for CO_2 sequestration from industrial flue gas containing 15.6% of CO_2 and 120 mg L^{-1} of H_2S and concluded that the high concentration of CO_2 and H_2S had an inhibitory effect on the growth of *C. sorokiniana*, and suggested a previous treatment on the flue gas before injecting it to the microalgae culture medium to maximize the algal biomass production.

3.2. Carbon capture case study: Cement plant flue gas mitigation

The cement industry used as a case study has a total area of 9.8 ha with an available zone of 3.8 ha for the installation of microalgae upstream and downstream facilities. An area of 3.3 ha was destined for the operation of the PBRs, and the remaining 0.5 ha for the downstream process of biomass. The PBR designed for microalgae cultivation was set to have a tubular shape. The configuration of PBR consists of 20 tubes distanced at 0.115 m vertically, 5 rows of a set of vertical line tubes distanced at 0.25 m. The dimensions of each PBR module are 60.36 m long, 2.23 m in width, and 3.49 m in height (Fig. 2A). The total volume of each PBR module is 34 m^3. To support this volume, an area of 134.3 m^2 of soil is occupied. With an available area of 3.3 ha, it would be possible to build 150 PBR modules totalizing 5101 m^3 of culture (Fig. 2B).

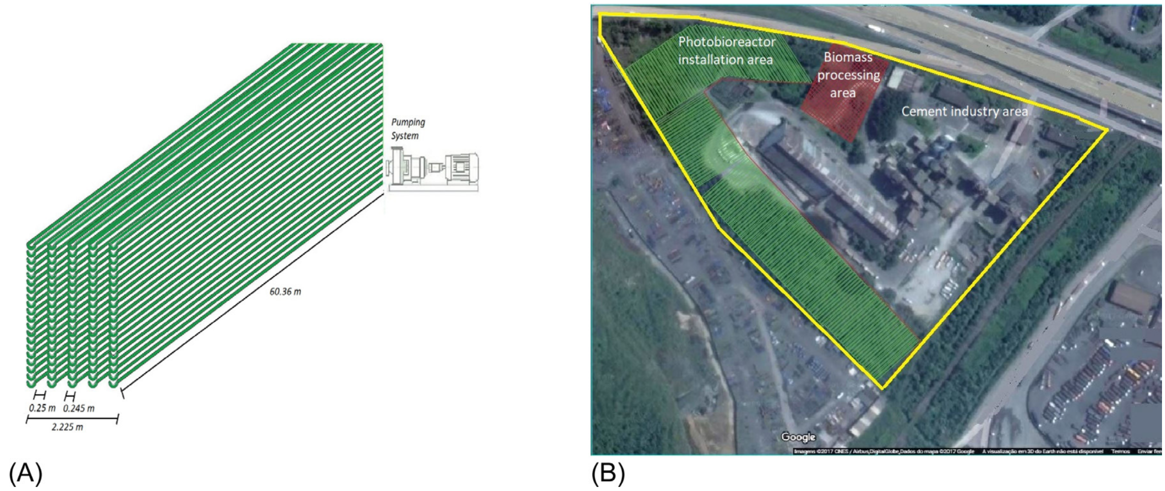

Fig. 2. Industrial microalgae cultivation process and biodiesel production plant. (A) Tubular photobioreactor module conception. (B) Upper view of the cement plant indicating the total area to be used for microalgae cultivation and processing.
Source: Adapted from Google earth [18].

The total amount of biomass that it will be possible to achieve when microalgae are cultivated under atmospheric CO_2 is 473 tons of biomass per year. Otherwise, when 15% of CO_2 from industrial flue gas is used to feed the microalgae cultivation system, it would be possible to achieve a maximum of 1268 tons of biomass per year. Considering the proposed model, it is necessary about 1 kg of CO_2 for the production of 1 kg of dry biomass of *C. vulgaris* [19] which corresponds to mitigation of about 0.68 kg m^{-3} of CO_2 per day of microalgae growth. Therefore, these values also correspond to an amount of 1268 tCO_2 $year^{-1}$ of mitigated CO_2 using 15% of CO_2 from the flue gas to microalgae cultivation.

Considering the base scenario of this study, which is used fossil fuel as the primary energy source in the cement production system, the total CO_2 mitigation corresponds to 5.65% of the annual emissions, when 15% of industrial flue CO_2 is applied to the culture medium. Otherwise, in the CDM scenario, in which the use of fossil fuel was replaced by natural gas on the CDM project, the additional algae-based CO_2 mitigation reaches the value of 10.57%.

Overall, the algae-based carbon capture efficiency depends on the microalgae strain, type of cultivation system, the CO_2 concentration, design, and operating conditions of PBR. The study conducted by Clément-Larosière et al. [20] has shown that *C. vulgaris* is a strong candidate for industrial CO_2 remediation, obtained a maximum CO_2 removal rate of 0.98 gCO_2 L^{-1} d^{-1} and the highest biomass concentration of 4.14 g DW L^{-1} at 13% CO_2. Seyed Hosseini et al. [21] have studied the possibility of using *C. vulgaris* for CO_2 sequestration in Alberta, Canada, using wastewater as a culture medium and in the presence of 20% of CO_2 in the total volume of the PBR. The authors have achieved mitigation of 100% of CO_2 during 36 h of cultivation. Klinthong et al. [22] have achieved a maximum CO_2 removal efficiency of 55.3% at 0.15% of CO_2 in the culture medium of *C. vulgaris*.

Furthermore, Quelhas et al. [23] have analyzed the productivity of *Phaeodactylum tricornutum* in different PBR volume to CO_2 biofixation and the results showed that the CO_2 mitigation efficiencies ranged 41 to 60% in cultures where the CO_2 was introduced into the PBR, corresponding to 2.3 to 2.5 g of fixed CO_2 per g of biomass.

A recent study published by Llamas et al. [24] reported that the utilization of microalgae carbon capture technology could be a promising tool to apply in the future carbon pricing mechanism foreseen in the Paris agreement.

3.3. Biodiesel production

In this study it was analyzed the potential of producing biodiesel from microalgae biomass after harvesting and drying the biomass cultivated at 15% of CO_2. The production of biodiesel was performed using the modified method described in [15]. The total content of lipid for *C. vulgaris* considered in this study was 22% and the maximum volume of lipid that can be recovered by the microalgae biomass using the SC-CO_2 is 2090 kg year^{-1}. After lipid extraction, the oil is refined and biodiesel production is performed by using the alkali-catalyzed transesterification reaction. The maximum potential amount of biodiesel achieved is 2037 kg year^{-1} or 2317 L year^{-1} using an oil density of 880 kg m^{-3}.

Several studies have analyzed the production of microalgal lipids to biodiesel production. Branco-Vieira et al. [10] have analyzed the production of *Phaeodactylum tricornutum* for biodiesel production using atmospheric CO_2 during 14 days of cultivation and achieved average productivity of 0.13 kg m^{-3} d^{-1}. Branco-Vieira et al. [15] modeled the annual production of 181 tons of algal biomass per year, using the same productivity of 0.13 kg m^{-3} d^{-1}, and estimated an amount of 15 tons of biodiesel per year.

Xia et al. [25] have analyzed the lipid productivity of *Chlorella sorokiniana* cultivated in a range of 5%–15% of CO_2 and found maximal productivities at 10% CO_2. Yusof et al. [26] have investigated the possibility of modifying lipid contents in *C. vulgaris* by varying the amount of carbon dioxide and light. The authors found that some fatty acids increased when the amount of CO_2 was raised from 1 to 10%.

Indeed, the microalgae ability of industrial carbon capture, considerably improves the environmental performance and the carbon footprint of the process. Additionally, the valorization of the microalgae compounds into the appropriate form of biofuel and other algal added-value products contributes to increase the economic valorization of the process. The possibility of using microalgae cultivation for carbon biofixation contributes to the sustainable development of any industrial bioprocess, making this approach a great and competitive promise to the carbon market foreseen in the Paris agreement.

4. Conclusions

The algae-based carbon capture alternative was analyzed in this study, using two different scenarios of CO_2 mitigation from a cement plant located in Cubatão, São Paulo, Brazil, and the microalgae biomass production was used for biodiesel production. Simulations indicated that *C. vulgaris* exhibited promising growth using 15% of CO_2 from cement industry flue gas, can generate a maximum microalgae biomass of about 1268 tCO_2 year^{-1}, reaching the same amount of CO_2 mitigation. These results indicated that the total CO_2 mitigation corresponds to 5.65% and 10.57% of the annual emissions in the base and CDM scenarios, respectively. The total amount of biodiesel produced was about 2317 L year^{-1}. In this regard, the utilization of microalgae-based CO_2 biofixation was identified as a good alternative to traditional carbon capture technologies, since microalgae biomass is highly versatile and can be used to generate valuable compounds and biofuels, and could be a competitive alternative in the future emission rights market.

CRediT authorship contribution statement

M. Branco-Vieira: Investigation, Formal analysis, Validation, Writing – original draft. **M.P.C. Lopes:** Investigation, Formal analysis, Validation, Writing – review & editing. **N. Caetano:** Supervision, Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] UNFCCC. Paris agreement [WWW Document]. 2015.
[2] UNFCCC. Paris agreement - Brazil's nationally determined contribution (NDC) [WWW Document]. 2020.
[3] EPE. Balanço Energético Nacional: Relatório Síntese. 2021.
[4] Izumi Y, Iizuka A, Ho H-J. Calculation of greenhouse gas emissions for a carbon recycling system using mineral carbon capture and utilization technology in the cement industry. J Clean Prod 2021;127618. http://dx.doi.org/10.1016/j.jclepro.2021.127618.
[5] SNIC. Roadmap tecnológico do cimento: potencial de redução das emissões de carbono da indústria do cimento brasileira até 2050 [WWW Document]. 2019.
[6] Cimentoorg. Cimento no Brasil [WWW Document]. 2017.
[7] Ruiz-Ruiz P, Estrada A, Morales M. Carbon dioxide capture and utilization using microalgae. In: Handbook of microalgae-based processes and products. Elsevier; 2020, p. 185–206. http://dx.doi.org/10.1016/b978-0-12-818536-0.00008-7.
[8] Ferreira A, Reis A, Vidovic S, Vladic J, Gkelis S, Melkonyan L, Avetisova G, Congestri R, Acién A, Muñoz R, Collet P, Gouveia L. Combining microalgae-based wastewater treatment with biofuel and bio-based production in the frame of a biorefinery. In: Hallmann A, Rampelotto P, editors. Grand Challenges in Algae Biotechnology. Cham: Springer; 2019, p. 319–69.
[9] Kumar PK, Krishna SV, Naidu SS, Verma K, Bhagawan D, Himabindu V. Biomass production from microalgae Chlorella grown in sewage, kitchen wastewater using industrial CO_2 emissions: Comparative study. Carbon Resour Convers 2019;2:126–33. http://dx.doi.org/10.1016/j.crcon.2019.06.002.
[10] Branco-Vieira M, San Martin S, Agurto C, Santos M, Freitas M, Mata T, et al. Potential of *Phaeodactylum tricornutum* for biodiesel production under natural conditions in Chile. Energies 2018;11(54). http://dx.doi.org/10.3390/en11010054.
[11] Caetano NS, Melo AR, Gorgich M, Branco-Vieira M, Martins AA, Mata TM. Influence of cultivation conditions on the bioenergy potential and bio-compounds of *Chlorella vulgaris*. Energy Rep 2020;6:378–84. http://dx.doi.org/10.1016/j.egyr.2019.08.076.
[12] Chinnasamy S, Ramakrishnan B, Bhatnagar A, Das KC. Biomass production potential of a wastewater alga *Chlorella vulgaris* ARC 1 under elevated levels of CO_2 and temperature. Int J Mol Sci 2009;10(518). http://dx.doi.org/10.3390/ijms10020518.
[13] Mountourakis F, Papazi A, Kotzabasis K. The microalga *Chlorella vulgaris* as a natural bioenergetic system for effective CO_2 mitigation—New perspectives against global warming. Symmetry (Basel) 2021;13(997). http://dx.doi.org/10.3390/sym13060997.
[14] He L, Subramanian VR, Tang YJ. Experimental analysis and model-based optimization of microalgae growth in photo-bioreactors using flue gas. Biomass Bioenergy 2012;41:131–8. http://dx.doi.org/10.1016/j.biombioe.2012.02.025.
[15] Branco-Vieira M, Costa DMB, Mata TM, Martins AA, Freitas MAV, Caetano NS. Environmental assessment of industrial production of microalgal biodiesel in central-south Chile. J Clean Prod 2020;266:121756. http://dx.doi.org/10.1016/j.jclepro.2020.121756.
[16] Becker EW. Micro-algae as a source of protein. Biotechnol Adv 2007;25:207–10. http://dx.doi.org/10.1016/j.biotechadv.2006.11.002.
[17] Kumar K, Banerjee D, Das D. Carbon dioxide sequestration from industrial flue gas by *Chlorella sorokiniana*. Bioresour Technol 2014;152:225–33. http://dx.doi.org/10.1016/j.biortech.2013.10.098.
[18] Google earth. Cubatão, São Paulo, Brazil. 2017.
[19] Doucha J, Straka F, Lívanský K. Utilization of flue gas for cultivation of microalgae *Chlorella* sp. in an outdoor open thin-layer photobioreactor. J Appl Phycol 2005;17:403–12. http://dx.doi.org/10.1007/s10811-005-8701-7.
[20] Clément-Larosière B, Lopes F, Gonçalves A, Taidi B, Benedetti M, Minier M, et al. Carbon dioxide biofixation by *Chlorella vulgaris* at different CO_2 concentrations and light intensities. Eng Life Sci 2014;14:509–19. http://dx.doi.org/10.1002/elsc.201200212.
[21] Seyed Hosseini N, Shang H, Scott JA. Biosequestration of industrial off-gas CO_2 for enhanced lipid productivity in open microalgae cultivation systems. Renew Sustain Energy Rev 2018. http://dx.doi.org/10.1016/j.rser.2018.04.086.
[22] Klinthong W, Yang YH, Huang CH, Tan CS. A review: Microalgae and their applications in CO_2 capture and renewable energy. Aerosol Air Qual Res 2015. http://dx.doi.org/10.4209/aaqr.2014.11.0299.
[23] Quelhas PM, Trovão M, Silva JT, Machado A, Santos T, Pereira H, et al. Industrial production of *Phaeodactylum tricornutum* for CO_2 mitigation: biomass productivity and photosynthetic efficiency using photobioreactors of different volumes. J Appl Phycol 2019;31:2187–96. http://dx.doi.org/10.1007/s10811-019-1750-0.
[24] Llamas B, Suárez-Rodríguez MC, González-López CV, Mora P, Acién FG. Techno-economic analysis of microalgae related processes for CO_2 bio-fixation. Algal Res 2021;57:102339. http://dx.doi.org/10.1016/j.algal.2021.102339.
[25] Xia JL, Gong SQ, Jin XJ, Wan MX, Nie ZY. Effects of simulated flue gases on growth and lipid production of *Chlorella sorokiniana* CS-01. J Cent South Univ 2013;20:730–6. http://dx.doi.org/10.1007/s11771-013-1541-8.
[26] Yusof YAM, Basari JMH, Mukti NA, Sabuddin R, Muda AR, Sulaiman S, et al. Fatty acids composition of microalgae *Chlorella vulgaris* can be modulated by varying carbon dioxide concentration in outdoor culture. African J Biotechnol 2011;10:13536–42. http://dx.doi.org/10.5897/ajb11.1602.