EFB Bioeconomy Journal 4 (2024) 100067

Contents lists available at ScienceDirect

EFB Bioeconomy Journal

journal homepage: www.elsevier.com/locate/bioeco

The potential of microalgae for carbon capture and sequestration

Marcella Fernandes de Souza[a,*], Erik Meers[a], Silvio Mangini[b]

[a] Laboratory for Bioresource Recovery (RE-Source), Department of Green Chemistry and Technology, Faculty of Bioscience Engineering, Ghent University, Coupure Links 653, Ghent 9000, Belgium

[b] Archimede Ricerche srl, Corso Italia 220, Camporosso 18033, Italy

ARTICLE INFO

Keywords:
Microalgae
CO_2 sequestration
CO_2 capture
CO_2 neutrality
Industrial symbiosis
Circular economy

ABSTRACT

Microalgae have been highlighted as a contributor to CO_2 sequestration due to their efficient photosynthetic system. However, calculations on their actual potential for CO_2 sequestration are often lacking. Here, we calculated the potential of microalgae for the capture of CO_2 by integrating it with a large emitter (gas-based energy plant) and a low emitter (dairy farms), and also discussed if such integrated systems can be considered as carbon sequesters given that the final use of the biomass often quickly releases the captured CO_2. Moreover, the CO_2 footprint of microalgal systems is highlighted as a critical point of attention for future developments. Such considerations are of utmost importance to avoid false promises that ultimately harm this sector, as large investments are made following untruthful claims that, when proven wrong, result in a loss of interest. Finally, key definitions are proposed to improve clarity and help in such discussions.

1. The need for CO_2 capture

Several environmental deals have been proposed and signed in the past decades to ensure that the global temperature rise resulting from greenhouse gas (GHG) emissions does not surpass 1.5–2 °C (UNFCCC, 2024; European Commission, 2024). Such deals mostly focus on reducing the environmental footprint of current processes. However, even if a significant decrease in GHG emissions is achieved, human activities will continue adding to the already released GHGs that accumulate in our atmosphere.

Therefore, not only the reduction of emissions but also the capture and storage (i.e., sequestration) of CO_2 from the atmosphere have been the target of intense research to reach the current climate targets. It is estimated that, by 2050, we should aim at annually removing around 8 Gt of CO_2 from our atmosphere (Dowell et al., 2017), with a more modest start at 500 Mt/year by 2030 (Rockström et al., 1979). From this, a question arises: can microalgae have a significant impact on this target?

To answer this question, we have calculated the potential of carbon capture by microalgae, which shows some positive results. However, when considering the GHG emissions of microalgal cultivation, a different conclusion is reached indicating that microalgae might be a source rather than a sink for CO_2 emissions. Therefore, it is imperative to assess carefully the whole picture before advertising microalgae as the solution to our environmental problems and once more cause the failure of the microalgal sector due to unfulfilled expectations.

2. Carbon capture potential of microalgae

The carbon content of microalgae is usually 0.5 kg C/kg dry weight (DW) (Derakhshandeh et al., 2021), leading to an average carbon capture potential of 1.8 kg CO_2/kg algae DW. The global microalgae production in 2019 (last updated known value) was 56,456 t (FAO, 2021). This is expected to be somewhat underestimated, as capturing data from all producers is challenging. Therefore, we will assume a round number of 60,000 t The algae market has been expanding with a compound annual growth rate of 4.3 % (FAO, 2020). Market value is not directly correlated with production volume, as a certain compound can become more valuable in the market without an increase in production. However, as no studies were found with a projection of microalgal production increase, the market growth projection was used to estimate the volume of algae produced in 2030, reaching an estimated production of 95,000 t

Therefore, by 2030, the global microalgae production would be expected to capture 171,000 t of CO_2 (0.171 Mt) yearly, contributing to only 0.03 % of the 500 Mt/year target. Nevertheless, awareness of microalgae's potential and benefits has been exponentially growing, especially in the EU, and thus a larger increase in the algae production

* Corresponding author.
E-mail address: marcella.fernandesdesouza@ugent.be (M.F. Souza).

https://doi.org/10.1016/j.bioeco.2024.100067
Received 29 April 2024; Received in revised form 7 June 2024; Accepted 7 June 2024
Available online 8 June 2024

capacity can be expected by 2030 if this trend continues.

To capture 50 Mt/year of CO_2 (10 % of the intended target), around 28 Mt of microalgae should be annually produced (Fig. 1). The productivity of microalgae strongly depends on the species being cultivated, the location (intensity of solar radiation), and the type of cultivation system used (van Duinen et al., 2020). Theoretical yields ranging from 10 to 100 t/(ha.year) (Tredici, 2010) should be regarded as the upper limits of practical yields. Therefore, between 280,000 and 2.8 million ha of land should be used for microalgal cultivation to capture 10 % of the target value by 2030.

The EU has estimated that around 10 million ha are potentially available for algae cultivation on land (van Duinen et al., 2020), showing that surface is not the first problem for the expansion of algae cultivation. Moreover, algae can be cultivated on marginal or even non-arable land and marine species can use seawater instead of freshwater, also minimizing land and water constraints for large-scale algae implementation.

The numbers shown thus far indicate that, even though a large expansion of the current microalgal industry is necessary, producing the amount of microalgal biomass required to contribute significantly to carbon capture seems feasible. For this, it is suggested that microalgae cultivation facilities should be set up in highly insolated coastal regions (tropical areas, e.g., Africa and South America) to boost productivity and promote easy access to water, and near CO_2 sources, promoting the concept of industrial symbiosis.

3. Industrial symbiosis for carbon capture by microalgae

To better understand the potential for industrial symbiosis, which is usually advocated when proposing microalgae for CO_2 sequestration, we have calculated the potential of microalgae to capture the CO_2 produced by large-scale electricity-producing plants and local-scale dairy farms.

Electricity and heat generation is the sector with the highest CO_2 emissions in the world, with a natural gas power plant emitting 0.39 kg CO_2 per kWh produced (US Energy Information Administration, 2024). A large gas power plant in the EU has an average capacity of 1500 MW (Statista, 2023), emitting 585 tons of CO_2 per hour (around 5 Mt/year). Therefore, between 28,000 and 280,000 ha would be needed for algae cultivation to capture all the CO_2 produced by the plant, when the plant itself only occupies around 0.15 ha (Ritchie, 2022).

Another possibility is to focus on local decentralized algae facilities, for instance, to capture the CO_2 generated from an anaerobic digestion system at a dairy farm. Dairy farms located in colder regions keep their cattle in barns for a large portion of the year, resulting in a significant amount of manure produced in a closed environment where it can be collected. Two dairy farms in Flanders were contacted to provide real numbers for these calculations. The first one is a 150-ha farm digesting around 25,000 t fresh matter (FM)/year of manure with the production of around 845,000 kg CO_2 recovered directly from the biogas. The second is a 68-ha farm digesting around 880 t FM/year of manure with the production of around 53,500 kg CO_2 after the combustion of the biogas to produce heat and electricity. To capture the CO_2 generated by each farm, 460 and 29 t of algae would have to be produced in each farm, respectively. Taking into consideration an average algae productivity of 50 t/ha, less than 10 % of the total area of each farm would be needed to meet the calculated volume, which might be feasible to implement.

Therefore, microalgae could contribute to some extent to carbon capture. However, they might be more recommended for synergies with businesses having a reduced CO_2 footprint.

4. CO_2 emissions by microalgae cultivation and processing

One important aspect that seems to be often forgotten is that most of the proposed uses for microalgae, such as food, feed, and fuels, would quickly emit the captured CO_2 back into the atmosphere during the use and degradation of these products. Therefore, even if microalgal production would be expanded to the levels previously discussed, most of the produced biomass would not qualify as a carbon sink as the captured CO_2 would shortly be returned to the atmosphere.

There are less-promoted applications for microalgae biomass that could result in carbon capture. For instance, the use of microalgae in cement (Nur and Dewi, 2024) or as a feedstock for biochar production and subsequent use as a soil amendment (Sayre, 2010) could entrap carbon in a stable form for decades if not centuries. Does this mean that at least a part of the produced microalgae can assist in CO_2 sequestration?

Unfortunately, this does not seem to be the case. The calculations shown thus far did not consider the emission of CO_2 by the microalgae production process. Zhang et al. (2023) calculated a net emission of up to 1.5 kg CO_2 per kg CO_2 captured (Zhang et al., 2023). Another recent study also concluded that the cultivation of cyanobacteria would result

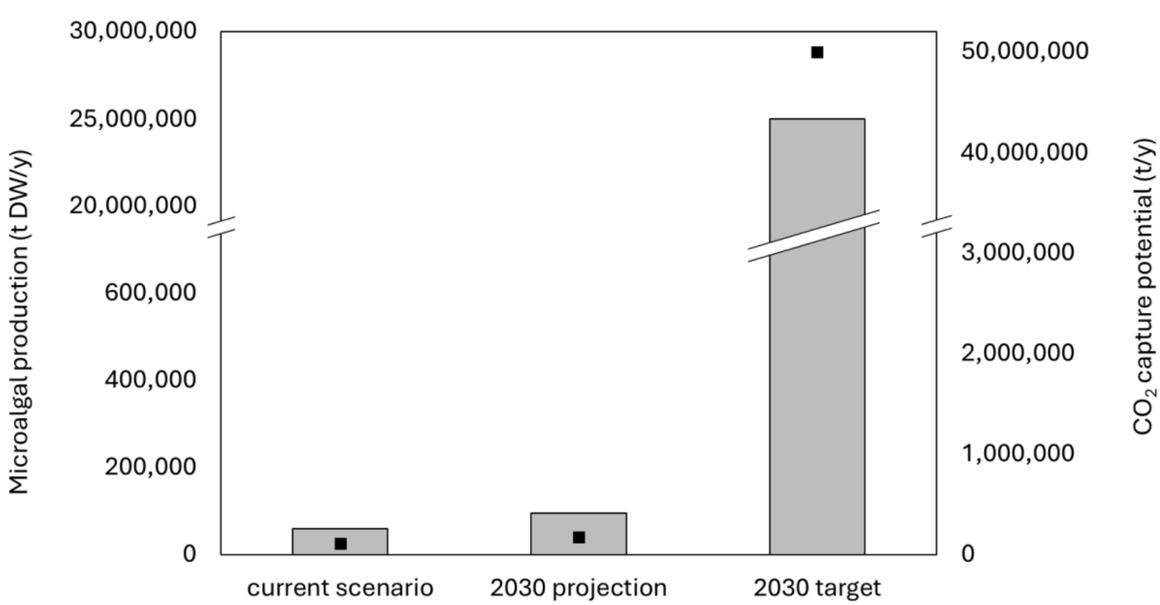

Fig. 1. Current and projected microalgal production (bars) and CO_2 capture potential of the produced microalgae (squares). The 2030 target was calculated assuming that microalgae would be sufficiently produced to capture 50 Mt CO_2 per year.

in the net production of 13.5 kg CO_2 eq/kg algae DW (Quintero et al., 2021). Thus, depending on the nutrients and energy supplies used for microalgal cultivation, the entire process can become a source of CO_2 instead of a way to remove it from the atmosphere.

Therefore, it seems that the potential of carbon sequestration by microalgae is limited, and efforts to promote microalgal technology should be careful in their assumptions and promises. Realistic numbers and projections are needed, or we will once more see the rise and collapse of the algae industry as it happened for the biofuels algae bubble in the early 2000s (Wesoff, 2017).

5. The way forward

It seems that the current technology cannot result in carbon sequestration by microalgae, and even the promised carbon neutrality seems far from real. Therefore, current efforts in microalgae R&D should focus on improving the energy efficiency of microalgal systems while other fields investigate reducing the carbon footprint of our energy sources altogether. For instance, using solar energy for microalgae production could result in a 50 % reduction in carbon emissions (Morales et al., 2019). Industrial symbiosis with exhaust heat producers, such as anaerobic digestion plants, could also be beneficial.

Nitrogen also has a great carbon footprint due to the Haber-Bosch process used for its production, which accounts for 1 % of the global energy consumption and CO_2 emissions. Hence, the investigation of nutrient recycling from waste streams could reduce the carbon footprint of microalgal cultivation, helping it become more carbon neutral.

Nevertheless, even if carbon neutrality is not achieved for microalgal systems, they should be compared against the current processes for obtaining the target product(s). If at least a reduced carbon footprint is achieved when compared to petroleum-based processes and other non-renewable sources, there is already a gain in environmental sustainability that might be sufficient for some fields.

With all these considerations, it seems that carbon sequestration discourses should not highlight microalgae cultivation as a suitable technique for this intent. Carbon neutrality, or at least a reduced carbon footprint, should be our goal when promoting microalgae as an environmentally friendly biomass for the bioeconomy. We encourage others to do the same exercise for macroalgae to shed light on their possibilities as carbon sinks or at least as carbon-neutral feedstock. We also invite researchers working in the field to submit their thoughts in agreement or disagreement with the contents of this paper to the EFB Bioeconomy Journal to create a dialogue that will help us further improve the microalgae field and its environmental advantages.

Finally, the use of adequate terminology is necessary for the exchanges around this topic, and we would like to propose the following definitions to be adopted by the (micro)algae community to improve clarity in its communications, further advancing the previous definitions by Li et al. (2023).

CO_2 capture: separation of CO_2 in such a manner as to produce a concentrated stream of CO_2 that can readily be transported for storage

SOURCE: ISO/TR 27,912 *Carbon dioxide capture — Carbon dioxide capture systems, technologies and processes*

CO_2 capture rate: (captured CO_2 mass flow rate)/(inlet CO_2 mass flow rate) in the CO_2 capture system; CO_2 capture rate is also named CO_2 fixation efficiency

SOURCE: ISO/TR 27,912, ibid.

Carbon sequestration: durable carbon capture based on removals that are permanent or provide sufficiently long-term storage (especially when used to offset GHGs with long atmospheric lifespans such as carbon dioxide) and include plans to manage potential impermanence

SOURCE: adapted from ISO IWA 42:2002, ibid.

GHG removal (aka sink): withdrawal of a greenhouse gas from the atmosphere as a result of deliberate human activities; types of removals include afforestation, building with biomass (plant-based material used in construction), direct air carbon capture and storage, habitat restoration, soil carbon capture, enhanced weathering (mixing soil with crushed rock), bioenergy with carbon capture and storage. In this document, the term "removal" includes storage, including the durable storage of CO_2, referred to as "carbon dioxide removal" by the IPCC.

Carbon footprint (CFP): sum of GHG emissions and GHG removals in a product system, expressed as CO_2 equivalents and based on a life cycle assessment using the single impact category of climate change

SOURCE: EN ISO 14,067:2018, 3.1.1.1 – modified.

SOURCE: ISO IWA 42:2002, ibid.

GHG mitigation: human intervention to reduce greenhouse gas emissions or enhance sinks

SOURCE: ISO IWA 42:2002, ibid.

Statement for algae farming credit claim

Algae farming claim shall provide net zero evidence and follow EU Regulation on Carbon Removals certification (CRC)

CRediT authorship contribution statement

Marcella Fernandes de Souza: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Erik Meers:** Writing – review & editing, Conceptualization. **Silvio Mangini:** Writing – review & editing, Writing – original draft, Conceptualization.

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.

Acknowledgments

The authors would like to thank the EU4Algae platform for creating an opportunity for the first and last authors to meet during a working group meeting to discuss CO_2 sequestration by algae. This work did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

UNFCCC, The Paris agreement, (n.d.). https://unfccc.int/process-and-meetings/the-paris-agreement (accessed February 12, 2024).
European Commission, The European green deal, (n.d.). https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en (accessed February 12, 2024).
Dowell, N.M., Fennell, P.S., Shah, N., Maitland, G.C., 2017. The role of CO2 capture and utilization in mitigating climate change. Nat. Clim. Chang. 7, 243–249. https://doi.org/10.1038/nclimate3231.
Rockström, J., Gaffney, O., Rogelj, J., Meinshausen, M., Nakicenovic, N., Schellnhuber, H.J., 1979. A roadmap for rapid decarbonization. Science (1979) 355 (2017), 1269–1271. https://doi.org/10.1126/science.aah3443.
Derakhshandeh, M., Atici, T., Tezcan Un, U., 2021. Evaluation of wild-type microalgae species biomass as carbon dioxide sink and renewable energy resource. Waste BioMass Valoriz. 12, 105–121. https://doi.org/10.1007/s12649-020-00969-8.
FAO, Global seaweeds and microalgae production, 1950–2019, 2021. https://www.fao.org/3/cb4579en/cb4579en.pdf (accessed February 12, 2024).
Business Insider, $4.6 Billion worldwide microalgae industry to 2027, (2020). https://markets.businessinsider.com/news/stocks/4-6-billion-worldwide-microalgae-industry-to-2027-impact-of-covid-19-on-the-market-1029602600 (accessed February 12, 2024).
R. van Duinen, C. Rivière, P. Strosser, J.W. Dijkstra, S. Rios, S. Luzzi, A. Bruhn, M.Olaf Nielsen, C. Göke, M. Bhagya Samarasinghe, E. Chassé, C.H. Nielsen, M. Thomsen, Algae and climate – final report, 2020. 10.2926/208135.
Tredici, M.R., 2010. Photobiology of microalgae mass cultures: understanding the tools for the next green revolution. Biofuels. 1, 143–162. https://doi.org/10.4155/bfs.09.10.
US Energy Information Administration, Frequently Asked Questions (FAQS), 2024 (2024). https://www.eia.gov/tools/faqs/faq.php?id=74&t=11 (accessed February 12, 2024).
Statista, Largest operational natural gas power plants by capacity in Europe as of 2021, (2023). https://www.statista.com/statistics/1263453/largest-operational-gas-plants-by-capacity-europe/(accessed February 12, 2024).
H. Ritchie, How does the land use of different electricity sources compare?, (2022). https://ourworldindata.org/land-use-per-energy-source#article-citation (accessed February 12, 2024).

Nur, M.M.A., Dewi, R.N., 2024. Opportunities and challenges of microalgae in biocement production and self-repair mechanisms. Biocatal. Agric. Biotechnol. 56, 103048 https://doi.org/10.1016/j.bcab.2024.103048.

Sayre, R., 2010. Microalgae: the potential for carbon capture. Bioscience 60, 722–727. https://doi.org/10.1525/bio.2010.60.9.9.

Zhang, X., An, L., Tian, J., Ji, B., Lu, J., Liu, Y., 2023. Microalgal capture of carbon dioxide: a carbon sink or source? Bioresour. Technol. 390, 129824 https://doi.org/10.1016/j.biortech.2023.129824.

Quintero, C.D., Ventura, A., Lépine, O., Pruvost, J., 2021. Eco-design of spirulina solar cultivation: key aspects to reduce environmental impacts using life cycle assessment. J. Clean. Prod. 299, 126741 https://doi.org/10.1016/j.jclepro.2021.126741.

E. Wesoff, Hard lessons from the great algae biofuel bubble, (2017). https://www.greentechmedia.com/articles/read/lessons-from-the-great-algae-biofuel-bubble (accessed February 12, 2024).

Morales, M., Hélias, A., Bernard, O., 2019. Optimal integration of microalgae production with photovoltaic panels: environmental impacts and energy balance. Biotechnol. Biofuels 12, 239. https://doi.org/10.1186/s13068-019-1579-4.

Li, S., Chang, H., Zhang, S., Ho, S.-H., 2023. Production of sustainable biofuels from microalgae with CO2 bio-sequestration and life cycle assessment. Environ. Res. 227, 115730 https://doi.org/10.1016/j.envres.2023.115730.