SASTA OLIPHANT SCIENCE AWARDS

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Science Writing

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THE APPLICATIONS AND LIMITATIONS OF ALGAL BIOREACTORS AND ALGAL BIOFUELS

INTRODUCTION

Climate change is one of the biggest challenges of our time and resulting heatwaves combined with long periods of drought were linked to Australian bushfires of unprecedented magnitude in the past few years, burning over 12 million acres of land.[1] The UN estimates that burning fossil fuels accounts for 76% of our greenhouse gas emissions (mainly carbon dioxide – CO_2), which are the main cause for climate change.[2] Despite the knowledge about the detrimental effects of fossil fuels, it has been predicted by the International Energy Agency (IEA) that they will still account for 77% of all fuels used by 2040.[3] It is therefore critical to develop novel effective ways to reduce greenhouse gas emissions and decrease the atmospheric CO_2 burden.

The application of algae could be the solution against climate change as they absorb large amounts of CO_2 (about 1.8kg of CO_2 per kg of algae biomass gained) and can be used for the production of sustainable ecofriendly fuel.[4] In particular hydrogen produced from algae as a clean source of energy could mitigate the environmental problems caused by the use of fossil fuels. While until recently the growth of algae had its technical limitations, improvements in algae bioreactor technology and culture conditions now allow an upscaling of algae production. The application of algae could therefore have the potential to fundamentally change the way energy is produced, while reducing atmospheric CO_2 concentrations.[5]

BACKGROUND

Algae are a diverse group of aquatic organisms ranging from large seaweed (macroalgae) to microscopic organisms (microalgae) such as *Spirogyra* which can be seen in figures 1 + 2.

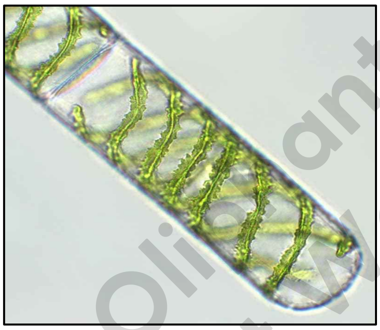

Figure 1. Algae Spirogyra under a light microscope (x40)
(Aytar, E., 2020. *Spirogyra Sp. Algae Under Microscopic View x40 - Chlorophyta.* [image] Available at: <https://www.dreamstime.com/spirogyra-sp-algae-under-microscopic-view-chlorophyta-image179352431> [Accessed 1 July 2021])

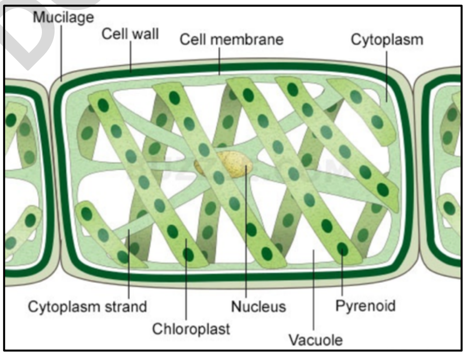

Figure 2. Algae Spirogyra cell diagram
(QS study, 2020. *Diagram Of Spirogyra*. [image] Available at: <https://www.qsstudy.com/biology/describe-with-labelled-diagram-the-structure-of-spirogyra> [Accessed 1 July 2021])

Most algae are capable of photosynthesis and utilize light energy to convert CO_2 and water into biomass and oxygen.[6] The chemical reaction for photosynthesis can be seen below.

$$6CO_2 + 6H_2O \xrightarrow{Chlorophyll\ and\ light} C_6H_{12}O_6 + 6O_2$$

[1] United Nations Sustainable Development. 2020. *Climate Change*. [online] Available at: <https://www.un.org/sustainabledevelopment/climate-change/> [Accessed 28 June 2021].
[2] Gobler, C., 2020. Climate Change and Harmful Algal Blooms: Insights and perspective. *Harmful Algae*, 91, p.101731.
[3] Steg, L., 2018. Limiting climate change requires research on climate action. *Nature Climate Change*, 8(9), pp.759-761.
[4] Budgen, J. and Le-Clech, P., 2020. Assessment of brewery wastewater treatment by an attached growth bioreactor. *H2Open Journal*, 3(1), pp.32-45.
[5] Ibid
[6] Steg, L., 2018. Limiting climate change requires research on climate action. *Nature Climate Change*, 8(9), pp.759-761.

Algae sequester CO_2 naturally during photosynthesis and approximately half of the algae biomass dry weight consists of carbon which is derived from CO_2 (figure 4).[7,8] Thus, photosynthetic algae have the potential to be used to sequestrate CO_2 out of the atmosphere.[9] Microalgae are of particular interest for researchers as they double their biomass every 24 hours and during their exponential growth phase can even double in mass as quickly as every 3.5 hours.[10]

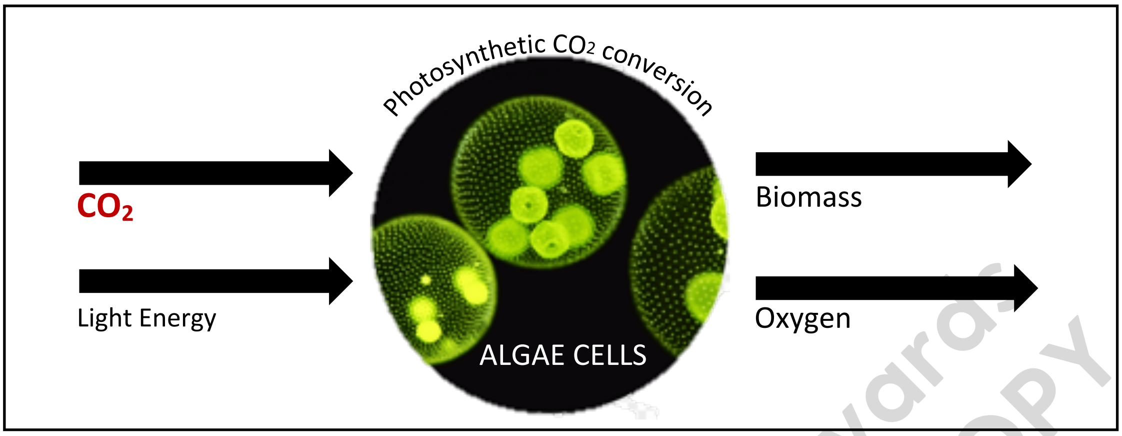

Figure 4. Photosynthetic conversion of CO_2 into microalgae biomass
Adapted from: Kativu, E., 2014. *Carbon Dioxide Absorption Using Fresh Water Algae And Identifying Potential Uses Of Algal Biomass.* [online] Core.ac.uk. Available at: <https://core.ac.uk/reader/39669356> [Accessed 20 July 2021].

Large-scale microalgae culture has been successfully achieved with green algae species such as *chlorella* and *spirulina.*[11] Open ponds are the most common means of cultivating algae as they are simple to construct and are low cost.[12] However, they face a variety of limitations, including low biomass conversion and loss of CO_2.[13] Therefore, for effective CO_2 sequestration and to maximise algae growth, photobioreactors have been developed. Photobioreactors contain large volumes of algae in an enclosed environment and vertical arrangement (figure 4).

Large-scale algae production still remains technically challenging, due to a variety of factors limiting algae culture (see table 1), as well as rapid, difficult to control algal growth.[14] However, recently the company Hypergiant from Texas, USA, developed an artificial intelligence (AI) bioreactor (figure 5) which not only uses AI to maximise algal growth by maintaining optimum temperatures and light intensities, but also monitors algal development without human intervention through computer learning.[15] Bioreactors such as the Hypergiant bioreactor allow the culture of algae in a controlled large-scale system for CO_2 sequestration and synthesis of products such as biofuel.[16]

Table 1. **Factors limiting microalgae growth**

Biotic factors	Presence of pathogens (viruses, bacteria and fungi) and competition from other algae.
Abiotic factors	Light, temperature, pH, salinity, presence of toxic chemicals, oxygen concentration, bioavailability of nutrients.

[7]Phillips, B., 2018. *Algae As Energy: A Look To The Future - Climate, Energy, And Society - College Of Liberal Arts - Auburn University*. [online] Cla.auburn.edu. Available at: <https://cla.auburn.edu/ces/energy/algae-as-energy-a-look-to-the-future/> [Accessed 21 July 2021].
[8]Steg, L., 2018. Limiting climate change requires research on climate action. *Nature Climate Change*, 8(9), pp.759-761.
[9] Ibid
[10]Marimuthu, D. and Jayaraman, A., 2018. Isolation and Growth Characterization of the Fresh Water Algae Chlorosarcinopsis Eremi on Different Growth Media. *Journal of Pure and Applied Microbiology*, 12(1), pp.389-392.
[11]Kativu, E., 2014. *Carbon Dioxide Absorption Using Fresh Water Algae And Identifying Potential Uses Of Algal Biomass.*. [online] Core.ac.uk. Available at: <https://core.ac.uk/reader/39669356> [Accessed 20 July 2021].
[12]Concas, A., Pisu, M. and Cao, G., 2018. Novel simulation model of the solar collector of BIOCOIL photobioreactors for CO2 sequestration with microalgae. *Chemical Engineering Journal*, 157(2-3), pp.297-303.
[13]Ibid
[14]Jalilian, N., Najafpour, G. and Khajouei, M., 2020. Macro and Micro Algae in Pollution Control and Biofuel Production – A Review. *ChemBioEng Reviews*, 7(1), pp.18-33.
[15]Hypergiant. 2020. *Green R&D -HYPERGIANT EOS BIOREACTOR*. [online] Available at: <https://www.hypergiant.com/green/> [Accessed 1 July 2021].
[16]Ibid

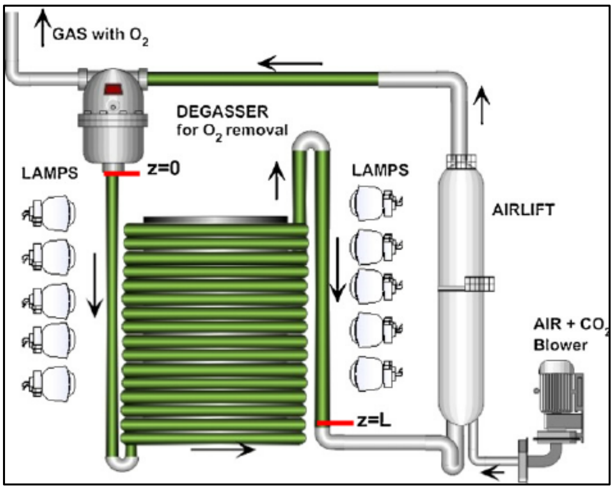

Figure 4. **Novel simulation model of photobioreactors for CO_2 sequestration of microalgae**
*(*Concas, A., Pisu, M. and Cao, G., 2018. Novel simulation model of the solar collector of BIOCOIL photobioreactors for CO_2 sequestration with microalgae. *Chemical Engineering Journal*, 157(2-3), pp.297-303.)

Figure 5. **Hypergiant AI Algae Bioreactor**
(Hypergiant 2020. HYPERGIANT EOS BIOREACTOR. Available at: https://www.hypergiant.com/green/)

The main biofuel produced from algae is biodiesel which relies on the lipid content of the organisms.[17] Biodiesel when combusting under optimal conditions compares favourably to petrol diesel, producing less CO_2 per kilogram combusted.[18] However, one issue with biodiesel can be the emission of nitric oxide which is poisonous and can contribute to acid rain.[19]

Recently, the culture of algae for the production of hydrogen as novel biofuel has been of particular interest.[20] Biohydrogen is considered clean and sustainable as its combustion only results in H_2O as an end-product, as can be seen below.[21]

$$2H_2 + O_2 \xrightarrow{Combustion} 2H_2O$$

Biological hydrogen is produced as an intermediate or end product of algal metabolic pathways under defined conditions. There are three potential mechanisms of biohydrogen production in algal cells: 1. Direct bio-photolysis, 2. Indirect bio-photolysis and 3. Dark fermentation (see below).

$$1.\ 2H_2O + light\ energy \rightarrow 2H_2 + O_2$$

$$2.\ 6H_2O + C_6H_{12}O_6 + light\ energy \longrightarrow 12H_2 + 6CO_2$$

$$3.\ C_6H_{12}O_{12} + 2H_2O \rightarrow 2C_2H_4O_2 + 4H_2 + 2CO_2$$

1. Bio-photolysis 2. Indirect bio-photolysis 3. Dark fermentation

Hydrogen photoproduction via direct photolysis has received increasing attention since it allows the breakdown of H_2O into molecular H_2 without an output of CO_2.[22] The pathway is termed 'direct biophotolysis' due to its direct pathway of electrons. During photosynthesis water is split at photosystem II (PSII) into electrons, protons and oxygen. The electrons then move from PSII to photosystem I (PSI) and are used for biomass production by the cell. However, under certain culture conditions, such as sulphur deprivation, the metabolism of green algae switches from biomass production to hydrogen production. The electrons are then utilised to activate the enzyme hydrogenase (H_2ase) which

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[17] Nandan, S., 2020. Biofuel Production Technology from Bioenergy Crop-Algae Biofuel. *SSRN Electronic Journal*.
[18] Tsai, D., Chen, P. and Ramaraj, R., 2017. The potential of carbon dioxide capture and sequestration with algae. *Ecological Engineering*, 98, pp.17-23.
[19] Dursun, N. and Gülşen, H., 2019. Methods of Biohydrogen Production and Usage of Bioreactors for Biohydrogen Production. *Journal of the Institute of Science and Technology*, pp.66-75.
[20]Khanna, N. and Das, D., 2012. Biohydrogen production by dark fermentation. *Wiley Interdisciplinary Reviews: Energy and Environment*, 2(4), pp.401-421.
[21] Ibid
[22] Fakhimi, N., Gonzalez-Ballester, D., Fernández, E., Galván, A. and Dubini, A., 2020. Algae-Bacteria Consortia as a Strategy to Enhance H2 Production. *Cells*, 9(6), p.1353.

catalyses the synthesis of H_2 from H^+ (see figure 6). Algal hydrogenase, however, is strongly inhibited by O_2 produced by PSII which is a limiting factor for hydrogen synthesis in algae.[23]

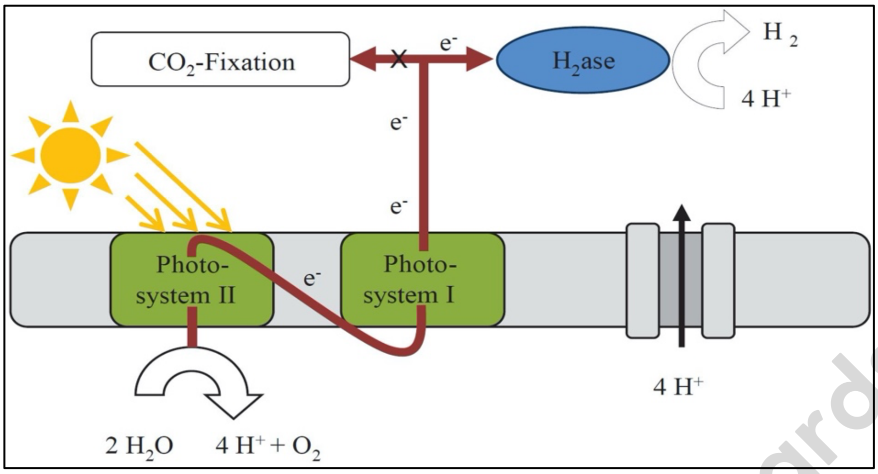

Figure 6. Electron transport reactions of hydrogen production in microalgae. (Seibert, M. and Torzillo, G., 2018. *Microalgal Hydrogen Production: Achievements And Perspectives*. Royal Society of Chemistry.)

Different strategies have been developed to overcome hydrogenase inhibition by O_2 and maximize hydrogen production, such as co-culturing algae with various bacteria.[24,25] A significant benefit of co-culturing heterotrophic bacteria with algae is that they can efficiently remove O_2 from the growth media.[26] Furthermore, the provision of fermentative metabolites such as acetic acid from bacteria to algae can establish specific nutrient fluxes that can benefit H_2 production and/or growth.[27,28] Some of the metabolites that can potentially be exchanged between algae and other microorganisms are shown in Figure 8.

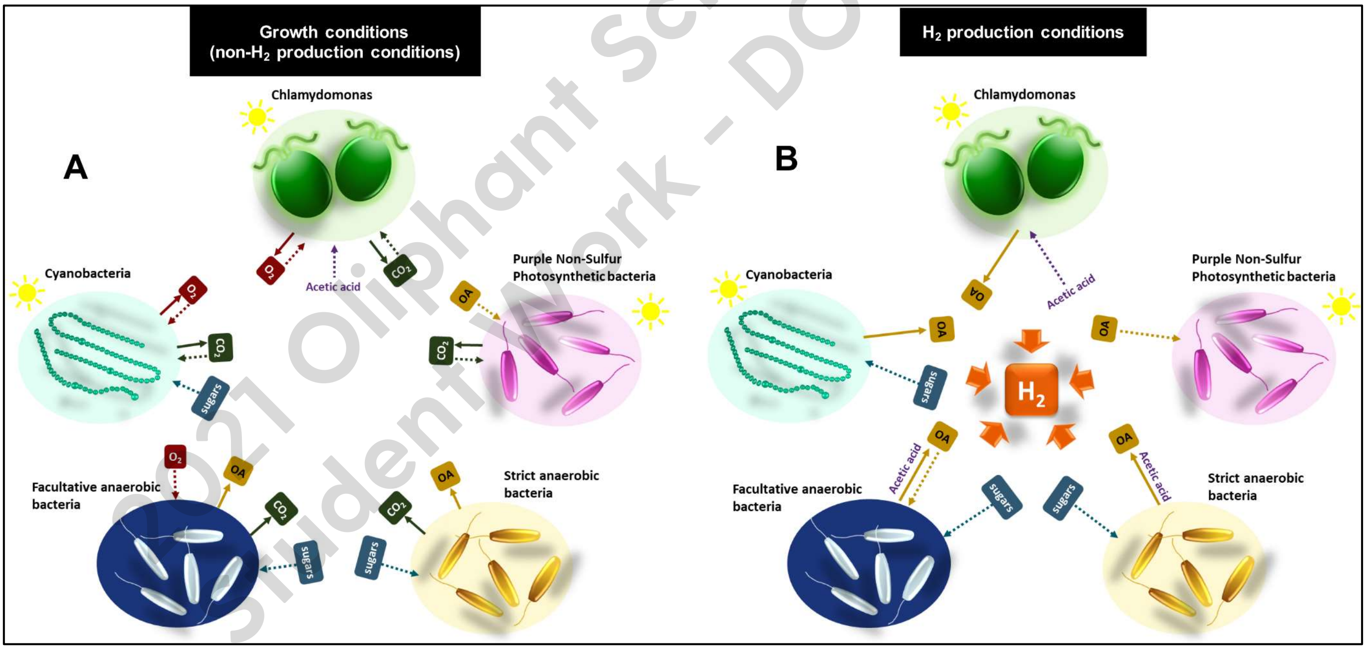

Figure 7. **Potential metabolites exchanged among different H_2 producing microorganisms during growth conditions (A) and H_2-producing conditions (B) (Organic acids (OA) mainly include ethanol, lactate, succinate, butyrate and glycerol.)** (Fakhimi, N., Gonzalez-Ballester, D., Fernández, E., Galván, A. and Dubini, A., 2020. Algae-Bacteria Consortia as a Strategy to Enhance H2 Production. *Cells*, 9(6), p.1353.)

[23]Fakhimi, N. and Tavakoli, O., 2019. Improving hydrogen production using co-cultivation of bacteria with Chlamydomonas reinhardtii microalga. *Materials Science for Energy Technologies*, 2(1), pp.1-7.
[24]Hwang, J., Church, J., Lim, J. and Lee, W., 2018. Photosynthetic biohydrogen production in a wastewater environment and its potential as renewable energy. *Energy*, 149, pp.222-229.
[25] Fakhimi, N., Gonzalez-Ballester, D., Fernández, E., Galván, A. and Dubini, A., 2020. *Op.cit* .p.1353.
[26]Bayro-Kaiser, V. and Nelson, N., 2017. Microalgal hydrogen production: prospects of an essential technology for a clean and sustainable energy economy. *Photosynthesis Research*, 133(1-3), pp.49-62.
[27] Seibert, M. and Torzillo, G., 2018. *Microalgal Hydrogen Production: Achievements And Perspectives*. Royal Society of Chemistry.
[28]Ibid

DISCUSSION

Applications to reduce greenhouse gas emissions and extract CO_2 from the atmosphere are desperately sought to help reduce attributed climate change and environment impact. Fossil fuel combustion for energy production produces more than 24 gigatons of CO_2 annually.[29] As a result, atmospheric CO_2 concentrations have risen from 295 parts per million (ppm) to 380 ppm over the last 100 years, and have been the cause of climate change.[30] The Intergovernmental Panel on Climate Change of the United Nation has therefore set the aim to reduce CO_2 emission levels by 25% from 2010 until 2030 and reach net zero emissions by 2050.[31] However, CO_2 emissions continue to rise, and the greatest concentration of CO_2 in the atmosphere in human history was measured in May 2020 at Hawaii's Mount Loa.[32]

Bio-sequestration of CO_2 with algae via photosynthesis has emerged as a promising application to reduce the emission of CO_2. Data shows that algae when used in conjunction with novel photobioreactors are up to 400 times more efficient in removing CO_2 from the atmosphere than trees.[33] Moreover, unlike terrestrial plants algae can be cultivated in vertical and compact systems, thus providing the opportunity for algae CO_2 sequestration to occur in densely populated cities.[34] This was shown last year when the company EcoLogicStudio installed 'urban curtains' in London.[35,36] The curtains consist of thin vertical arrays of algae and have been shown to be as effective as seven fully grown trees.[37.38] This is due to the uncomplicated cellular structure and rapid growth of microalgae resulting in a CO_2 fixation efficiency which is 10–50 fold higher than that of terrestrial plants.[39] Therefore, carbon-capture with algal bioreactors in the urban environment would potentially enable cities to become CO_2 neutral or even negative.[40] Furthermore, algae are known to grow in high CO_2 concentration environments and methods have been developed for the integration of flue-gas from power plants with algae production for the capture and utilization of CO_2.[41,42]

Scientific research has also shown that algae can represent a key substitute to current conventional biofuels, reducing negative environmental impacts and solving ethical concerns.[43] Currently, many of the leading sources of biofuel, such as corn, require large areas of arable land for their production and therefore compete with food production which is concerning in developing countries which are struggling to keep up with agricultural demand. Moreover, conventional biofuel production entails the removal of native vegetation, thus frequently being carbon positive. In contrast, algae can be grown on unproductive land and are much more efficient in their production than conventional biofuels (algae culture produces about 19,000 L of biodiesel per equivalent acre compared to soy which produces only about 220 L per acre).[44] Additionally, researchers from Exxon Mobil Australia have shown that algae fuel production is carbon neutral with the same amount of CO_2 being sequestered as is released.[45]

Biohydrogen from algae would be the perfect energy source against climate change as it only produces water vapor when combusted, thus being carbon neutral.[46] Although large-scale hydrogen production from algae has not been applicable yet due to technical issues (such as the high sensitivity of the process towards oxygen), significant progress has been made due to advances in culture strategies. Recently published research by N. Fakhimi, A. Dubini and D. Gonzalez-Ballester from May 2020 has shown an increase of hydrogen yield by 60% when combining the unicellular

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[29] United Nations Sustainable Development. 2020. *Climate Change*. [online] Available at: <https://www.un.org/sustainabledevelopment/climate-change/> [Accessed 28 June 2021].
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[34] Bonifield, J., 2020. *How This Aussie Brewery Incorporates Algae Into Beer Production*. [online] Greenbiz.com. Available at: <https://www.greenbiz.com/article/how-aussie-brewery-incorporates-algae-beer-production> [Accessed 3 August 2021].
[35] Ibid
[36] Nandan, S., 2020. Biofuel Production Technology from Bioenergy Crop-Algae Biofuel. *SSRN Electronic Journal*.
[37] BBC News. 2020. *Could These Plastic 'Trees' Help Save The Planet?*. [online] Available at: <https://www.bbc.com/news/av/business-49044832/algae-bio-curtains-architects-radical-solution-to-capture-carbon> [Accessed 21 July 2021].
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[44] Tsai, D., Chen, P. and Ramaraj, R., 2017. The potential of carbon dioxide capture and sequestration with algae. *Ecological Engineering*, 98, pp.17-23.
[45] Nandan, S., 2020. *Op.cit.*
[46] Tsai, D., Chen, P. and Ramaraj, R., 2017. *Op.cit.* pp.17-23.

algae Chlamydomonas reinhardii with E. coli bacteria.[47] The increased hydrogen production caused by higher respiration rates in the bioreactors during symbiotic growth, has led to the potential application of this system as a hydrogen-based fuel source.[48,49] Kristina Libby, the chief scientific officer at Hypergiant, stated "We see right now as a turning point in awareness to the potential that algae can play in the larger climate change conversation."[50] Next generation companies are recognising this opportunity and investing now. Testing and innovations are ongoing to further improve the efficiency of algae cultivation, reduce the inhibition of hydrogenase and allow the mass capture of algal biohydrogen.[51]

While the application of algae and photobioreactors for carbon sequestration could be the basis of a sustainable green future, there are still significant obstacles to overcome. An important factor currently limiting the widespread implementation are the costs. For example, the overall sum of biohydrogen production costs with algae were evaluated at 15 USD/GJ (in comparison, the production costs for natural gas are about 4 USD/GJ).[52] For photobioreactors to become more competitive, carbon taxes will have to be imposed by governments. Furthermore, to make the algae industry economically feasible, the production of algae will need to be combined with a biorefinery approach that provides a range of commercial algae products, such as biofuels, animal feeds and human dietary supplements. This would create an income stream and reduce the attributed cost of the algae production.

CONCLUSIONS

Algae absorb large amounts of CO_2 and their biomass can be converted to biofuels. However, their application has been constrained in the past due to technical limitations and costs. Latest scientific developments, such as AI photobioreactors, are now allowing large-scale application of algae culture for carbon capture and production of sustainable ecofriendly fuel. The upscaling of algae culture will make it more economically feasible and advance the development of additional fuel sources from algae, such a biohydrogen.[53] Biohydrogen production for fuel provides an attractive option as a clean fuel for the future, but microbiological obstacles such as O_2 inhibition of hydrogenase function are still preventing practical implementation of the process on an industrial scale. Nevertheless, recent advancements in the use of algal-bacterial co-culture are increasing the efficiency of hydrogen production. Optimization of key elements of the culture process as well as genetic and metabolic engineering of microalgae will make hydrogen production from algae increasingly cost-effective and sustainable.

Future novel applications are paving the way for an innovative future low-emission bioeconomy. Latest examples are the incorporation of algae CO_2 sequestration in the beer brewing process, as performed by the Australian Henry Banks Brewery, and scientific progress such as the research currently being undertaken by the Arizona University into the genetic modification of algae to produce hydrogenase enzymes which are oxygen resistant and would increase hydrogen production by 85%.[54,55] Algae's future, however, will ultimately depend on how seriously nations around the world consider the economic threats of climate change to the world population, compared to their own near-term economic self-interest.

WORD COUNT – 1544

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