# Recommendations for the Advancement of Combined Algal Biofuel and Carbon Capture Technology

Arya Sasne

MCSC UROP

Massachusetts Institute of Technology

Class of 2025

This paper examines the market failure that is global warming and strives to make recommendations that have the potential to resolve this failure. Algal biofuels combined with carbon capture have the growing potential to provide a renewable energy source with net negative carbon emissions. With this goal in mind, the following text explains the developments needed to further the equitable and economically efficient use of this technology.

**Sources of Market Failure**

Climate change is one of the largest market failures that we are currently facing. This can largely be attributed to two reasons. The first is that the atmosphere is an open-access resource. Since it doesn't belong to anyone, and no one can be excluded from using it, the atmosphere can be overused, or in this case, over-polluted.[1] This relates to the "tragedy of the commons," which is an ecological principle that suggests a resource that is owned by none, will be exploited by all. The second large cause is greenhouse gases as a negative externality. Since greenhouse gas production only benefits the producers but harms everyone, industries tend to prioritize their own profits. This results in a production of greenhouse gases in amounts greater than the ideal, leading to Pareto-inefficiency.[2]

**Rectifying Market Failure**

Some public policies that can be enacted to rectify this market failure would be to target the sources themselves. While it would be nearly impossible to make the atmosphere a private good, it is possible to charge industries for the greenhouse gases they produce. Carbon taxes are

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[1] Bowen, Alex, et al. "Why Do Economists Describe Climate Change as a 'Market Failure'?" *The Guardian*, Guardian News and Media, 21 May 2012, www.theguardian.com/environment/2012/may/21/economists-climate-change-market-failure.

[2] *Module 3 The Economics of Climate Change*. vi.unctad.org/tenv/docs/m3.pdf.

becoming more common, however, extending this idea to all pollutants and all industries/companies would make it so that greenhouse gas production is less of an externality and has a substantial impact on the producers.[3] Ideally, this would force industries to take responsibility for the greenhouse gases that they produce, shifting the system closer to Pareto-efficiency. However, it can be challenging to enact good policy from a purely top-down approach. For example, how do we identify an appropriate amount for a carbon tax? To build good policy to drive fast and responsible change, it is important to be aware of the technological choices companies have today and what is on the horizon. This paper will focus on one promising area that can reduce emissions of many important industries, algal biofuels and biochemicals.

**Algal Biofuels**

Algal biofuels have been a growing field of research in finding renewable alternatives to fossil fuels. Converting light, water, nutrients, and carbon dioxide through photosynthesis, into algae growth,[4] microalgae are easily convertible to a variety of fuels (See Appendix I).[5] With many different algae strains[6][7] that can be grown in both fresh and saltwater, algae is relatively easy to

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[3] Bowen, Alex, et al. "Why Do Economists Describe Climate Change as a 'Market Failure'?" *The Guardian*, Guardian News and Media, 21 May 2012, www.theguardian.com/environment/2012/may/21/economists-climate-change-market-failure.

[4] Shurin, Jonathan B et al. "Industrial-Strength Ecology: Trade-Offs and Opportunities in Algal Biofuel Production." Ecology letters. 16.11 (2013): 1393–1404. Web.

[5] "Biomass Energy." *National Geographic Society*, 14 Nov. 2012, www.nationalgeographic.org/encyclopedia/biomass-energy/.

[6] The most common of these strains is *Scenedesmus spp, a quick-growing freshwater algae.*

[7] "Algal Biofuel: The Answer to Independence from Fossil Fuels?: Earth.org - Past: Present: Future." *Earth.Org*, 7 Aug. 2020, https://earth.org.

use across the world.[8] When genetically modified algae is considered, these options grow further.[9] There are currently two major methods of algae growth. Open ponds are simple to construct, but suffer from extensive evaporation, high contamination risk, and large required growing spaces.[10] Algae photobioreactors (PBR) are more costly to assemble, but eliminate much of those risks.[11] PBR is a closed cultivation system, which allows for growth to be more space-efficient, and for growing conditions to be more easily controlled (See Appendix II).[12] The lipids produced alongside algae growth are extracted and processed through a series of harvesting and purification steps.[13] The end product is a third generation biofuel that can be used for transportation processes amongst others.[14] However, in comparison to 1st and 2nd generation biofuels like those derived from corn and soy, algae is much more land and resource efficient.[15] Much less resource and fertilizer dependent, algae are also nearly 50% lipid by weight.[16] This

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[8] Venteris, Erik R et al. "A GIS Cost Model to Assess the Availability of Freshwater, Seawater, and Saline Groundwater for Algal Biofuel Production in the United States." Environmental science & technology 47.9 (2013): 4840–4849. Web.

[9] Arora, Pratham et al. "Lifecycle Greenhouse Gas Emissions for an Ethanol Production Process Based on Genetically Modified Cyanobacteria: CO2 Sourcing Options." Biofuels, bioproducts and biorefining 14.6 (2020): 1324–1334. Web.

[10] Packer, Mike. "Algal Capture of Carbon Dioxide; Biomass Generation as a Tool for Greenhouse Gas Mitigation with Reference to New Zealand Energy Strategy and Policy." Energy policy 37.9 (2009): 3428–3437. Web.

[11] Jones, Christopher W. "Direct Air Capture of CO2 and Delivery to Photobioreactors for Algal Biofuel Production." *Energy.gov*, Georgia Tech Research Corporation, 23 Mar. 2021, www.energy.gov/sites/default/files/2021-04/beto-37-peer-review-2021-algae-jones.pdf.

[12] Harris, Kylee. "Economic and Environmental Sustainability of an Integrated Direct Air Capture System with Advanced Algal Biofuel Production." National Renewable Energy Laboratory.

[13] Halim, Ronald et al. "Oil Extraction from Microalgae for Biodiesel Production: Biofuels - II: Algal Biofuels and Microbial Fuel Cells." Bioresource technology 102.1 (2011): 178–185. Print.

[14] Alaswad, A et al. "Technologies and Developments of Third Generation Biofuel Production." Renewable & sustainable energy reviews 51 (2015): 1446–1460. Web.

[15] Lee, D. H. "Algal Biodiesel Economy and Competition Among Bio-Fuels: Biofuels - II: Algal Biofuels and Microbial Fuel Cells." Bioresource technology 102.1 (2011): 43–49. Print.

[16] Halim, Ronald et al. "Oil Extraction from Microalgae for Biodiesel Production: Biofuels - II: Algal Biofuels and Microbial Fuel Cells." Bioresource technology 102.1 (2011): 178–185. Print.

means that oil yield in terms of gallon per acre is much higher for algae than any other pre-existing biofuel.[17] Additionally, algae isn't currently used as a food source, so scaling algal biofuels wouldn't place major stress on food supply, like corn and soy-based fuels would.[18] Thus, not only is algal biofuel effective in terms of oil production, but it is also one of the most scalable renewable fuel sources.

## Carbon Capture Technology

Carbon capture is the process by which $CO_2$ is removed from flue gas exiting power plants. This allows for a potentially carbon-neutral source of electricity.  Companies use chemical filters to remove carbon dioxide from flue gas at prices nearing from $120/ton, according to the IEA.[19] Ideally, the carbon captured could be stored underground.[20] This conventional carbon capture, alongside $CO_2$ removal by photosynthesis to create algal biofuels, has the ability to create a system of renewable, net carbon-negative energy sources. However, even this solution is not perfect and requires significant development and investment.

## Current Policies

[17] "Biomass Energy." *National Geographic Society*, 14 Nov. 2012, www.nationalgeographic.org/encyclopedia/biomass-energy/.

[18] Hannon, Michael, et al. "Biofuels from Algae: Challenges and Potential." *Biofuels*, U.S. National Library of Medicine, Sept. 2010, www.ncbi.nlm.nih.gov/pmc/articles/PMC3152439/.

[19] Morison, Rachel, and Samuel Etienne. "Carbon Capture Tech Becoming Cost-Effective as Emissions Price Soars." *World Oil - Upstream News*, 13 Aug. 2021, https://www.worldoil.com/news/2021/8/13/carbon-capture-tech-becoming-cost-effective-as-emissions-price-soars.

[20] Packer, Mike. "Algal Capture of Carbon Dioxide; Biomass Generation as a Tool for Greenhouse Gas Mitigation with Reference to New Zealand Energy Strategy and Policy." Energy policy 37.9 (2009): 3428–3437. Web.

In recent years, there has been increased government support of this new technology,[21] with the United States subsidizing biofuels and putting in place carbon capture credits.[22] In 2005, with the Energy Policy Act, grants, tax credits, loans, and subsidies were all used to promote the development of biofuels.[23] The Renewable Fuel Standard was also introduced to ensure the blending of 7.5 billion gallons of biofuel with gasoline by 2012.[24] With the Energy Independence and Security Act of 2007, the Renewable Fuel Standard was expanded to 36 billion gallons by 2022.[25]

To enable carbon negative algal biofuels, $CO_2$ released from combustion of algal oil should be captured and stored underground. Carbon capture has been deployed to make combustion of fossil fuels nearly carbon neutral, but could be more impactful when combined with the already nearly-neutral biofuel combustion. However, to support such investigations, carbon capture incentives must be considered. In order to incentivize carbon capture technology, the United States put into place tax credits, given to those who capture and store carbon dioxide.[26] This monetary incentive was first introduced in 2008, under Section 45Q of the Internal Revenue Code of 1986. Initially, a credit was given for each metric tonne of carbon dioxide captured,

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[21] "Economics of Biofuels." *EPA*, Environmental Protection Agency, www.epa.gov/environmental-economics/economics-biofuels.

[22] Nasralla, Shadia, and Susanna Twidale. "Factbox: Carbon Offset Credits and Their Pros and Cons." *Reuters*, Thomson Reuters, 25 Feb. 2021, www.reuters.com/article/us-climate-change-carbon-offsets-idUSKBN2AP1FZ.

[23] Jones, Angela C., and Molly F. Sherlock. United States Congressional Research Service, 2021, *The Tax Credit for Carbon Sequestration (Section 45Q)*, https://crsreports.congress.gov/product/pdf/IF/IF11455.

[24] Guan, Zhengfei, and Juhyun Oh. "United States Biofuel Policies: Overview and Discussion." *IFAS*, University of Florida, 17 Dec. 2018, edis.ifas.ufl.edu/publication/FE974.

[25] "Economics of Biofuels." *EPA*, Environmental Protection Agency, www.epa.gov/environmental-economics/economics-biofuels.

[26] Rodgers, Michael, and Brandon Dubov. "US Tax Credit Encourages Investment in Carbon Capture and Storage." *White & Case LLP*, 29 Jan. 2021, www.whitecase.com/publications/insight/carbon-capture/us-tax-credit-encourages-investment.

capped at 75 million tons, across all projects.[27] However, this 75 million ton limit was quickly reached, making the policy ineffective on the large scale. Ultimately, in 2020, the policy was amended to remove the limit and increase the value of the tax credit. A tax credit worth $22.66 per metric ton in 2017 would increase to $50 by 2026, after which it would increase with inflation.[28] This added incentive renewed interest in the field. Alongside the carbon capture credits, there was an increase in federal funding towards carbon capture and sequestration research and development.[29] In 2019, The U.S. Department of Energy's Office of Fossil Energy announced $110 million in federal funding for the purpose of advancing carbon capture technology.[30] Collectively, these policies have increased the funding and viability of this new technology. For algal biofuels and carbon capture to successfully decrease net carbon emissions, it is important to incentivize the development and utilization of these technologies.

**Policy Tradeoffs for Algal Biofuels**

While incentivizing new technologies through subsidies and tax credits is imperative to the development of solutions like algal biofuels and carbon capture, these policies alone are not enough. Biofuel subsidies make this technology more economically viable, which is important, since in comparison to fossil fuels, algal biofuels are not currently economically viable.[31] While

[27] Jones, Angela C., and Molly F. Sherlock. United States Congressional Research Service, 2021, *The Tax Credit for Carbon Sequestration (Section 45Q)*, https://crsreports.congress.gov/product/pdf/IF/IF11455.

[28] "Economics of Biofuels." *EPA*, Environmental Protection Agency, www.epa.gov/environmental-economics/economics-biofuels.

[29] Jones, Angela C., and Molly F. Sherlock. United States Congressional Research Service, 2021, *The Tax Credit for Carbon Sequestration (Section 45Q)*, https://crsreports.congress.gov/product/pdf/IF/IF11455.

[30] "U.S. Department of Energy Announces $110M for Carbon Capture, Utilization, and Storage." *Energy.gov*, 13 Sept. 2019, www.energy.gov/articles/us-department-energy-announces-110m-carbon-capture-utilization-and-storage.

[31] Stavrakas, Vassilis, Niki-Artemis Spyridaki, and Alexandros Flamos. "Striving Towards the Deployment of Bio-Energy with Carbon Capture and Storage (BECCS): A Review of Research Priorities and Assessment Needs." Sustainability 10.7 (2018): 2206–. Web.

the current price for a barrel of petroleum is typically $40-$80 (although current price hikes have driven prices to about $110),[32] the price of the same amount of algae fuel is $300-$2600.[33] This vast price difference means that algal fuels are not viable unless the process or algae itself is further optimized and made less expensive. However, one important point to note, is that the market price of carbon dioxide in regions such as California has been around $200/ton, which means that a barrel of petroleum would actually regularly be around $140-$180[34], much closer to the $300 cost of algal fuel.[35] While still less expensive than the algal fuel, this is a key example of how policy changes and carbon taxes can be effective in largely decreasing the gap between the prices of fossil fuels and algal biofuel. Despite the benefits of policy incentivizing biofuels, these initiatives come with key tradeoffs. Algal growth, like most agriculture, is resource-intensive.[36] The cultivation of algae as a source of fuel would take away resources from other human activities, whether it takes land previously used for food growth, or drinking water.[37] Additionally, it has the potential to lead to the destruction of local ecosystems.[38] There is a very clear opportunity cost for the destruction of carbon-capturing resources, like forests, to create algal biofuel facilities. Another potential cost of this new technology is the risk of

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[32] "Crude Oil Price Today (BRENT)." *Business Insider*, Business Insider, markets.businessinsider.com/commodities/oil-price?type=brent.

[33] Hannon, Michael, et al. "Biofuels from Algae: Challenges and Potential." *Biofuels*, U.S. National Library of Medicine, Sept. 2010, www.ncbi.nlm.nih.gov/pmc/articles/PMC3152439/.

[34] tCO2/barrel * $/tCO2 = $/barrel + original price

[35] "California Air Resources Board." *LCFS Data Dashboard | California Air Resources Board*, ww2.arb.ca.gov/resources/documents/lcfs-data-dashboard.

[36] Singh, Anoop, Poonam Singh Nigham, and Jerry D. Murphy. "Mechanism and Challenges in Commercialisation of Algal Biofuels: Biofuels - II: Algal Biofuels and Microbial Fuel Cells." Bioresource technology 102.1 (2011): 26–34. Print.

[37] Guan, Zhengfei, and Juhyun Oh. "United States Biofuel Policies: Overview and Discussion." *IFAS*, University of Florida, 17 Dec. 2018, edis.ifas.ufl.edu/publication/FE974.

[38] "Economics of Biofuels." *EPA*, Environmental Protection Agency, www.epa.gov/environmental-economics/economics-biofuels.

pollution. The fertilizers used to grow algae have a tendency to leach out into the nearby ecosystems, causing eutrophication in the bodies of water.[39] The byproducts of energy generation and fuel use also have the potential to release toxic chemicals into the atmosphere.[40] The chance of decreased air and water quality, stresses on resources, and loss of fossil fuel jobs might create local opposition to the development of this “clean” technology. In order to prevent the creation of sacrifice zones, it is necessary that policies and incentives for biofuels are implemented alongside legislation that supports the communities in which these technologies will be placed in.

**Policy Tradeoffs for Carbon Capture Technologies**

Carbon capture credits, much like biofuel subsidies, have their own set of tradeoffs. While they reduce emissions as a whole, carbon capture is seen by some as extending the life of fossil fuels, by making it ‘acceptable’ to use them as long as some of the carbon is captured.[41] Additionally, many of the carbon capture incentives don’t specify the exact usage of said carbon. For example, carbon captured is often used in enhanced oil recovery (EOR) to offset the price of capture, actually causing a net increase in emissions.[42] The captured $CO_2$ is pumped into the ground and used to directly increase the amount of fossil fuels extracted and used.[43] In order for carbon

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[39] Hannon, Michael, et al. “Biofuels from Algae: Challenges and Potential.” *Biofuels*, U.S. National Library of Medicine, Sept. 2010, www.ncbi.nlm.nih.gov/pmc/articles/PMC3152439/.

[40] Raslavičius, Laurencas, Nerijus Striūgas, and Mantas Felneris. “New Insights into Algae Factories of the Future.” Renewable & sustainable energy reviews 81 (2018): 643–654. Web.

[41] Cairns, Shani. “Direct Air Capture.” *Scientists' Warning*, 21 June 2021, www.scientistswarning.org/2020/06/04/direct-air-capture/.

[42] Jones, Angela C., and Molly F. Sherlock. United States Congressional Research Service, 2021, *The Tax Credit for Carbon Sequestration (Section 45Q)*, https://crsreports.congress.gov/product/pdf/IF/IF11455.

[43] “Fact Sheet: Direct Air Capture.” *American University*, 24 June 2020, www.american.edu/sis/centers/carbon-removal/fact-sheet-direct-air-capture.cfm.

capture to be environmentally sustainable, the credits must be limited to projects not involving enhanced oil recovery.

Incentivizing the production of carbon capture technologies as they currently exist also has potential tradeoffs. Carbon capture is not yet perfected, and thus, it comes with risks. To begin with, while advancements have been made in securing the captured carbon dioxide, there is still a risk of $CO_2$ leakage from pipelines, or even worse, seismic activity initiated by carbon dioxide being stored underground.[44] Another key issue is the high energy needs of creating this carbon capture technology. The large energy and resource consumption of creating this technology reduces the effectiveness as a whole.[45]

**Key Players**

In the world of algal biofuels, the key players may be surprising to some. The vast majority of patents and research done in this field belongs to oil companies, their major competitors. With the economic ability and resources to engage in this developing technology, fuel companies like ExxonMobil, BP, Chevron, and Valero, have all invested in algal biofuels. While there were previously a number of specialized companies in the field, such as Sapphire, Algenol and Synthetic Genomics, low oil prices and Trump era hostility to climate change policy resulted in a shakeout, leaving oil companies dominating the field.[46] Due to uncertain demand, these

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[44] Funded by New Tax Credits, US Carbon-Capture Network Could Double Global CO2 Headed Underground. NewsRX LLC, 2018. Print.

[45] Despite the current high energy consumption of this technology, there has been increased progress towards reducing emissions by pairing it with industrial processes in order to use thermal energy byproducts as a replacement for some of DAC's energy needs.

[46] "The New Threat from Big Oil in Biofuels." *Transport & Environment*, 13 Jan. 2022, www.transportenvironment.org/discover/the-new-threat-from-big-oil-in-biofuels/.

companies hesitate to invest in this market as much as they could, slowing the energy transition compared to what is possible.

There are also a number of companies currently investing in carbon capture technology. Conventional carbon capture, attached to power plants, is becoming increasingly commercially viable. It already occurs on million ton scales per year, and is owned and operated by companies like Dow, Shell, Chevron, Mitsubishi Heavy Industries, and a few newcomers like Svante.

**Advancements in Technology**

As a number of players work to advance both algal biofuels and carbon capture technologies, it is important to understand where this progress will go, and how it will benefit society. Algal biofuels have a number of regions in which they can be optimized. The first is the strain of microalgae used.[47] Important to many working on this technology, and the large-scale effectiveness of algal biofuels, is how efficient the algal strain is for fuel production, growth, and purification.[48] Through the testing of many strains, as well as genetic modification, a lot of progress has been made to increase the production of lipids, the key component in fuel, with algae.[49] As algal strains become more optimized for fuel production, it is also important to look at the resources needed, and how the principles of industrial ecology can be applied to make the technology more feasible and environmentally effective in the long-term. Recently, there has

[47] Shurin, Jonathan B et al. "Industrial-Strength Ecology: Trade-Offs and Opportunities in Algal Biofuel Production." Ecology letters. 16.11 (2013): 1393–1404. Web.

[48] Kazamia, Elena, et al. "Synthetic Ecology – a Way Forward for Sustainable Algal Biofuel Production?" *Journal of Biotechnology*, Elsevier, 5 Apr. 2012.

[49] Arora, Pratham et al. "Lifecycle Greenhouse Gas Emissions for an Ethanol Production Process Based on Genetically Modified Cyanobacteria: CO2 Sourcing Options." Biofuels, bioproducts and biorefining 14.6 (2020): 1324–1334. Web.

been increasing amounts of research into using wastewater to grow the microalgae for biofuels, thus growing a source of fuel, while bioremediating wastewater at the same time.[50] So far, the research shows that this idea may be feasible on a large scale.[51] The algae can remove much needed nutrients such as nitrogen and phosphorus, from the wastewater, allowing for a new water source that doesn't place undue strain on the nearby communities.[52]

Carbon capture technologies also have many advancements that can be made in the near future. One of the most pressing concerns with the technology is that it is not currently effective enough. Over long periods of time, some of these plants have only been able to capture around 10% of the $CO_2$ emitted, meaning that it is unable to be as helpful as often portrayed.[53] However, if work is done to increase the efficiency of the technology, it may become possible for it to make an even larger impact on global carbon emissions. If these advancements are able to be made, the combination of algal biofuels and carbon capture has the potential to revolutionize the energy industry. This technology could help strongly mitigate the damages of climate change.

**Conclusion**

The world that we live in today is rapidly approaching a dangerous tipping point. Current standards, trends, and technologies suggest that there is little that can be done to prevent the

[50] Pittman, Jon K. "The Potential of Sustainable Algal Biofuel Production Using Wastewater Resources." Bioresource technology 102.1 (2011): 17–25. Print.

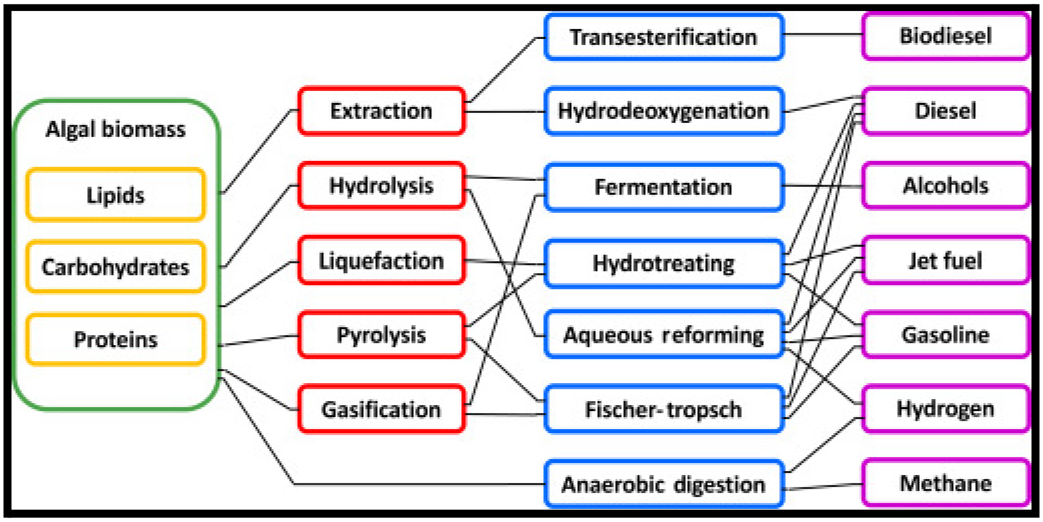
[51] Razzak, Shaikh A et al. "Integrated CO2 Capture, Wastewater Treatment and Biofuel Production by Microalgae Culturing-A Review." Renewable & sustainable energy reviews 27 (2013): 622–653. Web.

[52] Zhou, Wenguang et al. "Environment-Enhancing Algal Biofuel Production Using Wastewaters." Renewable & sustainable energy reviews 36 (2014): 256–269. Web.

[53] Kubota, Taylor. "Study Casts Doubt on Carbon Capture." *Stanford News*, 25 Oct. 2019, https://news.stanford.edu/2019/10/25/study-casts-doubt-carbon-capture/.

devastating global effects of climate change. It is for this very reason that algal bio-energy and carbon capture are fields that need to be further explored and invested in. If optimized for the social, economic, and environmental well-being of local and global communities, this technology has the potential to equitably reduce the massive emissions of energy generation. Because of their quick growth, low resource consumption, and ease of cultivation, algal biofuels are a promising solution for industries currently dependent on fossil fuels. By further improving cost and resource efficiency, as well as using carbon capture technology alongside these algal biofuels, some of the barriers to implementation could be reduced from a technological perspective. However, we must also consider the broader tradeoffs to ensure equity and community goals are not disrupted by this technology. These technologies can only be effective and ethical long term if they deeply consider the communities in which the technology is placed in, ensuring that no one is left behind or harmed in this push for progress.

## Appendix I




*The processes used to turn algae into a wide variety of fuels and usable products.*[54]

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[54] Siegler, Hector De la Hoz. "Process Intensification for Sustainable Algal Fuels Production." *Handbook of Algal Biofuels*, Elsevier, 3 Dec. 2021.

**Appendix II**

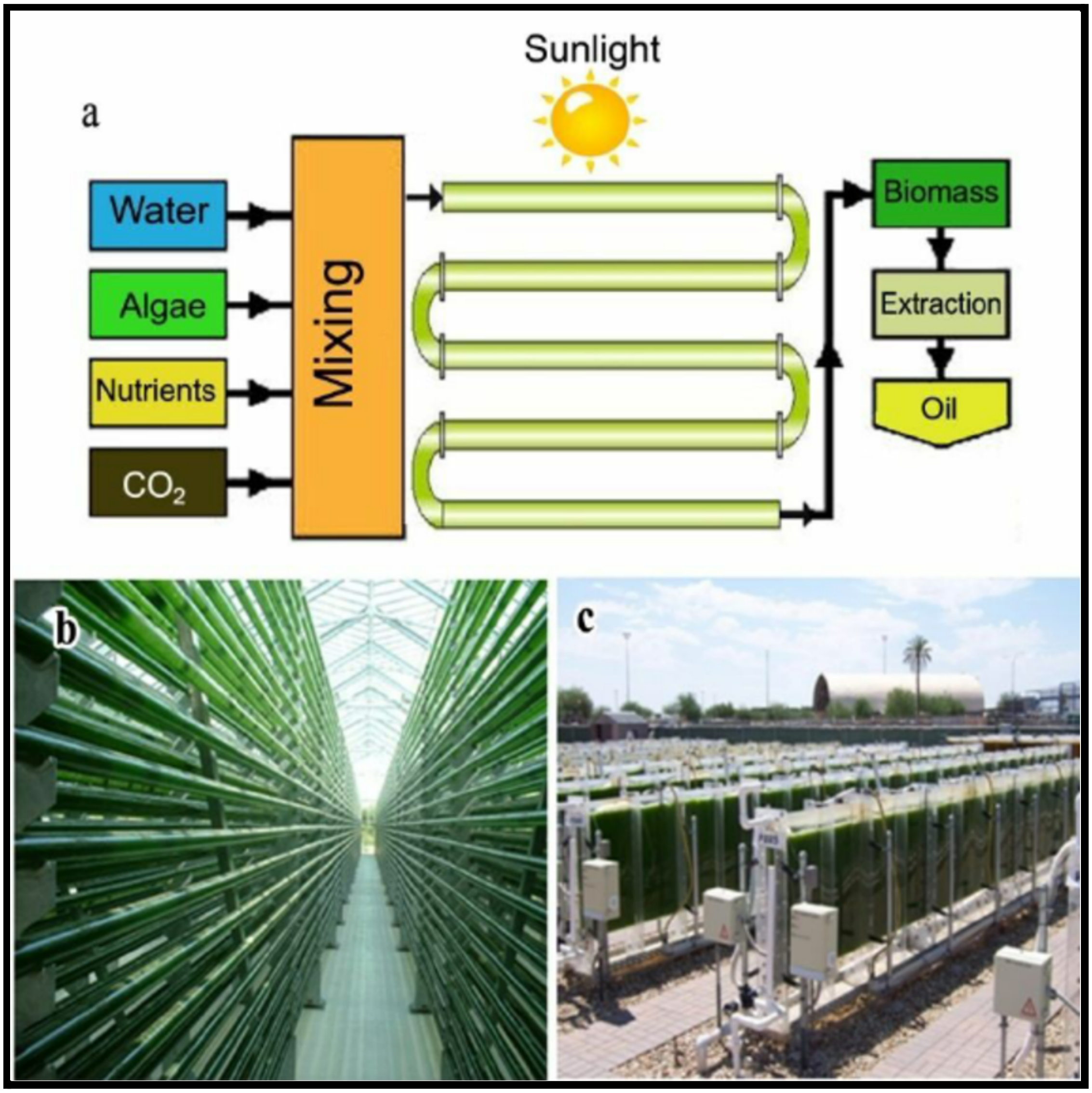


*Diagram and images of a photobioreactor (PBR) system growing algae.*[55]

[55] El-Sheekh, Mostafa & Abomohra, Abdelfatah. (2016). Biodiesel Production from Microalgae.

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