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Evaluating Algae Based Biofuels as a Replacement for Vehicular Fossil Fuels

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Abstract: ***In this paper, we explore the viability of algae-based biofuels as an alternative to fossil fuels to mitigate the detrimental environmental impact of fossil fuels. This review paper examines the pros and cons of algae-based biofuels in terms of their environmental impact as well as their economic viability, given that it is imperative that we find a cleaner alternative to fossil fuels to alleviate the impacts and risks of climate change. Algae-based biofuels appear to be among the most promising alternatives.***

Keywords: algae-based biofuels, renewable energy, climate change, sustainability, environment

1. Introduction

Climate change is emerging as the most worrisome and urgent global issue. All studies recently have echoed the finding of the UN report on Climate Change which stated that "Fossil fuels – coal, oil and gas – are by far the largest contributor to global climate change, accounting for over 75 per cent of global greenhouse gas emissions and nearly 90 per cent of all carbon dioxide emissions". {1} Despite its known dangers, the use of fossil fuels has only increased and the world "burns over 4,000 times the amount of fossils fuels burnt during 1776".{2}. This large-scale use of fossil fuels has increased the proportion of greenhouse gases like carbon dioxide (CO2) and nitrous oxide (N2O) into the atmosphere, which intensifies the greenhouse effect, by trapping the heat and increasing the Earth's average air temperatures. Unfortunately, these greenhouse gases can remain in the atmosphere for decades to hundreds of years and there is no means of eliminating them. Besides the damage caused by the greenhouse gases, Coal-fired power plants are also known to generate dangerous mercury and sulphur dioxide emissions and dangerous particulate matter that has led to the increase in air pollution and proved detrimental to human health and the eco system's natural balance. The faster and unseasonal melting of glaciers caused by settling of Airborne particles on snow which increases absorption of sunlight rather than allowing it to be reflected by the otherwise clean glacier surface is one grave example of the dangers posed by this form of pollution to put larger ecosystem.

We cannot afford to just focus on the human element alone and ignore the far-reaching impact on the other species. Increased acidification of our oceans and other water bodies due to acid rain and earth contamination caused by the reaction of Sulphur dioxide (SO2), nitrogen oxides (NOx), and carbon dioxide (CO2) with water vapor, oxygen, and other chemicals has had a huge impact on the aquatic ecosystem.

These warning signs, make it vital for our scientific community to come up with sustainable alternatives to meet our rising energy demands. It is in this context, that Biofuel produced from algae has garnered a lot of attention lately. {3} Referred as the third-generation biofuel, it is produced from algae. Algae are photosynthetic organisms that use light energy, water, carbon dioxide and a few inorganic nutrients to develop and multiply. This group of organisms have a wide range of types ranging from microscopic, single celled forms (microalgae) to large seaweeds (macroalgae which can be as much as 100 feet long. Although they photosynthesize and contain chlorophyll, they do not have true roots, stems or leaves and hence have never been counted among the plants in the real sense. This species has been in the news for its ability to become a useful and sustainable energy resource.

Researchers have successfully studied how oil extracted from different varieties of algae can be converted into biofuel. Studies have revealed that Algae could potentially produce up to 60 times more oil per acre than land-based plants like corn. {4} The fact that Algae can grow in uncultivable areas and can also grow using wastewater and seawater not suitable for conventional crops makes it an attractive option.

However, there are quite a few impediments in making it a popular and economically viable option. for example, the arduous process of separating the water from the algae at harvest, the higher demand for water for its healthy growth, specially at a time when the world is facing acute water shortage, and its expensive extraction are concerns that need to be worked on urgently.

In this paper we evaluate the potential of this energy source at a time when alternative fuels are the need of the day.

2. Why is Algae considered a useful oil and energy alternative?

(a) The chemical composition advantage:
Studies have shown that a large portion of crude oil is of microalgal origin, with diatoms being the most likely candidates, considering their lipid profiles and productivity. {6} They are the principal constituents of the organic carbon buried in oceans that play a relevant role in the formation of crude oil deposits in coastal and marine environments. {7,8,9,10}. Algae contain various nutrients such as protein, carbohydrates, lipids, fibre, and others. Its high lipid content which can on an average account for 20–40% of algal dry weight going up to as much as 85% in some species. Their ability to adapt to various ecological habitats and to produce and store substantial amounts of triacylglycerols (TAG) photo-oxidative stress or other adverse environmental conditions, makes them {11} a very interesting option for

oil production as compared to other terrestrial plant sources like corn and palm.

(b) Relatively easier potential for genetic engineering:
To make algal fuels a more popular option and available for mass extraction, Genetic improvement and modifications are essential to construct superior microalgae for manufacturing industries using various methods such as selection of novel strain, stress tolerance, resistance to pathogens, product development and metabolic pathways and cellular contents. {12} With potentially millions of species, algal diversity gives researchers many options for identifying production strains that may have greater utility for fuel production. This sheer variety provides sources for genetic information that can be used to improve these production strains. The microalgal species being investigated as potential biofuel crops originate from groups whose ancestral relationships are significantly broader than the most diverse land plants, providing a wealth of genetic diversity {12,13}. Moreover, their rather simple cellular structure compared to other terrestrial plants with the potential for extraction of oils, offers more opportunities for genetic engineering modification. Unlike most other plants, algae do not have complex tissue structures, which simplifies genetic modifications through direct DNA insertion or other genetic engineering methods like CRISPR-Cas9.

(c) Rapid growth in diverse conditions:
Algae is known to adapt to various growing conditions and is more adaptable as compared to other plants. They are found not only in fresh and marine waterbodies but also on terrestrial habitats such as soil, tree trunk and man-made substrates and can be found growing abundantly even in extreme habitats which is indicative of their higher adaptability as compared to other species. {15} Sometimes algae are extremophiles, found growing in extreme environments such as hot springs, deserts, cold waterbodies, polar regions, permafrost, high or low pH and high levels of CO2 {16}. Numerous studies have shown their astounding response to desiccation stress, making them one of the most adaptable species known. For example, they produce specialized spores that would remain dormant during harsh periods and revive once the favourable conditions return. Their thick cell walls and mucilage sheath are protective mechanisms that delay desiccation. They are also known to produce and gather organic osmolytes that protect them from desiccation, high irradiation and UV light. Studies have revealed the existence of unique membrane associated proteins in D. salina that can change structure and composition to help it adapt to various salinity levels. {17} They have the ability to survive the harsh cold and desert topography of harsher regions like Leh, Ladakh, Antarctica and Arctic which shows that they have the ability to not only face the cold but also to light stress caused by the bright and high UV radiation. The Zygnema strains studied from Arctic and Antarctic habitats had a high amount of antheraxanthin and zeaxanthin known to give it the light-tolerating mechanism that adds to its adaptability asset. This makes it very attractive as a fuel alternative as it is not as restricted by geography and allows every nation across the world to use it to their advantage.

(d) Zero Carbon footprint with great utility of ecological repair.
Algae has a reduced impact on the environment compared with other terrestrial sources of biomass used for biofuels. {18}] they do not compete with other crops and can be grown on non-cultivable land. They are in fact extremely important for our ecosystem as they produce approximately half of the atmospheric oxygen on earth, while also helping in mitigating the problem of the greenhouse gases that have become a major environmental cause of concern given their impact on climate change and global warming. Their ability to grow relatively faster and in a wide variety of conditions and with relatively less sunlight requirements make them an ideal ecological tool. Algae such as spirulina absorb a large quality of carbon-dioxide (CO 2), nitrogen dioxide (NO 2) and sulphur dioxide (SO 2) from the polluted air as nutrients for their photosynthesis process to generate oxygen. Algae has a distinct advantage over other traditional and recycling methods like industrial recycling, usage of alternative fuels and planting trees, as they are not completely devoid of a carbon footprint and can be very cumbersome. For example, creating forests is a long-term solution that requires vast tracks of cultivable land. Algae has the advantage of being geographically unrestricted in its growth patterns, does not eat into cultivable land, cost effective, renewable and sustainable, can tolerate harsh and fluctuating environmental conditions including varying temperature, pH and salinity and yet delivers on the conversion of greenhouses gases into oxygen with greater efficiency. {19,20}

Water polluting elements like potassium, calcium, sodium, magnesium, sulphur, chlorine, bicarbonate, ammonium salts, phosphate, and heavy metals that cause water pollution can also be remedied using alga varieties that have the capacity to remove phosphorus and nitrogen-rich nutrients from wastewater. Algae benefit wastewater treatment by producing oxygen that allows aerobic bacteria to breakdown organic contaminants in the water removing excess nitrogen and phosphorus in the process. It is an affordable alternative as compared to most wastewater treatment practices. {21} studies have also repeatedly revealed how algae can be used as a cost effective and useful tool for the removal of salt from saline water for meeting the shortage of fresh water.

(e) Easily adaptable substitute for petroleum:
The internal combustion engine model is the most commonly used in vehicles, production machinery, and manufacturing equipment. The Diesel ones are preferred over the petroleum ones due to energy conversion efficiency and cheaper fuel costs and are the favored power source in electric generators, machinery, and equipment that are used in various sectors including construction, agriculture, and heavy industry, as well as among road vehicles and maritime transport fleets, {22} Unfortunately, diesel engines are infamous for their excessive emissions of air pollutants and it was for this reason that studies focused on looking for a more environmentally safe replacement were conducted and led us to biofuels. Since algal biodiesel's physical and chemical properties have many similarities with diesel. These similar properties make the blending of biodiesel easy, as well as the use of biodiesel does not require the engine to be seriously modified. {23}It is very important to

note that the oxygen content in these fuels is much higher than conventional fossil based fuels and hence they brun more cleanly and reduce the number of unburned hydrocarbons. One of the biggest differences between biodiesel and diesel fuel is the oxygen content. While the oxygen content of diesel is very low or even absent, biodiesel is an oxygen-rich fuel. Oxygen content in biodiesel is about 10 to 12% weight depending on the type of biodiesel. {24} Biodiesel has also been found to have a higher cetane number (CN) as compared to diesel. The higher the cetane number, the shorter the time between the start of fuel injection into the combustion chamber and the ignition process. The higher the cetane number, the better the ignition quality of the fuel. {25,26}, this is one of the most crucial indicators in the selection of a fuel. The advantages of having a higher cetane number in biodiesel are manifold. These include shorter ignition delay, lower NOx emissions, and a decreased incidence of knocking during the combustion process. {27,28}

(f) Minimal wastage and multiple uses:

It is important to note that once algal oils have been extracted with organic solvents or removed in some other way, the remaining biomass will be made up of approximately equal amounts of carbohydrates and proteins, which can be used as healthy. Carbohydrates can be used to produce methane by anaerobic digestion or ethanol by fermentation. Proteins can be used for animal feed or even human food. {29} Besides being the largest so called oxygen generators/ producers in the world, algae are essential for maintaining the aquatic ecosystems by providing all living organisms of water bodies with preliminary nutrients and energy required. {30} Algae's presence and abundance are vital for the biodiversity and productivity of marine and freshwater habitats. They create habitats and provide food resources for various species, influencing community structure and ecosystem dynamics. {31} growing understanding of this species have made them popular for their nutritional value. They are now marketed as “functional foods” or “nutraceuticals”; terms for foods that contain bioactive compounds, or phytochemicals, that may benefit health beyond the role of basic nutrition (e.g., anti-inflammatories, disease prevention). {32, 33} Researchers have found algae particularly useful in resolving severe malnutrition, oxidative stress-related diseases and several chronic infections, as it is a crucial source of several important metabolites such as flavonoids, terpenes, phenols, carbohydrates, PUFA, pigments, omega-3 and vitamins and are known as complete food, leading their way in the nutraceutical industry {34,35} Besides Algae has always been considered crucial in the medical and pharmaceutical sector due to its extensive therapeutic properties like anticancer, antiviral, anti-inflammatory and antioxidants. {36} it’s a popular ingredient in cosmetics due to its antioxidant, moisturizing, antiaging and anti-tanning properties. It is mostly used in the form of extracts to eliminate chances of contamination in industries that are formulated into skin sensitizers, sunscreens, thickening agents, antiwrinkle creams, hair care products and moisturizers. {37} The list is long and validates how crucial this plant could be to our planet’s future.

3. Impediments to its viability as a fuel source:

Despite the above-mentioned numerous benefits of using algae as a fuel, it has failed to make a larger impact due to the following challenges that impede its commercialization:

1) To make algal fuels commercially viable to compete with fossil fuels, there are several issues to be resolves. Mass production will require huge availability of land and water resources which may not be easy to find out and may eat into cultivable land and precious water resource, especially at a time when the world is staring at a future where both food and water shortage seems imminent.
2) The whole process of converting algae into biofuel involves genetic, biological, agricultural and chemical engineering processes which are expensive and increase the cost of production and making them economically less competitive to fossil fuels, making it a disheartening alternative especially in cost sensitive countries and regions. The fact that leading like Algenol, Shell and Chevron who pumped in huge investments to explore this alternative at a commercial level, reported failures also increased the scepticism around it. studies have estimated that producing a kilogram of biodiesel requires 3.73 tonnes of water, 0.33 kg of nitrogen and 0.71 kg of phosphate. In a situation where the world’s, finite phosphate resources have peaked and there are alarms being raised that the existing reserves are expected to be completely depleted in 50 to 100 years, and peak phosphorus will be reached by the year 2030, we cannot choose a phosphorus dependent option. Moreover, production and supply of this source depends on variables that bring in unwanted tentativeness in supply chains. Biofuels’ promise of energy security also proves to be an illusion
3) Genetic modifications to algae which is a crucial part of the food chain or make it better for oil yield has the potential to bring in unforeseen and possibly unsafe changes in our ecosystem.
4) If this option becomes popular, the rich nations will first try and exploit the land and the water resources of the poorer nations, impoverishing them even more. The high expense and environmental protection of land developed nations like the United States and developed nations will force them to look for cheaper land tracks in less developed countries. Already, reports of unscrupulous governments confiscating land from villagers and burning forests wholesale to make way for lucrative biofuel plantations are making the rounds on a regular basis. {38} There is well-documented “green grabbing” of land in Latin America and Africa and Asia for cheap acreage and water rights needed for cash crops. A 2010 World Bank analysis revealed that wealthier countries including Saudi Arabia, South Korea, and China have already bought or leased more than 27 million acres of foreign land and water rights for remote cultivation of food, industrial, and biofuel crops. The chief locations for such appropriations are Sudan, Mozambique, Liberia, and Ethiopia, where governments are not protective of citizen land rights

and more than 12 million persons are living hand-to-mouth on aid from the UN World Food program. {39}

5) Energy return on investment (EROI), is the key index for measuring the sustainable value of an anergy source. It is the proportion of energy produced by a given source to the energy required to produce it. When the EROI is less than 1, more energy is needed to create a fuel than is found in the fuel and coproducts. Studies conducted on algal biofuels produced in open ponds or photobioreactors, the predicted EROI ranges from 0.13 to 0.71. this is far lesser than the desired figure of 3 for it to be categorised as an efficient sustainable energy source. {40}
6) The estimated cold flow properties (CFP) of biodiesel are not as good as that of the fossil derived fuels like petrol and diesel. This is attributed to the presence of saturated and unsaturated fatty acid esters. This makes them unsuitable for usage in cold weather conditions. {41}
7) Good fuels have greater stability of oxidation which is a good index of their resistance to oxidative reactions, which can lead to the formation of harmful by products, degradation of the fuel quality, and potential engine performance issues. The oxidative stability of biodiesel fuel is influenced by the number of bis-allylic sites present in unsaturated biodiesel compounds. Factors such as the biodiesel's age, the composition of fatty acid methyl esters, and storage conditions contribute to biodiesel's oxidation stability. {42} Its molecular structure, makes biodiesel fuels more susceptible to oxidative degradation compared to fossil diesel fuels. {43}

4. Conclusion

Despite the warnings of unprecedented climate change and global warming the demand for fuel across the world is rising unabated. The world's consumption of fossil fuels climbed to a record high last year, driving emissions to more than 40 gigatonnes of CO2 for the first time, according to a global energy report. The worrisome fact is that despite a record rise in the use of renewable energy in 2023, consumption of fossil fuels continued to increase too, an annual review of world energy by the Energy Institute found. {44} This clearly shows that nations and people across the world have failed to internalise the lurking danger in their consumption patterns despite evident unprecedented warming and flooding happening across the world, warning us of the risk of ignoring climate change.

The Energy Institute, the global professional body for the energy sector, has statistics that indicate that energy industry emissions may have reached a peak in advanced economies, but continue to rise in the developing ones that are outing their short-term development goals ahead of the environment at these environmentally precarious times. In densely populated areas like India, reports show an 8% increase in their consumption of fossil fuel. In fact, India has used more coal than Europe and North America combined in the calendar year 2023, said Energy Institute and KPMG in a report titled 2024 Statistical Review of World Energy. {46}

This clearly shows that the consumers haven't fully woken to the reality of the rampant use of fossil fuels and that their focus hasn't gone beyond the direct costs that they bear for their fuel consumption. This cost does not factor in the hidden cost often termed as the externalities that impact them in the form of environmental and health damage, which can impact their families and future generations. It is important that these externalities though sometimes not very obvious and easy to comprehend on a daily basis Externalities are sometimes easy to see, such as pollution and land degradation, and can be less apparent, but assume very dangerous consequences in the form of costs of asthma and cancer, or the impacts of sea level rise which could threaten the very existence of large swathes of human population living along the costs and acidification of water bodies that will affect the aquatic life too. {47} We tend to overlook that there are huge hidden costs associated with every stage of the fossil fuel supply chain. While extraction processes can exacerbate land degradation and air and water pollution, and harm local communities, its Transportation itself could lead to harmful leakages and spills, their combustion emit most of the carbon emissions, nitrogen and polluting particulate matter and toxins and global warming emissions, their waste products are no less harmful and known to cause land and water pollution. {48, 49, 50, 51, 52} Environmental damage and its repercussions on human health are already beginning to have a telling effect on economies specially the poorer ones.

It is in this context that algal fuels were seen as a pathbreaking source that would not only be a good fuel source but could also help reverse the environmental damage. Algae's high-lipid content found in some species coupled with its high per-acre productivity, its ability to grow in diverse environments and its ability to absorb harmful carbon and nitrogen dioxide could be the answer to a lot of environmental problems. No other species as this ability to make a difference without competing for pace in the cultivable areas. Besides, scaling up algae farming could lead to other commercially viable products besides fuel, making it very lucrative. Though there was a great deal of excitement about in the 90s with large oil corporations like Shell and Chevron pumping funds into its progress, their patience was short lived, and they abandoned the program. Hope still exists as some like the ExxonMobil continues its work in the area collaborating with startups in the genomics area to look for CRISPR editing to come with varieties that are richer in lipids and can thrive with lesser quantities of water as it is becoming a precious resource.{53} They are not ready to give up till they find a solution to make this biodiesel economically viable by adding scale. Some of these efforts were criticised as mere green washing efforts. The world needs to know that although using fossil fuels that come from resources built hundreds of years back is a quicker and more economically convenient option, it can and is already endangering the world and is a very high risk option. Governments and international bodies will have to be focused on encouraging investments and asking oil companies to divert some of their profits to meaningful research. There are no miracles, and the world needs to know that. It might be an expensive and arduous process, but the world doesn't have much choice especially at a time

when all declared fuel emission goals are too far-fetched and becoming impossible to achieve.

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