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Barriers to Accessibility of Algal Biofuels

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Abstract

Algal biofuel is a promising alternative to traditional fuel and electricity sources, but its development lacks both deep technological research and discussions of accessibility and implementation. This review seeks to partially address the lack of complementary work by providing an in-depth analysis of a variety of factors relating to the accessibility of algal biofuel. Technological advances must be coupled with critical thinking about how the cost and environmental impact of those advances can be lowered. The current status of biofuel infrastructure must be taken into consideration when developing new production systems for algal biofuel. Furthermore, the adoption of algae systems must consider the geographical, political, and wealth distribution of consumers, among other demographics. Only by matching the speed of innovation with the confines of reality will we be able to develop a sustainable and functional energy grid. This review serves as a companion piece to algal biofuel research with the goal of synthesizing relevant, contemporary considerations about how to expand algal biofuel to a modern society.

Introduction

Biofuels are receiving ever-increasing attention as a renewable source of liquid fuels, which the global economy depends on for transportation and the production of plastics and other hydrocarbon-based chemicals (Hannon et al., 2010). Unlike non-renewable fossil fuels, which come from the geological remains of living matter, biofuel is produced directly from renewable, living matter. Bioenergy production has evolved through four different generations, each dependent on different biomass sources: first generation fuels are fermented from food biomass such as corn and sugarcane; second generation fuels come from cellulosic sources such as perennial grasses; third generation fuels are extracted from algal biomass; and fourth generation fuels come from genetically modified algal species which are engineered to increase yield (Moravvej et al., 2019). First generation biofuels are well established and commercially viable; the most common of these is corn ethanol. As of yet, second, third, and fourth generation biofuels either lack commercial mechanisms of production or are not cost-competitive with existing options (Hannon et al., 2010). As there is substantial ongoing research but a lack of commercial viability, third generation biofuels are of great contemporary interest. Fourth generation biofuels are a newer field of similar interest, but GMO algae technology faces similar cost barriers and technical challenges to natural algae. As such, algal biofuel generally (third and fourth generation) is one of the most promising areas for contemporary biofuel research.

Algal biofuel comes from the oils of fast-growing algae and is utilized for transportation and energy production. As one of the fastest-growing primary producers, algae can produce more biomass than other plants when given the same resources. Additionally, algae can thrive in environments where other plants falter. This is due to algae's independence from soil conditions and tolerance for poor water quality (Ullah et al., 2015). These qualities enable the cultivation of algae without competition with food-bearing plants for land or water. Thus, algal biofuel may be a valuable alternative to other energy sources which have high demands for land and other natural resources.

There are numerous methods of extracting biofuels from algae. Biodiesel can be isolated from algae through an oil extraction process, which leaves behind "green waste". This waste can be processed to produce butanol, which can be mixed with or substituted for gasoline (Pittman et al., 2011; Ullah et al., 2015). In 2009, a prototype part-algal jet fuel was part of a successful proof-of-concept test flight (*Algae Used in Biofuel on U.S. Jet Test Flight*, n.d.). Although there has also been research into the production of hydrogen and methane using algal digestion systems, much research has focused on liquid biofuel systems (Ullah et al., 2015). Currently, the primary challenge in developing algal biofuel technologies is the high cost and difficulty of isolation procedures. Therefore, most research is focused on improving these processes until a commercially viable system can be designed.

The purpose of this review is to complement research into algal biofuel. We believe that understanding the barriers to algal bioenergy access, and the improvements that must be made for the technology to become commercially viable, is essential to nationwide adoption. We must promote education about algal biofuels for both consumers and producers. We must also consider the costs and necessary infrastructure for biofuel in order to make adoption economically feasible as well as scientifically possible. Finally, we must consider the social and environmental impacts of algal biofuels so that they become an equitable resource. Only with all these factors in mind can researchers and policymakers develop an applicable and effective algal biofuel industry while maintaining the large-scale goals of a clean energy future. It is critical to start diversifying energy supply chains and shifting away from the United States' nonrenewable sources of energy. Nonrenewable sources are not only disappearing, but have negative health and environmental effects, especially for the socioeconomically disadvantaged. Algal biofuels have the potential to revolutionize our energy sector with healthy, cost-effective clean systems. To design an energy future that is accessible and thoughtful, we must ensure a holistic approach to biofuel research.

Education

One of the first limitations of algae-based biofuel development is a lack of public accessibility to information regarding this energy source. Finding ways in which potential consumers can be educated will play a major role in the acceptance of algae-based biofuels as a reliable option for powering their homes, businesses, and vehicles (Cacciatore et al., 2012). Education can also act as advertisement for emerging companies, highlighting key information on the nature of algae itself, the processes involved for cultivation, harvest and refinement, its advantages in comparison with traditional fossil fuels, and the environmental benefits it offers, all while presenting their products to the public.

To increase accessibility to information about algae-based biofuels, companies can operate websites to document their efforts to produce biofuels. For example, the California-based company Solazyme has an online catalog which is focused on their industrial products (*Home Page*, n.d.). It includes information about each of their biofuel products as well as information on their performance. This company also provides information about their partnership with the US Navy to develop military grade biofuels that meet nautical specifications. Aside from making information on their fuel products and their performance available, Solazyme provides information regarding their fuel-making process, carbon footprint, and water and land usage. This type of transparency aids in countering misconceptions regarding algae-based biofuels and makes it easier for the public to inform themselves about the algae-based biofuels, which can allow for a more seamless adoption of alternative fuel sources.

However, these efforts to minimize barriers in accessibility to information do not guarantee public acceptance. Skepticism may arise in consumers as they make sense of the information provided, creating a barrier to widespread implementation of algae-based biofuel. Methods of presenting information about algal biofuels need to be updated to overcome this barrier. Currently, the US Department of Energy's Solar Decathlon site includes free resources for teachers, from kindergarten to 12th grade, to include renewable fuels in their curriculums (Beatty et al., 2019; Beatty et al., 2019; Beatty et al., 2019; Beatty et al., 2019;). However, these resources group algae-based biofuels under biomass fuels and contain little information about algal energy. This lack of information presents a challenge for adoption as misconceptions and generalizations about algae-based biofuels could take place without the initial exposure. If the United States wants to make algae-based biofuels a prominent source of energy, it must ensure that public education introduces algae-based biofuels in its classrooms to cultivate familiarity with this energy source, and it must ensure that teachers emphasize its differences from other land biomass.

Aside from effort from companies to make information about their products, sources, and processes as accessible to the public as possible, governmental organization should make efforts to increase education around algae-based biofuels. For instance, the 2022-2023 AlgaePrize competition by the US Department of Energy aims to engage high school and university students in the development of innovative algae usage methods, including biofuel (Lane, 2022). Educational initiatives not only have the potential to push important research forward but to increase awareness around algae-based products in young researchers, which initiates trickles down education of peers. The overall integration of discussions on algae-based biofuels into educational institutions can help educate people and break down barriers in the future usage of alternative fuels.

Infrastructure

Although algae cultivation has a historical context, contemporary cultivation has roots dating back to the 1940s during wartime with modern commercial applications for chemicals, nutrients, pharmaceuticals, and other valuable products. Given the modest industry present in the US and a microalgal biomass market valued at about $1.25 billion, existing infrastructure can be expanded to make algal biofuels a significant contributor to global energy needs (Patel et al., n.d.).

One form that algae can contribute to fuel demands is bioethanol, a well-established domestic biofuel from the first-generation bioenergy push spurred on by the 1970s oil crisis. Since the United States is one of the leading countries in biofuel production, with 187 commercial bioethanol facilities, the infrastructure to process algal biomass is already partially present. With about 1 million barrels of bioethanol per day produced in the

US, bioethanol is used in contemporary automobiles. It can power traditional gasoline engines with no extensive modifications and can be mixed with oils, like in standard ethanol-gasoline fuel mixtures (Khan et al., n.d.).

In addition to bioethanol, algal oil can also be processed into biodiesel, the other common form of biofuel. As crude algal oil is chemically similar to petroleum, today's oil processing technologies could theoretically be shifted to algal oil. This conversion also presents an opportunity for established energy companies to apply and utilize their logistical infrastructure and experience to optimize the transportation and storage of fuels (Hannon et al., 2010). Biodiesel presents an array of advantages and disadvantages. For starters, biodiesel is energetically and chemically equivalent to modern-day diesel gas. One of the significant advantages of using biodiesel is that it can be used in existing diesel engines without negative impacts on operating performance. Biodiesel is the only alternative fuel for heavyweight vehicles which does not require any unique injection or storage modifications (*Biofuel Basics*, n.d.). Currently, the availability of animal fat-based biodiesel is scarcer than for ethanol-based gas, which is reflected in the fact that there are only 423 biodiesel gas stations across the United States in 41 different states. (*Diesel vs. Biodiesel vs. Vegetable Oil | Homegrown Fuels - Consumer Reports*, n.d.). Since animal fat-based biodiesel is compositionally comparable to algae-based biodiesel, the lack of biodiesel stations reflects a barrier for the distribution in the future, as there would need to be an increase in stations to make algae-based fuels competitive with petroleum-based fuels.

Scalability is another challenge for algal bioenergy, as it is estimated that about 12 million hectares would need to be dedicated to algal oil production to meet the US oil need (Hannon et al., 2010). With the most extensive commercial algal cultivation sites no larger than 5 hectares, uncertainties with large-scale algal cultivation must be addressed to encourage its investment and adoption. Consideration for selecting cultivation systems, especially between open and closed systems, represents a point of contention between the higher initial costs of closed systems and the challenges of open systems. While 98% of algal biomass production occurs in open-pond systems, these sites are highly susceptible to external issues such as algal pathogens, contaminations, or environmental stress (Patel et al., n.d.). In addition to land use, algal cultivation sites will need significant water and nutrient inputs that can be somewhat mitigated initially through wastewater usage. These other infrastructure questions must be considered as algal production scales up for domestic needs.

However, it is also important to note the advantages that third-generation bioenergy has over previous generations. For instance, algae can be grown nearly anywhere, regardless of the quality of land or water; growth procedures can be cost-effective with greater effort; algae is more energy- and oil-dense with higher yields per acre than traditional bioenergy crops. Algae can also sequester more CO_2, and is faster-growing when compared to many crops, in addition to the unique advantage of being capable of bioremediation.

Cost

While there are many benefits to using algae as a biofuel, cost is a major drawback. Producing algae for use as a biofuel is complex and expensive. However, there are ways to reduce the cost of algae production systems. Since there is so much potential in this area, it is worth exploring the energy inputs and various costs associated with algae production.

To begin, it is important to note the relative price of algal biofuels in relation to other fuel sources. In October 2021, gasoline in the U.S. cost about $3.25 per gallon, and ethanol (E85) cost $2.73 per gallon (Bourbon & Science, 2021). Algal biofuel, on the other hand, costs over $8 per gallon (*Algae Biomass Factsheet*, n.d.). Algal biofuel is more than double the cost of gasoline and is about 3 times as expensive as ethanol. Algae is also significantly more expensive than other sources of biofuel. In October 2021, biodiesel B99/B100 cost $3.80 per gallon in 2021, and biodiesel B20 cost $3.21 per gallon (Bourbon & Science, 2021). Soybean oil costs $4 per gallon (*Algae Biomass Factsheet*, n.d.). The high price of algal biofuel relative to other sources of biofuel discourages the use of algae if other sources of biofuel are available.

There are varying methods for producing algae as a biofuel, including raceway systems (which are considered open pond systems), bubble column photobioreactor systems, and tubular photobioreactor systems (Dasan et al., 2019). Dasan et. al. compare the cost and energy investments of these methods. Of these three, high biomass-productivity tubular photobioreactor systems require the highest energy input at about 1777.70 megawatt hours/year (Dasan et al., 2021). In comparison, open pond systems and bubble column photobioreactors require around 1140 megawatt hours/year. Much of this energy goes into evaporating water, heating reactions, and evaporating solvent to recycle it. Although the high biomass-productivity tubular photobioreactor system is the most energy-intensive out of the three, it also has the lowest life cycle cost due to high productivity levels. Life cycle cost is defined as the total cost of something throughout its lifetime. It stands to reason that the more productive a system is, the less it will cost over the course of its life. Analyzing the life cycle cost of algal biofuel operations is beneficial because it allows companies to attain more profitability while not wasting money on items that will not be useful later. A low life cycle cost means that less tubular photobioreactors are needed to achieve the same effect as bubble column photobioreactors or open pond systems (Dasan et al., 2021).

Capital cost contributes to life cycle cost and should also be analyzed when considering algal biofuel production systems. Capital costs are defined as costs for the start-up of a business, and include cost of equipment, land, buildings, and anything else needed to initially get the business running. For low biomass-productivity bubble column photobioreactors, capital cost accounted for 81.17% of the total cost, making this method of production more expensive than tubular photobioreactors or open pond systems (Dasan et al., 2021). On one hand, high capital investment raises the cost of production. On the other hand, high capital investment in equipment or materials that work efficiently and last a long time may lower the overall cost of the production system over time. Thus, high capital investment in the right areas will prove useful over time. There are several ways that the capital cost of photobioreactors can be reduced initially. One such way to reduce the cost is to use less expensive materials to construct the photobioreactors (Dasan et al., 2021). Additionally, cost can be reduced by incorporating shade panels, which improve photosynthesis. This, in turn, improves biomass-productivity and reduces cost (Dasan et al., 2021).

Generally, it is said that open pond systems cost less than photobioreactor systems (Slade & Bauen, 2013). It is estimated that open pond systems cost about $0.3 to $0.4 for every kilogram of algae produced (Trilokesh & Uppuluri, 2021). However, open pond systems are water-intensive. Additionally, algae grown in open pond systems are subject to stresses like solar variability and non-optimal water temperature, which could negatively impact algae productivity.

Lower algae productivity in turn can negatively impact revenue (Kleiman et al., 2021). When sustainable revenue is not guaranteed, this can lead to debt and a consequential lack of funding for algae producers (Kleiman et al., 2021). Additionally, climate change contributes to environmental variability and environmental stresses that get placed on algae in open pond systems. Harsh weather conditions, such as hurricanes, can also negatively impact production (Efroymson et al., n.d.). This in turn causes greater fluctuations in the price of algae production (Kleiman et al., 2021). Low biomass-productivity open pond systems also have a high operating cost. Operating cost includes things such as labor and raw materials (Slade & Bauen, 2013). For such systems, the operating cost is 45.73% of the life cycle cost (Dasan et al., 2021). Open pond systems have a high capital cost as well, although not as high as that of bubble column photobioreactors.

One way that capital cost of low biomass-productivity open pond systems can be reduced is by increasing the speed at which algal cells are circulated through the pond system (Moazami et al., 2012). This circulation enables the algae to have an easier time accessing nutrients and light (Moazami et al., 2012). This in turn allows for greater biomass production, and thus smaller, cheaper, higher-producing ponds can be used (Dasan et al., 2021). Another way to reduce the cost of open pond systems is to reduce the cost of nutrients that are required for the algae production process (Efroymson et al., n.d.). Required nutrients include carbon dioxide, nitrogen, and phosphorus. One way to obtain carbon dioxide at a lower cost is to use carbon dioxide waste from nearby power plants or industries (Efroymson et al., n.d.). For this to be possible, an open pond system must be built near a power plant or other industry. Similarly, nitrogen and phosphorus from nearby wastewater can be utilized for algae production (Efroymson et al., n.d.). Again, this requires strategic placing of an open pond system near the desired nutrient source.

Another way to reduce costs is to take the leftover biomass that will not be used as biofuel itself and feed it back into the algal processing technology systems as sources of power and nutrients (*Algal Logistics*, n.d.). The Bioenergy Technologies Office aims to produce algal biofuel for as little as $3 per gallon by 2030 (*Researchers Strive to Reduce Cost and Time of Algal Biofuel Production*, n.d.). If this is achieved, it will mean that algal biofuel will be $0.25 cheaper per gallon than recent gasoline prices. Producing algal biofuel that is cheaper per gallon than gasoline will encourage more companies and people to frequent it as a fuel source.

It is necessary to note that if algae is going to be a sustainable, profitable source of biofuel, the total net energy gain of production must have a value above one (Efroymson et al., n.d.). Net energy gain is defined as the difference between the amount of energy used to obtain energy from a given source and the amount of energy yielded from the same source. When open pond systems, bubble column photobioreactors, and tubular photobioreactors were considered in terms of cost and profit, it was found that they all yielded a net energy gain of less than one. In other words, current systems in place for producing algae as a biofuel are not economically favorable, especially when compared to the net energy gain of fossil fuels. However, if ways to reduce cost are successfully implemented in the production of algae, then it is possible algae could be the future of biofuel.

Demographics

In addition to possible monetary barriers, third generation biofuels also have demographic barriers that can hamper accessibility and prevent distribution. In terms of geographical location, the use of algae can be both advantageous and unrealistic, depending on the growing environment. Algae can be set up in ponds, wastewater collection centers, algae facilities that involve the use of sizable growing tanks, or other water sources that do not serve any current use in their environments. This gives a much larger range of suitable growing environments than first generation biofuels that have to be converted from edible crops.

While this provides opportunities for readily available growing sources for algae feed stocks in aquatic environments, it raises problems in areas that do not contain large amounts of water mass. States with higher percentages of water area, such as Michigan and Maryland, have over 20% of their land area belonging to water. On the other hand, states in the Southwest desert region of the United States, such as Arizona and Nevada, contain less than 1% water (Reilly, 2008). Consequently, these drier areas would have to rely on artificial algae facilities that require an outside water source to maintain their viability. This would require large amounts of water to be redirected from the population in an area where droughts frequently cause scarcity. A possible alternative to alleviate the stress of trying to grow algae for biofuel locally would be to ship large amounts of already refined biofuel to these drier areas. This method would be similar to the gasoline distribution infrastructure that is already largely in place across the country. Additionally, these water sources would have to be publicly owned or would have to be leased to manufacturers. These water areas would also have to be outside of environmentally protected areas and would have to get clearance from governmental organizations to ensure that they are environmentally secure. Locally growing algae for biofuel consumption is more feasible in areas with more readily available water than in drier regions.

Additionally, age demographics play a role in the integration of biofuels. Using algae-based biofuels would essentially be another green alternative method for transportation, similar to electric cars. Green energy trends are more widely supported among younger, more environmentally conscientious generations. A study conducted in Norway found that the owners of electric vehicles were younger, had higher education levels and incomes, reported more car use, and had more knowledge about electric cars as compared to owners of conventional cars (Simsekoglu, 2018). EV owners also had a higher level of understanding of the environmental effects of car use and felt more responsibility to do something about it (Simsekoglu, 2018). Likewise, U.S. residents in the Northeast were surveyed and millennials were 31% more likely to consider the purchase of an electric vehicle than baby boomers. Younger generations understand the gravity of environmental issues and are more likely to buy into methods to solve these problems. Since this age demographic is more likely to buy electric vehicles, they also should be more apt to transition from traditional oil to algae-based biofuels and would be more likely to support the initiative. However, this also means that efforts will be required to incentivize the purchase of electric vehicles and biofuels among older generations.

Another important demographic to consider is the difference in availability based on socioeconomic class. In recent years, several major car manufacturers have promised to increase their output of flex-fuel vehicles, vehicles which can run on gas that contains typically 10% ethanol (E10 gas), or 85% ethanol (E85 gas) (US EPA, 2015). E85 gas is significantly cheaper than ethanol free gasoline. The average price of a gallon of gas in the United States is over three dollars, compared to just over a dollar for E85 gas (Farrell et al., 2018). However, E85 gas is not as fuel efficient as normal gasoline, with 1.5 gallons of E85 being energetically equivalent to one gallon of ethanol-free gasoline. Therefore, the cost between the two fuel sources ends up being closer than is initially expected. However, it is still cheaper to use E85 for a tank of gas for flex-fuel vehicles. Additionally, the United States currently offers a tax credit to those who drive flex-fuel vehicles as a way to incentivize citizens to use this cleaner fuel source. Perhaps expanding this tax credit to include the use of algae fuel products would incentivize more people to consider this as a valid fuel source. Likewise, another important demographic to consider is gender. Studies have shown that women are slightly more likely to be environmentally conscious than men, so this could be an important area to explore in terms of convincing people to adopt this cleaner fuel source (Pearson et al., 2017). Another problem to consider is in terms of the availability of gas stations that provide E10 or E85 gas. Currently, there are only 3,300 gas stations in the United States that sell E series gas out of over 168,000 total gas stations (Brown et al., 2021). These 3,300 gas stations are spread across 42 states, meaning that a sizable chunk of the country does not have access to flex-fuel at all. To make algae-based ethanol more mainstream, partnerships would need to be formed with major gasoline companies to ensure that the public would have universal access to this product.

Environmental Impact

On top of the demographic barriers, there are environmental impacts to consider when approaching the use of algae-based biofuels. The growth of algae requires a variety of nutrients such as nitrogen, phosphorus, and potassium. To acquire enough algae to produce commercially, specific amounts of micro and macronutrients, light intensity, CO_2, and water are needed (Bošnjaković & Sinaga, 2020; Pearson et al., 2017). Fertilizers such as ammonium nitrate have significant impacts on climate change. The production of fertilizer requires large amounts of natural gases, so algal biofuel would not eliminate the use of fossil fuels. Not only is the production difficult, it also has environmental impacts that should be considered. Exposing the environment to high concentrations of fertilizers can create problems with water quality, air quality and aquatic life.

Another impact of the cultivation of algae is the increase of N_2O in the atmosphere. The effect this has on the ozone layer can negatively impact both human health and the environment. A study found that nitrogen sources used to grow algae negatively impacted N_2O emissions. For example, the usage of NO_2^- rather than NO_2^- under CO_2 sparging conditions would increase the N_2O when farming algae (Bauer et al., 2016). The depletion of the ozone layer is linked to increased levels of UV radiation and would be detrimental to global life cycles, food chains, and human health. While algae can decrease greenhouse gas production via consumption, the impact of other detrimental gases must be considered. It is important to minimize the quantity of ozone-depleting substances in the atmosphere, so that the ozone layer has a chance to recover ("The Montreal Protocol on Substances That Deplete the Ozone Layer," n.d.).

Wastewater and genetically modified microalgae can negatively impact ecosystems. Problems can arise from the failure to manage wastewater and distribute it safely into the environment. Algae can grow quickly in a variety of environmental stresses, meaning that distribution of microalgae into the environment can affect native organisms via competition for resources (Pugazhendhi et al., 2020). This is a large concern because it can create algae blooms in local bodies of water. These algae blooms compete with native organisms for nutrients and add toxins to the environment. Although harmful, algal blooms can be mediated by making research data more accessible, and by using certain algicides to kill excess algae (Lopez, et. al., 2008).

Water consumption for algae is an issue that needs to be considered before using algal fuel for mass production. The water required for one kilogram of microalgae biodiesel would take 3.5 to 3726 kilograms of water, depending on the type of microalgae (Pugazhendhi et al., 2020). Current practices in algae farming would require higher water consumption, even as water usage is already an issue in many parts of the US. Careful consideration of the location, water usage, and resource availability would be necessary to make algae production successful.

Despite the environmental challenges of algae cultivation, there are still benefits to using algal diesel. Biodiesel usage has a lower emission rate of pollutants by eliminating tailpipe emissions and takes less energy to produce. These pollutants include SO_x, CO, and particulate matter (Gao et al., 2012). Algae can be produced domestically more than traditional fossil fuels. This allows easier access and lowers fuel imports (Huang et al., 2013). Although using algal fuels is not entirely carbon-neutral, it has a positive influence on air quality. Pollutants can negatively impact those with respiratory disease or weaker immune systems. Algal biofuel can lower pollutant emissions, which will be beneficial to the environment and the health of the community.

Although wastewater is a concern in cultivating algal fuel, this waste can be recycled and reused to grow more algae (Mobin & Alam, 2014). Wastewater contains nutrients necessary for algal growth. Reusing wastewater is beneficial to the environment and requires less resources. This means that clean water is not necessary to grow algae. The main concern of reusing water is not having enough nutrients. Although the water already contains some nutrients, extra resources may still be necessary for efficient algal cultivation. Despite the lack of neutrality in the recycling of waste, this energy solution shows great potential.

Future Directions

This review has explored various challenges to the adoption of algae-based biofuels, but many opportunities remain available to reduce or eliminate such accessibility barriers. There are two main avenues to address the aforementioned concerns: further research to improve economic and environmental viability of algal biofuels, and publicizing and incentivizing the use of biofuels to gasoline companies and the public.

Currently, the most essential algal research focuses on optimizing procedures for large-scale cultivation of algae and extraction of energy sources, as well as genetic engineering of algae strains and ecological construction of algal habitats. Structural and engineering research can inform the optimum culture environment, which is likely to be a modified version of photobioreactors or open raceway ponds. As previously discussed, photobioreactors allow for a more controlled environment that results in greater biofuel production at an extremely high operating cost, while open raceway ponds can be cheaper but more susceptible to algal pathogens and inefficiency (Hallenbeck et al., 2016). Culturing systems will also require a method of water recycling, given the high economic and environmental cost of algae's water usage (Farooq et al., 2015). Water availability also necessitates strategic placement of algae farms, with the most economically ideal locations being wastewater areas. Algae has the ability to remediate certain wastewaters by using "contaminants" as nutrients for growth (Mobin & Alam, 2014). However, different species of algae require different conditions (including sunlight, temperature, and water/nutrient conditions) for optimal growth, which necessitates careful design on behalf of algae project-planners in order to match the best algal strain to its location and necessary nutrient supplementation (Farooq et al., 2015; Kour et al., 2019). Designing a system with minimal nutrient or fertilizer input will be especially beneficial to keeping algae's environmental footprint small - not requiring the input of nutrients obtained through methods that might be transported or obtained using fossil fuels (Bošnjaković & Sinaga, 2020). Optimizing and balancing the algae ecosystem will be important for long-term sustainability of individual algae farms.

Additionally, chemical engineering is being optimized for maximal lipid and biomass extraction using low energy techniques: Hallenbeck, et al. cites promising new research into "switchable solvent" and "wet lipid extraction" protocols that do not require centrifugation steps (Hallenbeck et al., 2016). These engineering puzzles are gradually being solved by biologists: genetic engineering has become a powerful tool to alter algae species to increase lipid production, increase environmental tolerances (Adeniyi & Burluka, 2018; Kour et al., 2019; Rodionova et al., 2017), and engineer properties to make the harvesting process more feasible, such as cells which settle out of solution quickly (Hallenbeck et al., 2016). Comprehensive practical studies that model an algal system can prove the utility of these techniques (Yadav et al., 2021), and promote acceptance and adoption of algae-based biofuel farms on a national scale.

Finally, as algae technology demonstrates the feasibility of algal biofuels, top-down incentives can help to promote widespread use of algae biofuel. Since algae biofuel is still in its early stages of development, research and development require significant financial support in order to allow the technology to reach a commercially competitive state. Government intervention has previously contributed towards the large-scale use of first- and second-generation biofuels as well as solar photovoltaic technologies (Haase et al., 2013), which suggests that similar policies benefiting third-generation biofuels could provide much-need momentum to algal biofuels (Doshi et al., 2016). An example of government intervention encouraging biofuel usage is the Energy Policy Act of 2005 which required the integration of 7.5 billion gallons of renewable fuels into standard gasoline by 2012. The Energy Independence and Security Act of 2007 has since increased the quantity of renewable fuel incorporation to 36 billion gallons by 2022, in addition to requiring these biofuels to emit 50 percent less greenhouse gas emissions when compared to emissions from fossil fuels (US EPA, 2014). These types of legislation create a place for biofuels in the US market, encourage research and the expansion of biofuel infrastructure. Clearly, there are many potential avenues for research to improve algal biofuel accessibility, and with all convergent algal research working in synergy, algae-based biofuels have the potential to shape the future of sustainable energy.

Conclusion

While algae biofuel presents a promising alternative to conventional fuel sources, barriers to widespread adoption remain. This review discusses the barriers associated with the accessibility of algal biofuels.

An important element in the adoption of algal biofuels is the education of the populace. Even though US companies like Solazyme and Algenol Biotech are at the forefront of algal bioproduct development, public school curriculum fails to include lessons on third-generation biofuels indicating shortcomings in alternative energy education. Without an understanding of what algal biofuels are, it is difficult to successfully advocate for their adoption.

A constraint to the accessibility of algal biofuels is the infrastructure required for the growth of algae and conversion to biofuels. Given the novelty of algae as a biofuel feedstock, there are no significant established facilities capable of processing or growing large amounts of algae compared to first or second-generation feedstocks. Investment into algae growing and processing frameworks is a necessary step towards the accessibility of algal biofuels. In order to be an economically viable substitute for conventional fuel sources, the production cost of algal biofuels must be an equal or lesser value compared to other fuel sources. One aspect of algal biofuel production that is especially costly is the growing and processing of algae before conversion into fuel. Decreasing the price of production of algal biofuel reduces the economic barriers associated with accessing alternative fuels.

Demographically speaking, the availability of resource inputs to algal biofuels production plays a role in the accessibility to algae biofuels and the feasibility of biofuel production across the United States. The utilization of resources such as water must be balanced in such a way that allows for consumption both by humans and industrial-scale algae production. In addition, the prevalence of vehicles capable of combusting biofuels and the number of gas stations selling biofuel are limited, presenting a hurdle to the widespread adoption of algal biofuels.

While biofuels are often valued for their positive environmental impacts, algal biofuels are still associated with negative environmental impacts and greenhouse gas emissions, presenting a barrier in the campaign toward a net-zero society. To reduce and balance out negative impacts research and development are necessary. New technologies can present a path toward accessibility, improving infrastructure, reducing cost, and mitigating environmental impacts. Though new technologies are a large part of the quest to make algal biofuels more accessible, ultimately a multifaceted approach is necessary, incorporating improved technologies with education initiatives and economic policies.

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