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Algae Technology And The Future Of Sustainable Energy

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As we enter an era where our dependence on sustainable energy is becoming higher than ever, finding solutions that will outlast and outperform fossil fuels is quickly becoming imperative. Even though many alternative energy sources are gaining popularity, we still heavily rely on fossil fuels due to their high quantity and easy access. If we cannot bring our greenhouse gas and carbon emission levels down, it is unlikely that we will be able to reduce or prevent the irreversible damage that climate change has already caused. One of the answers lies in one of the newest biofuel sources: algae biomass. Due to the fact that algae biofuel can grow in large quantities sustainably, is a completely renewable and natural resource, and combats carbon dioxide emissions, investing finances and effort into the development of algae biofuel is imperative to moving closer to a world built on sustainable energy. Despite the many hurdles that still stand in the way of algae fuel mass production, such as the lack of production space and harvesting resources, algae biofuel is the best sustainable replacement for liquid fossil fuels and batteries that can power our shipping and aviation industries for years to come.

While biofuels seem to be a relatively new energy source, they are actually described as the original fuel and the different variations of biofuels have evolved with supporting technologies (Cavelius, 2023). The first generation of biofuels can be traced back to the global oil crisis in the 1970s as organic plant matter, such as maize, sugarcane, and bean sprouts were burned to mimic the effects of oil production. The second generation of biofuels is defined as fuel produced from agricultural waste, organic waste, and wood. The third generation of biofuels began showing promising results in 2019 after scientists realized they could convert microalgae and cyanobacteria biomass into liquid fuel. Finally, ideas for the fourth generation of these fuels have just started to gain momentum with genetically modified biomass from the previous generations looking to become the future of sustainable agriculture and energy production (Cavelius, 2023). Over the last few decades, we have seen biofuel quickly become a prominent source of energy from individual households to large corporations as biofuel now accounts for roughly 13% of energy consumption globally, mostly deriving from bioethanol and biodiesel (Pienkos, 2018). That number is expected to rise to 40% before 2040 (Praveena, 2023). As we transition from third to fourth generation, one of the premier renewable energy sources has become biofuel derived from microalgae.

Algae-based biofuel, while a relatively new source of renewable fuel, has already begun to show lasting global impacts in the energy industry. The process of transforming algae into an effective biofuel takes place through five different stages: cultivation, harvesting, drying, extraction, and transesterification, or the final stage of transforming lipids into fuel matter (Pienkos, 2018). In Figure 1, the process of algae cultivation is shown since, depending on the type of fuel being produced (i.e. bioethanol, biodiesel, biogas, etc.) different techniques and materials are needed to allow for various fuel treatment plans (Pienkos, 2018). Cultivation and the harvesting of microalgae is rather simple, requiring only a contained and humid space, continuously flowing water, and a steady supply of nutrients, such as nitrogen and phosphorus. While the drying stage used to be a constant in early-stage algae transformation, it is now only seen as optional with new technologies making a "wet route" possible, cutting out the drying process and lowering production costs. Finally, transesterification is the process of extracting the lipids from the microalgae and combining them with various alcohols and catalysts, such as an acid, base, enzyme, or biocatalyst, to create the foundation of biofuel in the form of fatty acid methyl esters (Naghdi, 2016).

Since microalgae have many factors and steps that are still in the trial era, there have been many different techniques and strategies being used to extract lipids and convert them into usable liquid fuel. The two main categories of extraction methods are known as either traditional extraction methodologies or emergent extraction methodologies with the main difference being that the more traditional methods are simple operations with relatively low costs, however, they produce a higher amount of waste and use more energy than emergent methods (Zhou, 2022). Over the past few years, new scientific breakthroughs have allowed microbiologists to extract the algae lipids in ways that are quicker, more cost and fuel efficient, and do not release nearly as much toxic waste. Illustrated in Figure 2 are various methods of lipid extraction that have been shown to cut down on significant amounts of time, costs, and physical labor (Zhou, 2022). One of the methods is called the pulsed electric fields method (PEF). Designed originally for the food industry, the PEF method (diagram E) uses high-voltage electrical fields to separate the lipids from the algae cell membrane, extracting the lipid mass without damaging the overall cell. Researchers have found this to be one of the most promising extraction methods as the lipid recovery rate within the cell is said to be 90% and can extract up to 12% more mass than the next leading method. Since this method does not release any type of pollution and one batch can process a greater amount of samples than other types of extraction, the pulsed electric field method is showing great promise in the renewable energy industry. Another technique that is quickly gaining popularity is the enzyme-assisted extraction method (diagram F). This treatment does not require any additional equipment and simply uses various enzymes to break down the cell wall to extract the desired lipid content. While it does break down the cell wall, the recovery rate of proteins and carbohydrates has been proven to be significantly higher as well as the lipid extraction rate to range from 75 to 88% higher than traditional methods. While one of the simplest methods of extracting lipid contents with low costs, different types of microalgae require different enzymes, resulting in more preparation and variation (Zhou, 2022).

Even though algae biofuel has made significant progress in the renewable energy field, many are still skeptical about its usefulness and problems that still have to be worked out if we ever hope to produce algae fuel on a large scale. One of the biggest challenges biofuel producers face is the overall cost of harvesting algae biomass. While the algae market generates over $1 billion globally every year, a large portion of that income comes from the food and wellness industry as well as the beauty industry. Compared to the $2,000 to $3,000 that it costs to produce one kilowatt of coal energy, one kilowatt of algae energy costs approximately $3,500 to $4,000 (Marsh, 2024). Another factor that has deterred many from investing in algae fuel is the amount of resources required to properly produce the fuel on a big enough scale. Producing a single liter of algae biofuel currently uses up to 3,650 liters of water for cultivation (Marsh, 2024). Alongside the massive amounts of water and nutrients needed to properly produce algae fuel, the amount of physical space needed for algae production is space that many corporations do not have access to, and those that do have found it more economical to invest that space in standard agriculture. Knowing that the United States uses approximately 19 million barrels of oil per day, the Energy Information Association has calculated that nearly 30 million acres would need to be dedicated to algae fuel production to keep up with the high demand (EIA, 2022). While there has been a significant improvement in algae production technology over the last few decades, some believe that costs are still too high, space is too limited, and not enough research has been done to create a solid plan to increase our reliance on algae biofuel.

It is no secret that algae biofuel still has a long way to go, however, there have been many developments that prove that this is a viable energy source and is slowly establishing itself as a competent renewable energy source. One of the biggest issues that algae fuel has faced is the lack of funding and economic resources to support more in-depth research in hopes of finding solutions to the problems that have arisen. In April 2024, the U.S. Department of Energy's Bioenergy Technologies Office (BETO) and Office of Fossil Energy and Carbon Management (FECM) announced that they would spend $18.8 million on algae fuel research and development. Introduced as the Mixed Algae Conversion Research Opportunity (MACRO), this funding announcement is dedicated to supplying universities and laboratories with ample funds to find more cost-effective ways to meet our sustainable fuel needs - specifically concerning aviation fuel. With this additional funding, we have already begun to see universities begin to dive head first into furthering algae research. At the University of Buffalo, the Department of Civil, Structural, and Environmental Engineering has begun to track how different environmental settings will change the algae's DNA and RNA in hopes of altering the amount of lipid production at a low cost. This program is in direct association with the Georgia Institute of Technology as they are monitoring the results with artificial intelligence to predict what changes may need to be made. University of Buffalo's leading expert on algae fuel, Professor Ian Bradley, has already expressed confidence in the upcoming results as he claims that polyculture farming and genetic engineering will make algae fuel more accessible to the general public and private institutions (Murphy, 2024).

Alongside the fact that funding for algae fuel has become much more accessible, progress has also been made in decreasing the amount of resources needed to sustain mass algae growth and production. With over 3,000 different species of microalgae, it is an incredibly resilient organism with the ability to grow in almost any type of environment, including in wastewater treatments. As technology develops, scientists have begun to have success with recycling water back through the treatment plants once being run through a system, a process known as fertigation, to filter out any harmful bacteria and pollutants, such as nitrates, phosphates, and sulfates. When in tight-knit cultivation conditions, microalgae can absorb nearly 90% of excess carbon dioxide while being filtered in wastewater treatment centers, proving that not only is algae fuel a better alternative to fossil fuels, but also combats the high amounts of carbon dioxide and other greenhouse gases in the atmosphere as it grows (Ali, 2022). Even though we are still in the early stages of algae fuel production, there has already been significant economic and production growth that lends itself to believing that many of the original concerns of relying on algae fuel are quickly being solved.

Apart from the exponential progress that has been made in producing algae biofuel, its importance has also begun to make itself clear as algae biofuel is the only form of sustainable energy that produces a liquid fuel. Opposed to solar, hydropower, geothermal, or any other type of sustainable energy, algae creates a liquid fuel that can power aviation and nautical vesicles rather than just create a clean electricity source. The current primary source of aviation fuel, kerosene, is singlehandedly responsible for 12% of Greenhouse gas emissions (GHGs) and is contributing to the rising rate of fossil fuel and oil extraction up to 4% yearly (Desai, 2022). Aware of how problematic this can be, airlines have begun to tap into the algae fuel market with over 250,000 planes currently operating on a fuel blend of algae and kerosene known as Sustainable Aviation Fuel (SAF). With these new clean energy developments, analysts believe that by 2040, algae can reduce the amount of Greenhouse gas emissions from jet fuel by 90% and stay on track with the goals of the Department of Energy to release net-zero GHGs by 2050 along with the Paris Climate Agreement and other internationally recognized organizations (Desai, 2022). Cargo ships have also started to take advantage of biofuels as, an industry responsible for over one billion tons of carbon dioxide emissions and 3% of annual GHG emissions, algae fuels can lower carbon emissions by 60-100% (Solakivi, 2022).

As we begin an era where real change must be made if we hope to repair some of the damages that climate change and greenhouse gas emissions have caused, biofuel production and research are more important than ever. By 2050, the Department of Energy hopes that the United States will consume energy with net zero emissions with many countries following along, as seen by the establishment of the Paris Climate Agreement stating the global goal to reduce greenhouse gas emissions by 43% by 2030 (EIA). Alongside this, Data Bridge Market Research claims that from 2024 to 2031, the biofuel industry will grow from $8.01 billion to $12.59 billion for a 5.76% compound annual growth rate, shown in Figure 3. From a clean jet fuel source, biodiesel to power our cars, and a source of ethanol that produces the least amount of waste, advancing microalgae technology is one of the most important and cost-effective investments that we can make if we hope to increase our biofuel consumption.

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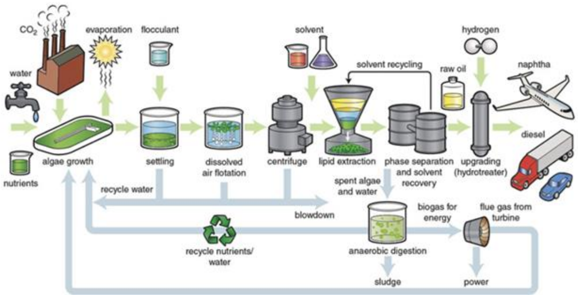

Figure 1. An illustration of the algae cultivation process showing the various stages from harvesting to processing and transesterification.

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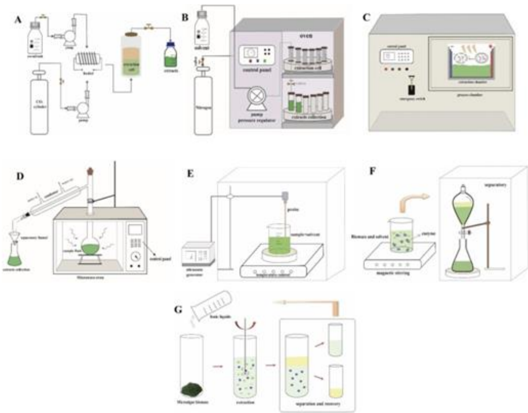

Figure 2. Diagrams explaining the different variations on modern algae lipid extraction. A) Supercritical Fluid Extraction B) Pressurized Liquid Extraction C) Pulsed Electric Fields D) Microwave-assisted Extraction E) Ultrasound-assisted Extraction F) Enzyme-assisted Extraction G) Ionic Fluids

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Figure 3. Graph representing the global algae market and the amount of profit each region is expecting to see from the years 2024 to 2031.

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