www.envsciarch.com

ENVIRONMENTAL SCIENCE ARCHIVES
ISSN: 2583-5092
Volume IV Issue 1, 2025

REVIEW

OPEN ACCESS

A Comprehensive Review on the Effect of Climate Change on Algal Biofuel Production

Received: 2025/01/22
Accepted: 2025/03/06
Published: 2025/03/21

Sangeeta[1], Aditya Pratap Singh[2], Vijay Kumar Sinhal[1], Lalit Kumar Pandey[1], Jagat Narayan Maurya[1]

[1]Department of Plant Science, MJP Rohilkhand University, Bareilly 243006, Uttar Pradesh, India
[2]Department of Microbiology, MJP Rohilkhand University, Bareilly 243006, Uttar Pradesh, India
*Correspondence for materials should be addressed to JNM (email: jnmaurya@mjpru.ac.in)

Abstract

The exponential increase in world population has put enormous increased motorization that led to an overwhelming pressure on the earth's finite supply of fossil fuels. For the benefit of human well-being, renewable and sustainable energy sources must be developed because the lack of fossil fuels is negatively affecting the environment and the economy. Algae with high cellulose/starch/lipid accumulation can be the best substitute for food crops in the case of economic and environmental concerns. These algae can be used to produce bioethanol, a sustainable fuel. Some types of algae can directly contribute to the generation of ethanol by producing it during dark-anaerobic fermentation. Production of algal-based biofuel is an economically effective and environmentally friendly energy source that seems to be a promising alternative for the future generation of biofuel. In the 2030 Agenda for Sustainable Development, sustainable transport is mainstreamed across several SDGs and targets, especially food security, health, energy, economic growth, infrastructure, and cities and human settlements. It aims to make cities and human settlements inclusive and identify ways to develop and implement low-carbon and resilient transport strategies. The current review describes the state of the field of algae biofuel in the past present and future. The likelihood of producing biofuel energy from algae cells in the future can be increased by implementing a sophisticated plan to increase biofuel output. Current theories regarding algal potential for producing biofuel are compiled in this study. It discusses each phase of the process, scientific accomplishments, current issues, and recommendations for future research aims and objectives.

Keywords: Microalgae; Climate change; Biofuel; Fossil fuel; Future generation; Carbon fixation

Introduction

First acknowledged at the 1992 United Nations Earth Summit, the role of transportation in sustainable development was reaffirmed in Agenda 21, the summit's conclusion document. During its nineteenth Special Session in 1997, the UN General Assembly conducted a five-year review of Agenda 21 implementation and added that, over the next two decades, transportation is expected to be the primary driver of the world's increasing energy demand (in fact, it is currently the largest end-use of energy in developed countries and the one that is growing at the fastest rate in the majority of developing countries). Additionally, the Johannesburg Plan of Implementation (JPOI), the final document of the 2002 World Summit on Sustainable Development, once again included the significance of transportation. In the context of infrastructure, public transit systems, commodities delivery networks, affordability, efficiency, and ease of transportation, as well as enhancing urban air quality and health and lowering greenhouse gas emissions, JPOI offered several anchor points for sustainable transportation.

The 21st century widely acknowledges the indefensibility of using fossil fuels due to the ongoing shortage of biofuels, making substitutes for petroleum-derived fuels and chemicals increasingly necessary. Every day, there is more demand. The resources that are now accessible are dwindling quickly and are likely to disappear shortly. In such cases, renewable energy must be given greater consideration. Fossil fuels are widely utilized worldwide but unsustainable since they raise CO2 levels and build up greenhouse gases that harm the ecosystem. Renewable and ecologically friendly fuels must be developed to preserve sustainability and keep the environment clean (Schenk, 2008). 20% of the world's total energy consumption is attributable to the transportation industry. Even though they make up only 5% of all bioenergy consumption today and only 3%-4% of all road transport fuel (József Popp et al., 2016). In the long run, next-generation biofuels are likely to require the most capacity growth and financing, despite severe competition from other renewable energy sources. While most of the attention is focused on liquid biofuels for transportation, globally, only a small amount of biomass is now utilized for biofuel production.

There have already been According to (Dufey, 2006), biofuels are liquid fuels derived from the biomass of various crops. Biodiesel, an alternative to petroleum-based diesel, is currently being generated from cellulose, algal lipids, corn, soy, sugar cane, camelina and jatropha, rapeseed, methane, animal fat, and forest products. They are also characterized as the biodegradable fraction of industrial waste. Vegetable oils (Shay, 1993), biobutanol (Dürre, 1997), *Jatropha curcas* (Becker and Makkar, 2008), and algae (Roessler et al., 1994; Sawayama et al., 1995; Dunahay et al., 1996; Sheehan et al., 1998) are all used in the production of biodiesel. The top three countries in the world for producing biodiesel are Brazil, the US, and the EU (Balat, 2007). 35 billion liters of biofuel are anticipated to be produced annually (O European Commission, 2006) However, the widespread cultivation of these crops for the generation of biodiesel is putting the local economy and food supply at risk, raising the cost of food and commodities globally. As a result, efforts are being made to find A feedstock for biodiesel made from non-food, non-terrestrial materials like microalgae.

Their ability to develop without much attention to waste nutrients makes them a superior source of biodiesel production compared to other sources, which generally consist of food-producing plants (Patil et al., 2008; Roberts, 2013). Microalgae are a possible alternative source because they effectively use photosynthesis to transform light energy into chemical energy that is then converted into organic compounds like lipids and carbohydrates. Carbon dioxide (CO_2) found in the atmosphere is used to make these molecules. Diatoms (Bacillariophyceae) are a type of algae that fix a significant portion of the CO_2 in the ocean, ranging between about 41% and 50%. (Field et al., 1998; Williams and Laurens, 2010). In some circumstances, microalgae synthesize secondary metabolites (Mimouni et al., 2012; Gordon and Seckbach, 2012; Bhuyar et al., 2019a; Heydarizadeh et al., 2013; Spolaore et al., 2006). Algal cells contain 30% more lipids than other sources, such as soybean and palm oils (Lam and Lee, 2012; Kligerman and Bouwer, 2015). They may thrive in dry, semiarid, or desert environments and can even grow on non-arable terrain. In comparison to other terrestrial crops, they also need less water for growth and survival (Yeang, 2008). Unlike other crops, which are frequently only harvested once or twice a year, algae may be harvested all year round (Chisti, 2007). Compared to petroleum, algae contain about 80% more energy (Chisti, 2007; 2013). Algae can effectively identify and remove hazardous elements from water, aiding in the clean-up of wastewater.

Investigating the process of using algae to produce new types of biofuels can help solve this issue. Eukaryotic photosynthetic algae may be found in a range of habitats. Algae are photosynthetic organisms that use carbon dioxide from the environment and solar energy to create their biomass (Demirbas, 2010). They range in size from microscopic to enormous kelps, in number of cells from one to many, and in form from spherical to filamentous. Algae are seen favorably for the manufacture of biodiesel because of several benefits, including high photosynthetic efficacy, rapid growth, and high biomass productivity (Amaro et al., 2011; Demirbas and Demirbas, 2011).

Since microalgae, like diatoms, are among the biological groups most susceptible to hydric stress, they are useful markers of previous hydrological conditions. To improve the direction of stream management initiatives, benthic diatom communities are crucial for the development of predictive models for water quality. With microalgae serving as the main feedstock for biodiesel, there is a lot of potential for applications. Diatoms need high water or at least high humidity (Evans, 1960). Therefore, we require either an extra water supply for the panel or a water-impermeable chamber. Desiccation does not destroy diatoms, and in fact, it enhances the output of oil (Evans, 1958; Evans, 1959). Because cells can survive longer when drying more slowly (Evans, 1959). They are appropriate sources to be cultivated on a large scale due to their remediating and bioindicator roles in wastewater treatment and their high sources of biodiesel (Pittman et al., 2011; Kligerman and Bouwer, 2015).

The finite quantity of fossil fuels on earth has been under tremendous strain due to the exponential rise in energy use and the expanding global population. It is possible to produce energy (biofuel) from algal lipids using a sustainable biological process. Algal lipid formation is a naturally occurring process; however, water pollution makes it worse. Point-source pollution is defined as pollution that comes from a single source. such as air deposition, runoff from agricultural or industrial stormwater systems, residential and industrial wastewater, and non-point source pollution.

Additionally, anthropogenic sources are those that were produced by humans. Prospects are bright for the production of algal-based biofuel, which is a cost-effective and ecologically responsible energy source. The present state of algal biofuel research is discussed in the current publication. We looked at the number and biovolume of lipid bodies (LBs). In areas with severe metal pollution, eight distinct diatom species exhibited considerably larger numbers and biovolumes of large bodies (LBs) compared to all other studied diatom taxa identified in Khetri and Zawar. Conversely, these diatom species in the less polluted areas showed noticeably reduced LB counts and biovolumes. Under Cu stress, the genera *Navicula* and *Nitzschia* showed considerably higher lipid body induction (in both number and biovolume), a finding in line with earlier research (Pandey and Bergey, 2016; Pandey et al., 2015). Lipid bodies are often stored by diatoms as a reserve food source, and these bodies may become more noticeable in response to certain kinds of stress (Ramachandra et al., 2009). especially deprivation from nitrogen (Jiang et al., 2012). The concentration of CO_2 and Fe^{+3} determined the fatty acid chain's length and degree of unsaturation. The combination of low Fe and 2% CO_2 created the ideal environment for the synthesis of short carbon chain FA and the accumulation of large amounts of SFA. According to (Carpio et al.,2015), This work presented the possibility of adjusting the quantities of CO_2 in aeration and Fe^{+3} in the growth medium to change the lipid content of the freshwater green alga, *C. vulgaris* Beij.

These lipid bodies investigations will also help establish diatoms as a tool for biofuel production. Due to Flue gases like CO_2 concentration increasing in the environment, the algal biomass increases. The algae lipid may be converted into energy (biofuel) using the sustainable biological method. Lipid production occurs naturally in algae but it is increased by water pollution and climate change. The purpose of this work is to examine how different aspects of climate change affect algae's capacity to synthesize lipids. The likelihood of producing biofuel energy from algae cells may be increased using a sophisticated technique for boosting biofuel production. This study summarises the most recent theories about the production of biofuels using algae. It details each phase, scientific breakthroughs, current issues, and recommendations for further research aims and objectives.

Potential feedstock for biodiesel production generation by generation

First-generation

Food crops are used directly to make first-generation biofuels. the most commonly used first-generation biofuel feedstock. 1. Most of the corn used to make gasoline-ethanol in the world originates from the United States. About one-fourth of the nation's petrol needs could be met by maize. Rejected – It is good food and it becomes costly by utilizing it as biofuels (Khammee et al., 2020), which leads to famine all over the world and increases the demand for additional pesticides and fertilizers, which is not only expensive but also pollutes the soil and water. Sugar cane the majority of bioethanol is produced in Brazil, which is one of the biggest customers for the product and the country's second-largest producer after the US; however, just 1% of Brazil's fertile land is used for sugar cane farming. However, due to its monocot status need for a certain environment, and lots of sun exposure, sugar cane is not a crop that can be cultivated in most of the world. As a result, most nations are unable to produce sugar cane for bioethanol. Soybeans are grown across most of North America, South America, and Asia, unlike corn and sugar cane. Rejected: According to growing soybeans typically require more energy than can be obtained from their fuel. The amount of farmland utilized worldwide for biofuels is presently between 30 and 35 million hectares or around 2%. The amount of land needed to grow feedstocks is reduced to 1.5% of the total cropland by substituting coproducts for grains and oilseeds (József Popp, et al., 2016). Biofuel is created from agricultural oil crops like soybean and oil palm; however, the yield is only about 200 barrels (30,000 L) of algal oil per hectare of land when oleaginous algae are mass-cultured, which is 100–200 times more than soybean oil.

Second generation

Scientists developed second-generation biofuel to lessen the issues first-generation biofuel had. Non-food crops are used in second-generation biofuel for example Two categories serve as the major divisions for second-generation biofuels. 1. Homogeneous 2. Non-homogeneous. Whitewood chips and agricultural and forestry waste are examples of homogenous materials. Non-homogeneous materials include low-value feedstock and municipal solid waste, according to (Lee and Lavoie (2013).

A major reason for the rejection of first and second-generation biofuel sources-
1. The land and water are contaminated by using more pesticides and fertilizers.
2. The cost of food rises, leading to global food scarcity. Shows in Fig 1.
3. One of the causes of the hunger crisis is a decrease in agriculture.
4. Due to the high cost of its growth and harvest, its price is likewise quite high.

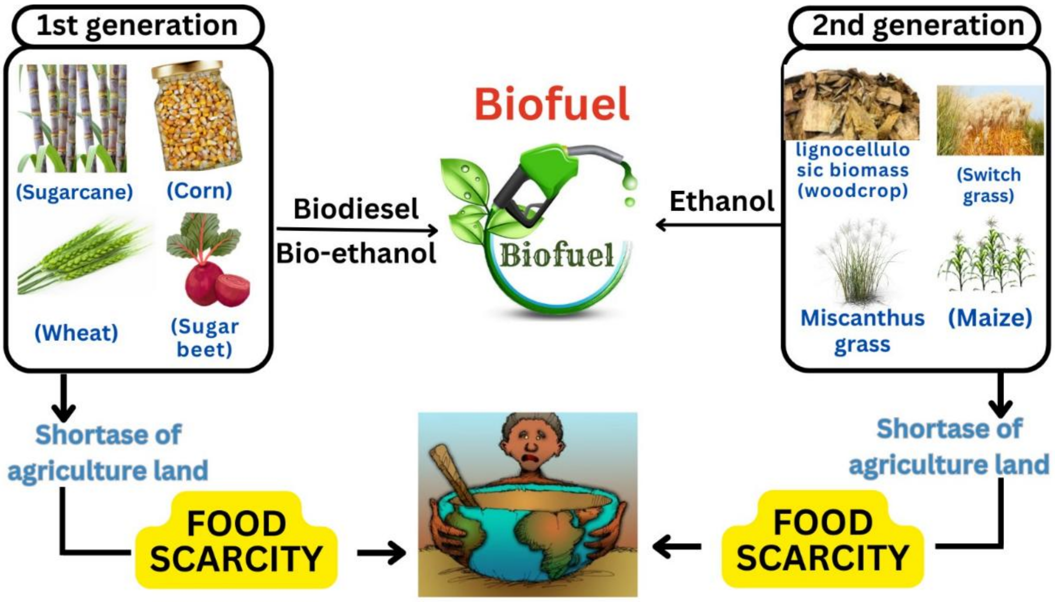

Fig.1. This image shows food scarcity due to the use of first- and second-generation biofuel products

Food versus fuel

Grain reserves are finite, as is the amount of arable land on Earth. Wheat is usually kept in storage for thirty days at a time. Prices decrease and there is a glut when the supply lasts 33 days; at 27 days, prices soar. The limited amount of grain currently being utilized for biofuel mostly oilseeds, sugarcane, and maize has caused a chain reaction that has doubled the price of all grains. There won't be much grain available for emergency food assistance, and this will quickly spread throughout the food chain, doubling the price of all foods. In addition, burning grain to power expensive cars when starving people raises bioethical concerns. The developed world is getting close to the highest yields that are practically possible. By using more fertilizer and pesticides, yields could be somewhat increased, but this would not be very cost-effective and is frequently not ideal for the environment. The developing nations who practice subsistence agriculture and have yields that are below the third world average will need to provide the long-term yield improvements necessary to sustain (strictly speaking) human nutritional needs (which they reduce down).

With grain subsidized from the West and sold below production prices (referred to as "dumped" in economic parlance), these emerging regions should be able to produce at a level of competitiveness thanks to the doubled grain prices. How rapidly this turnaround can occur is an interesting subject. It appears that governments in developing nations should handle this directly, as was recently done in Malawi, rather than relying on international help, which is always accompanied by conditions.

Third generation

However, the renewable source of biodiesel that can supply all of the world's transportation fuel needs in the coming years will be microalgal biodiesel. A wide variety of aquatic conditions, from freshwater to brackish water, support the growth of microalgal species. Microalgae are capable of effectively consuming CO_2 and account for between 35% and 40% of global carbon fixation (Bellou et al., 2014; Ramaraj et al., 2015). Marine-based microalgae are commonly believed to produce CO_2 sequestration. The greatest choice for biofuel among these possibilities is algae. All microalgae can accumulate lipid bodies within their cells that are rich in energy-rich bio-oils (Bhuyar et al., 2019a, b). For example, it has been shown that some *Botryococcus* species retain up to 20% to 45% of the lipid content as long-chain hydrocarbons of their dry mass (Gerken et al., 2013). Several thousand species of algae, including diatoms, have been investigated for their high lipid content. (Guliyev et al., 2001; Sheehan et al., 1998; Sommerfeld et al., 2008; Imahara et al., 2006). Polyunsaturated fatty acids, which account for around 25% of the mass of algae, have been determined to have a lower average melting point than saturated fats over the previous few decades. Historically, it has been believed that a significant portion of third-generation biofuels comes from single-celled algae known as diatoms. Two frustules and a variable number of girdle bands make up the transparent diatom silica shell, which shields the oil droplets within and absorbs the light required for their formation (Round et al., 1990; Cox et al., 1996). Diatoms are unique in that lipids may be taken from them without causing harm, just like cow milk can be without causing death, due to their hard siliceous cell wall (frustule). (Ramachandra et al., 2009) named this process of removing lipids from diatoms "milking" diatoms. Microscopic cyanobacteria and eukaryotic algae comprise microalgae. Compared to conventional oil seed crops, these algae have the potential to produce significantly more biodiesel while using quite less water and agricultural area. The expectation that biotechnology methods based on microalgae will yield higher productivity than any cultivated agricultural plant per unit surface area of Earth is another reason to be interested in them (Cadoret and Bernard., 2008, Chisti 2007). For example, it is estimated that the production of diatom oil will be two to six hundred times more per unit surface area than oilseed crops (Demirbas, 2009) shown in Fig. 2.

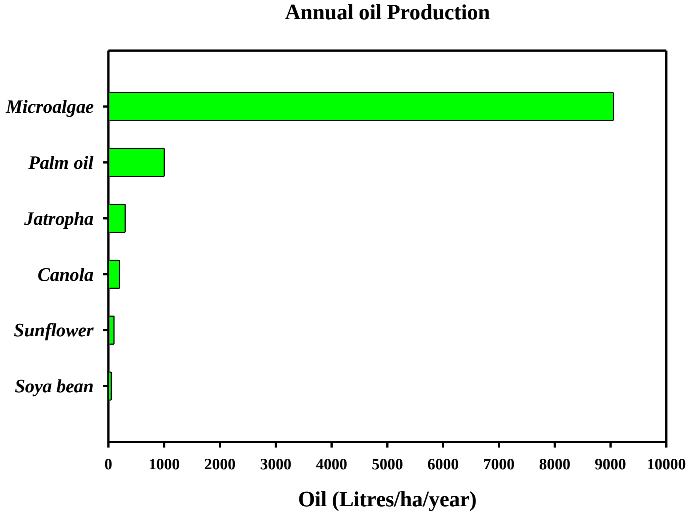

Fig. 2. Potential oil yield per hectare per year (adapted from Emily, 2009)

While algae have been cultivated since the 1950s, mostly for use in pharmaceutical products, their capacity to produce biofuels has only recently come to light. Algae, which produces a significant amount of biofuel, can produce biomass in marine and freshwater environments (József Popp et al., 2016). Algal biofuel doesn't contain any dangerous compounds, therefore after burning, the environment may be maintained clean. However, producing even 1 kg of algae biomass in a lab setting is difficult. We are aware that algae fix 40% of the organic carbon in the planet, and that using algae for biofuel will significantly influence both the world's primary productivity and the quality of its air. If we can solve all of the aforementioned issues, the diatom is a fantastic source for the manufacture of biofuel. But regrettably, the diatom family is declining, there are several reasons for this, the primary ones being water pollution and climate change. Numerous factors can contribute to water pollution. Of all the types of water pollution, metal pollution poses the greatest threat to freshwater diatoms like *Navicula*.

Mechanism behind lipid production in diatoms stress conditions

As with other microalgae, diatoms store lipids in oleosomes (Yatsu et al., 1971). Also referred to as spherosomes, lipid droplets, lipid bodies, oil droplets, etc., diatoms' oleosome count increases under stress as do green algae, as shown by (Davidi, L., Katz, A., and Pick, U. 2012). The endoplasmic reticulum and chloroplasts mediate lipid synthesis in diatoms. As is generally believed by numerous intricately linked events involving the endoplasmic reticulum, it is most likely fatty acids cannot travel directly from chloroplasts to oleosomes, much like in higher plants (Heydarizadeh et al., 2013). The proteome study of isolated oleosomes from the diatom *Fistulifera solaris* JPCC DA0580 has provided the first evidence supporting this theory. This investigation has identified one particular protein that exhibits a domain similar to that of the quinone protein alcohol dehydrogenase (Nojima et al., 2013). It was found that the protein used a fluorescent tag to target the endoplasmic reticulum, where it may play a role in forming oleosomes (Maeda et al., 2014). Exocytosis may be the mechanism by which oleosomes are transported, as seen in the Chlorophyceae alga *Dunaliella salina* (Zhang et al., 1993). It is sufficient to note that the evolution of diatoms has involved multiple endosymbiotic events, such as those involving cyanobacteria and red algae (Moustafa et al., 2009) as well as a chlamydial invasion (Becker et al., 2001), to convince one of this intricacy. Diatoms were able to establish themselves in a variety of ecological settings, such as freshwater, brackish, marine, and hypersaline settings that varied in terms of pH, temperature, and nutrient availability, thanks to the gene enrichments produced by these events (Armbrust et al., 2004). Some people might be categorized as extremophiles (Kociolek, 2007; Sternburg et al., 2007).

Their capacity for colonization is a reflection of their highly flexible metabolism, which enables them to adjust to a wide range of environmental restrictions (Berth et al., 2001; Nguyen-Deroche et al., 2012; Masmoudi et al., 2013; Rohacek et al., 2014). Metabolic changes, such as the synthesis of secondary metabolites, are frequently a part of long-term adaptation mechanisms (Sharma et al., 2012; Darko et al., 2014). The algae "interpret" stress conditions like salinity (Cheng et al., 2014), nutrient deficiency (Gacheva and Gigova, 2014), temperature, and high light stress (Hasunuma et al., 2014) as "dangerous," leading them to accumulate high-energy molecules like lipids and carotenoids (Lemoine and Schoefs, 2010; Sharma et al., 2012; Cheng et al., 2014; Maeda et al., 2014). For example, it has been demonstrated that diatoms can produce twice or three times as much oil when under stress due to silicon or nitrogen depletion (Burrows et al., 2012; Taguchi, S.; Hirata and Laws, 1987; Zhang et al., 2014). Algae may produce thick mucus sheaths through desiccation, which are frequently discovered to contain oil or starch (Badour and Gergis, 1965). Diatoms can store energy as lipids or as chrysolaminarin (Beattie et al., 1961); therefore, we'll need to figure out how to bias production in favor of oil. While algae with low oil content, like *Dunaliella*, divide more quickly and can be collected every day, High oil content algae (e.g., *Botryococcus*) mature slowly and are harvested only seldom. Because of this, the majority of industrial applications employ algae strains with a lipid concentration of 20% to 40%. To maintain a high rate of division, diatoms can rely on their greater ability to fix CO2 than other phytoplanktonic groupings (Thomas et al., 1978).

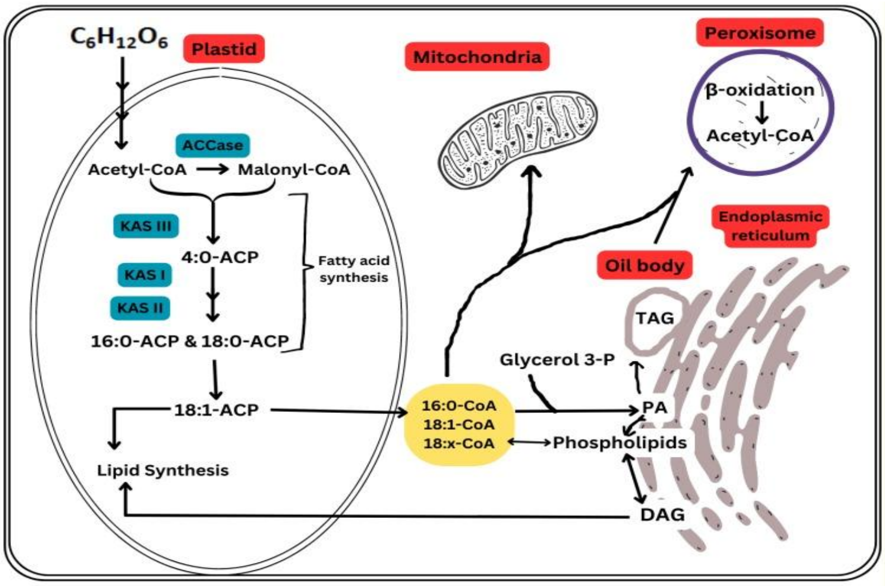

Fig.3. This figure shows how CO2 fixation product glucose is used for the lipid biosynthesis

One of the main forces behind economic growth is energy. Because fossil fuels are running out and have negative environmental repercussions, humanity needs to develop sustainable and renewable energy sources. Carbon is an essential ingredient that controls microalgae growth and function. Different pathways are used by microalgae cells to assimilate various carbon sources. The CO_2-concentrating mechanisms (CCMs) mostly use inorganic carbon sources, while microalgae primarily absorb organic carbon sources via the Embden-Meyerhof-Pranas (EMP) and pentose phosphate pathways. Thus, microalgae mostly use the Pentose Phosphate Pathway (PPP) and the Embden-Meyerhof-Pranas (EMP) Pathway to absorb the excess carbon input. As a result, the generation of microalgae biomass and lipid accumulation are significantly impacted by the addition of carbon sources (Xiangmeng et al., 2022). The processes of microalgal lipid synthesis and carbon absorption were described in this work; this process is shown in Fig. 3, and the effects of different carbon conditions (forms, quantities, and addition processes) on lipid formation during the production of biodiesel and microalgal biomass were extensively explored.

The potential possibilities for the manufacture of biodiesel are also highlighted in this analysis, along with recent developments in the large-scale commercialization of microalgae lipid culture. Regarding the cost-benefit analysis of producing microalgae biodiesel on a wide scale. Practical solutions are suggested as well as current obstacles. The effectiveness of CO_2 collection depends on the kind of microalgae, the biochemical makeup of the nutrient medium, and environmental factors including light, humidity, and pH. This efficiency is influenced by the design of the developing system (open system/photobioreactor) (Nath et al., 2023). Microalgae may be cultivated in open or closed environments and need nutrients and carbon dioxide, which can come from burning fossil fuels or sewage. To quickly fix carbon into microalgae, researchers are also interested in CO_2 collection through photosynthesis and how to use CO_2 in different ways for humans. In these reviews, topics like genetic engineering and metabolic changes to improve CO_2 capture are covered, along with photosynthesis, CO_2 fixing, and culture tactics for microalgae.

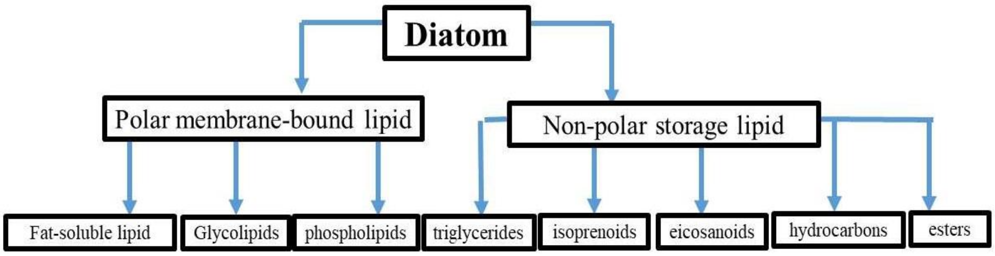

Fig. 4. Classification of diatom lipids

Table 1. Table showing the type of fatty acids found in different diatom species

Type of fatty acid found in different diatom species							
Species	**Linolenic**	**Oleic**	**Stearic**	**Palmitic**	**Linoleic**	**Palmitoleic**	**reference**
Chlorella vulgaris	21.3	18.7	14.1	5.6	-	5	Velasquez-Orta et al. (2012)
Spirulina platensis	17.79	4.11	1	41.21	12.64	3.39	Nautiyal et al. (2014a,b)
Scenedesmus sp.	8.26	49.64	3.43	18.42	11.3	2.31	Chen et al. (2012a,b,c)
Nannochloropsis salina	0.58	37.52	2.53	13.49	14.49	12.99	Patil et al. (2011)
Caulerpa peltata	-	5.04	4.58	36.82	18.19	5.04	Suganya et al. (2014)
Enteromorpha compressa	-	2.38	2.95	70.26	-	3.71	Suganya et al. (2013)

Fatty Acid Profile

Algal cells contain tightly packed lipid particles called TAGs in their cytoplasm. Saturated fatty acids such as stearic and palmitic acids and unsaturated fatty acids such as palmitoleic, oleic, linoleic, and linolenic acids make up the oil found in algae shown in Fig. 4. Most of the fatty acids in Scenedesmus obliquus oil are saturated and monounsaturated, according to Mandal and Mallick (2009), which provides biodiesel and generates a high level of oxidative stability. Table 1 compares the fatty acid content of biodiesel produced from several types of algae. Arachidonic acid, three polyunsaturated acids, docosahexaenoic acid, eicosapentaenoic acid, and algae are known to be generated in large quantities and may provide a problem for the generated biodiesel's stability (Frankel et al., 2002). Because the oil contains more unsaturated fatty acids, it lowers the pour point and cloud point of the biodiesel, improving its cold-temperature properties (Serdari et al., 1999; Stournas et al., 1995).

For biodiesel to function effectively, it needs to contain the right ratio of saturated and unsaturated fatty acids. This is because biodiesel made from highly unsaturated acids (polyunsaturated) loses stability. After all, it oxidizes more quickly than regular diesel and forms insoluble fragments.

The Processes for Biofuel Production Using Algae vs. Crop Plants (First- and Second-Generation Sources)

Algae offer a straightforward way for extracting fatty acids, and the process used to separate biodiesel on a small or experimental scale is mixing. While drying crops and other food-producing plants requires energy, drying algae with sunlight is more cost-effective. In contrast to other plants, the thermochemical drying process in algae is also simple (Banerjee et al., 2002; Tsukahara and Sawayama, 2005), as shown in Fig. 5.

Algal biomass gathering and algal density

Field samples were weighed for their entire dry weight. Microalgae were quantified per unit area/volume using a 1 m x 1 m quadrate and a 10 volume. A quadrate measuring 1 m x 1 m was used to gather the macroscopic algal biomass from the lakes. At this location, these floating algae were thoroughly cleansed before being taken to the lab for further separation. The samples were carefully cleaned with deionized water following microscopic examination, and they were then concentrated by centrifuging additional lipid extraction. After carefully scraping the pellet with a spatula, it was let to air dry at room temperature. In case they were needed again, the samples were preserved.

Table 2. An overview of how the FA profiles of marine animals have changed after being exposed to pollutants. Free fatty acids are denoted by FFA, saturated fatty acids by SFA, monounsaturated fatty acids by MUFA, and polyunsaturated fatty acids by PUFA. N/A indicates unavailable; N/I indicates little or no change in different diatom species.

Contaminants of exposure (time/concentration)	Contaminant's mode of action	Species name	SFA	MUFA	PUFA	References
Triazine 100 and 150mg/l atrazine	The quality of the photosynthetic activity of diatom cells is impacted by interference with the function of photosynthesis in plants, including some algae.	*Seminavisrobusta*	N/I	N/I	N/I	De Hoop et al., (2013)
1,2,4-Trichlorobenzene (used in the production of organochlorine pesticides) 0.245mg/l 5days	over prolonged exposure periods, causes the most changes in morphology and fatty acid composition.	*Cyclotella meneghiniana*	16:0, 15:0, 18:00	16:0	20:05	Sicko-Goad et al. (1989a)
1,3,5-Trichlorobenzene: this chemical is utilized to make pesticides that contain chloroform. 0.245 mg/l five days	generates the highest amount of morphological and fatty acid composition changes in 24 hours. modifies the ability of photosynthetic reaction and reduces cellular lipid stores	*Cyclotella meneghiniana*	16:00, 18:00, 14:00	18:01	20:05	Sicko-Goad et al. (1989b)
1,2,3-Trichlorobenzene: this chemical is used to make insecticides that contain chloroform. 0.245 mg/l five days	The steady rise in lipid volume, along with a reduction in the so-called "fibrous" vacuole and less notable alterations in the composition of FAs	*Cyclotella meneghiniana*	18:00	16:01	0.83339 1204	Sicko-Goad et al. (1989c)
Pentachloro benzene, which is a raw material for organochlorine insecticides 0.245 mg/l for five days	causes alterations in diatom Lipid volume in diatoms is increased by FA content and cell shape.	*Cyclotella meneghiniana*	15:00, 18:00	18:01	20:05	Sicko-Goad et al. (1989d)
Chloroacetamide herbicide: metolachlor 20um added once	Inhibition of long-chain fatty acid biosynthesis	*Melosira cf. moniliformis*	14:0, 16:0, 18:0	6:1(n-7) 18:1 (n-7)	16:2, 16:3, 16:4 18:4 (5,8,11,14) 18:5 (5,8,11,14,17)	Robert et al. (2007)
PCBs, or polychlorinated biphenyls, N/A	Growth suppression and alterations in the FA profile	*Thalassiosira pseudonana*	16:00	16:01	N/A	Fisher and Schwarzenbach (1978)

Why are diatoms used as biofuel?

When we make biofuel from crops, the crop is harvested only once and gets destroyed; if we produce biofuel from algae, it can be reused. Ramachandra et al. (2009) mentioned in their review that just as a cow does not have to die to extract milk from it, similarly, lipid extraction can be done from algae (diatoms) without killing them. Ramachandra et al. (2009) compared the process of extracting dairy milk to crushing cows and is accepted as inevitable. For example, many organisms, including photosynthetic microalgae, employ the same inputs. But unlike cows, you cannot milk them. It would help if you destroyed them (Lane, 2015).

The demand for nitrogen/phosphorus fertilizers would be decreased or eliminated if only hydrocarbon high-value molecules (HVM) were milked (Rickman et al., 2013). The idea behind milking is that the cells shouldn't be killed during extraction. Because of this, milking eliminates the requirement for periodic culture and reestablishing of the entire algae stock, which usually takes a few hours to several weeks.

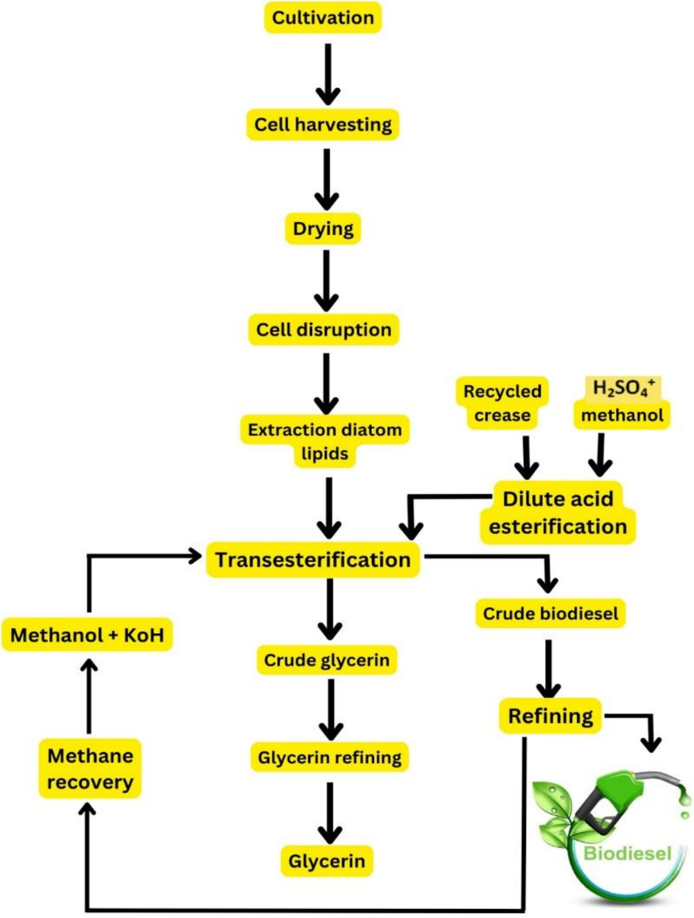

Fig.5. Process of extraction of biodiesel from algal lipid

What we now refer to as extraction was referred to as "milking" in some of the literature because the distinction between extraction and milking was not made (Zhang et al., 2011). Likewise, secretion and extraction were formerly included in the category of "milking" (Yadugiri et al., 2009). We believe that rigorous differentiation between these approaches will facilitate more fruitful discourse.

When provides some food for thought regarding the progress of microalgae milking, specifically concerning diatoms, in the article. The main lines of reasoning that we have outlined to reach our goal are (a) the creation of substitute methods for harvesting and extracting HMV; (b) the construction and management of photobioreactors; (c) biochemistry; and (d) diatom (stress) physiology. In this contribution, they are addressed individually and, if feasible, accompanied by unique findings on the accumulation of lipids by diatoms. We call these algae "oleaginous diatoms." While most of the topics included in this contribution have been covered in recent reviews (Hildebrand et al., 2012; Hasunuma et al., 2014), none of them specifically addressed diatoms and milking.

Algal oil extraction

The secret of milking is to extract HVM without destroying the cells that produce it. In the case of higher plants, this idea was initially used in the milking of rubber 2000 years ago (Ciesielski 1999); maple syrup both historically (Svanberg et al., 2012) and prehistorically (Nearing and Nearing, 2000;

Munson 1989); turpentine dating back to Hippocrates (Haller, 1984); and more recently, halophilic bacteria (Saver and Galinski 1998; Van-Thuoc et al., 2010); and microalgae.
Biocompatible solvents were employed in the initial applications with algae to extract HVM (Hejazi et al., 2004). Using organic solvents. (Gillet, 2015) recently computed the plasma membrane's molecular dynamics during milking. This section's goal is to offer a thorough examination of these options within the context of a milking strategy. Although heating and microwaving can cause damage in moderation, we do not think about them (Ghasemi Naghdi et al., 2014). However, they can also cause milking.

Pulsed Electric Field

Diatoms and other microalgae have been electroporated, albeit mostly to enable genetic change. (Dunahay et al., 1992; Coll, 2006; Leon and Fernandez, 2007; Miyahara et al., 2013; Gao, 2014; Zhang, 2014). On the other hand, high-value compounds can also be released from cells more favorably by applying trains of electric pulses. Using this technique, electric pulses pierce cell membranes, causing the constituent parts of the cell to leak out. The technique was developed initially with yeast (Ganeva et al., 2003; Stirke et al., 2014) and more recently with photosynthetic organisms such as microalgae. (Coustets et al., 2013; Coustets et al., 2015) and cyanobacteria (Sheng et al., 2011). The "punctured" cells subsequently recover and continue to be alive, allowing the same batch of algae to be used again to extract more HVM (Reep and Green, 2012). Electric pulses can cause irreversible electroporation in bacteria (Joubert et al., 2013) algae (Antezana Zbinder et al., 2013) and mammal cells (Deipolyi et al., 2014). Therefore, choosing the electric pulses' length, intensity, polarity, repetition frequency, and other parameters requires striking a balance between milking efficiency and algal survival.

Physical parameter adjustment is important since the strength of the electric therapy is directly proportional to the size of the cell, meaning that a smaller cell will have a greater effect. (Coustets et al., 2013; Sixou and Teissie, 1990; Bellard and Teissie, 2009). Diatoms, or microalgae, are beneficial for biofuel generation because of this.

Spontaneous oozing

There are now confidential reports indicating that certain bacteria (Tsukagoshi et al., 1983; Raetz, 2001; Wald, 2015), green algae (Frenz et al., 1989), and cyanobacteria that have undergone genetic engineering (Liu et al., 2011; Joule, 2012; Robertson et al., 2011; Liu et al., 2011; Reppas and Ridley, 2010) can secrete lipids (Ladd and Venter, 2010) from their cytoplasm into the surrounding environment. According to Vinayak et al. (2014), the mechanics underlying oozing are still unknown. The droplets gather in the cytoplasm (oleosomes) or the chloroplasts (plastoglobules).

Mechanical Pressure

One may infer that applying HVM leakage from algal cells could be caused by mechanical pressure, such as ultrasonic or tactile stimulation. that don't have a built-in oozing mechanism. Ultrasound has been employed in procedures to enhance lipid extraction of *Chlorella vulgaris* (Araujo et al., 2013), like electric pulse treatment (Rosello-Soto et al., 2015).

The ultrasonic treatment's parameters should be selected in a way that maintains the cells' viability and qualifies them for use in the milking process. For example, when comparing the yield attained without treatment, Araujo et al. (2013) reported that Chlorella vulgaris treated with ultrasound significantly improved in terms of lipid recovery. However, since only a slight improvement was noted, the treatment's effectiveness depends on the strength of the cell wall. Diatom cells are special in that they have a cell wall made of hydrated silicon dioxide, known as the frustule. The forms and embellishments of frustules vary greatly (Sterrenburg et al., 2007; Round et al., 1990).

Additionally, one valve can fit inside the boundary of the other since one frustule is somewhat larger than the other. each diatom possesses defective bilateral symmetry. This, along with the frustule's resilience, makes mechanical approaches potentially one of the most potent ways to encourage the release of HVM. Testing the oozing capacity of more diatoms with an apical pore field (Kociolek and Stoermer, 1988) would be intriguing. We can presume that the force needed to shatter an isolated diatom valve is significantly less than the force needed to exert oil on a live diatom, even if this force has not yet been measured. The mechanical properties of several diatoms under tensile and compressive loads were published by (Hamm et al., 2003). Additionally, they mentioned that an isolated diatom valve had a breaking force of 750 µN.

Centrifugation

We still don't know if the centrifugal force that kills them is less than the one that releases oil. In that case, centrifugation might be used as a method of milking. Algal separation is now accomplished by centrifugation (Abodeely et al., 2013). Lipids ascend to the centripetal end of sea urchin eggs centrifuged at 9000× g and exert sufficient buoyancy to split the egg in two (Anderson, 1970).

Fatty acid composition using GC–MS

The component of fatty acids was assessed using mass spectrometry (Agilent Technologies 5975C insert MSD with triple-axis detector) and a gas chromatograph (Agilent Technologies 7890C, GC System). The injection and detector temperatures were maintained at 250°C and 280°C, respectively, in accordance with ASTM D 2800. A 1 ml injection of sample was made into the column, which had a starting temperature maintained at 40°C. The oven temperature was raised at a rate of 10 degrees Celsius per minute after one minute. Afterward, the oven was heated to 230°C at a rate of 3°C per minute, and then, at a rate of 10°C per minute, to 300°C, where it remained for two minutes. A silica column was loaded with the methylated sample utilizing split-free helium gas as the carrier. 47.667 minutes was the calculated run time. By comparing the obtained retention period to that of established standards, fatty acids were identified.

Lipid extraction and biodiesel production

After ethanol manufacturing, the wasted solids underwent the Soxhlet extraction procedure to separate the lipid for biodiesel synthesis. Less than 2% of the lipid recovered from algal biomass contained free fatty acids, it was discovered. To create a sodium methoxide solution, 50 ml of methanol was mixed with around 0.5 g of NaOH pellets to create biodiesel from the obtained lipid. Algal oil was next carefully incorporated with the sodium methoxide solution.

Conclusion

Microalgae are one of the most effective third-generation generating organisms at turning solar energy into chemical power, which is then utilized to absorb and transform atmospheric carbon dioxide into biomass. The principal source for biodiesel, microalgae, has demonstrated excellent application potential. The upstream cost limits lipid output from microalgae, which prevents large-scale biofuel production from being realized. The focus of attempts to boost microalgae's lipid content and productivity over the past few decades has been on altering lipid-rich microalgae cells. Fatty acids may be extracted from algae using a straightforward process, and biodiesel can be separated on a small or experimental scale by mixing. While drying crops and plants that produce food requires energy, drying algae with sunlight is more cost-effective. In contrast to other plants, the process of thermochemical drying is also simple in algae. This work aligns with the Sustainable Development Goals (SDGs) 2030. Producing biofuel from microalgae (diatoms) instead of crops allows agricultural land to be used for food cultivation. This supports SDG Goal 2 of the 2030 Agenda, which aims to end hunger, ensure food security and improved nutrition, and promote sustainable agriculture.

References

Anderson EA (1970) Cytological study of the centrifuged whole, half, and quarter eggs of the sea urchin Arbacia punctulata. J Cell Biol 47: 711–733.

Armbrust EV, Berges JA, Bowler C, Green BR, Martinez D, Putnam NH, Zhou S, Allen AE, Apt KE, Bechner M, et al. (2004) The genome of the diatom Thalassiosira pseudonana. Ecology, evolution, and metabolism. Science 306: 79–86.

Amaro HM, Guedes A, Malcata FX (2011) Advances and perspectives in using microalgae to produce biodiesel. Applied Energy 88: 3402–3410.

Abodeely J, Stevens D, Ray A, Schaller K, Newby D (2013) Algal Supply System Design—Harmonized Version [Report INL/EXT-13–28890]; Idaho National Laboratory (INL): Idaho Falls, ID, USA.

Antezana Zbinden MD, Sturm BSM, Nord RD, Carey WJ, Moore D, Shinogle H, Stagg-Williams SM (2013) Pulsed electric field (PEF) as an intensification pretreatment for greener solvent lipid extraction from microalgae. Biotechnol Bioeng 110: 1605–1615.

Araujo GS, Matos LJ, Fernandes JO, Cartaxo SJ, Goncalves LR, Fernandes FA, Farias WR (2013) Extraction of lipids from microalgae by ultrasound application: Prospection of the optimal extraction method. Ultrason Sonochem 20: 95–98.

Beattie A, Percival E, Hirst EL (1961) Studies on the metabolism of the Chrysophyceae. Comparative structural investigations on leucosin (chrysolaminarin) separated from diatoms and laminarin from the brown algae. Biochem J 79: 531–537.

Badour SS, Gergis MS (1965) Cell division and fat accumulation in Nitzschia sp. grown in continuously illuminated mass cultures. Arch Mikrobiol 51: 94–102.

Bertrand M, Schoefs B, Siffel P, Rohacek K, Molnar I (2001) Cadmium inhibits epoxidation of diatoxanthin to diadinoxanthin in the xanthophyll cycle of the marine diatom Phaeodactylum tricornutum. FEBS Lett 508: 153–156.

Banerjee A, Sharma R, Chisti Y, Banerjee UC (2002) Botryococcus braunii a renewable source of hydrocarbons and other chemicals. Crit Rev Biotech 22(3): 245-79.

Balat M (2007) An overview of biofuels and policies in the European Union. Energy Sources B Econ Plann 2(2):167-81.

Becker K, Makkar HPS (2008) Jatropha curcas: A Potential Source for Tomorrow's Oil and Biodiesel. Lipid Technol 20(5):104-7.

Becker B, Hoef-Emden K, Melkonian M (2008) Chlamydial genes shed light on the evolution of photoautotrophic eukaryotes. BMC Evol Biol 8, Article Number 203.

Bellard E, Teissié J (2009) Double-pulse approach of electrogenotherapy: An analysis at the single cell level. IEEE Trans Plasma Sci 37: 538–544.

Burrows E, Bennette N, Carrieri D, Dixon J, Brinker A, Frada M, Baldassano S, Falkowski P, Dismukes G (2012) Dynamics of lipid biosynthesis and redistribution in the marine diatom Phaeodactylum tricornutum under nitrate deprivation. BioEnergy Res 5: 876–885.

Bellou S, Baeshen MN, Elazzazy AM, Aggeli D, Sayegh F, Aggelis G (2014) Microalgal lipids biochemistry and biotechnological perspectives. Biotechnol Adv 32: 1476–1493. https://doi.org/10.1016/j.biotechadv.2014.10.003

Bhuyar P, Rahim MHA, Yusoff MM, Maniam GP, Govindan N (2019a) A selective microalgae strain for biodiesel production in relation to higher lipid profile. Maejo Int J Energ Environ Commun 1 (1): 8–14.

Bhuyar P, Sundararaju S, Rahim MHA, Ramaraj R, Maniam GP, Govindan N (2019b) Microalgae cultivation using palm oil mill effluent as growth medium for lipid production with the effect of CO2 supply and light intensity. Biomass Convers Biorefin 1–9 https://doi.org/10.1007/s13399-019-00548-5.

Cox EJ (1996) Identification of Freshwater Diatoms from Living Material; Chapman & Hall: London.

Ciesielski A, Limited RT (1999) An Introduction to Rubber Technology; Rapra Technology Limited: Shrewsbury, UK.

Coll JM (2006) Methodologies for transferring DNA into eukaryotic microalgae. Span J Agric Res 4: 316–330.

Chisti Y (2007) Biodiesel from microalgae. Biotechnol Adv 25: 294–306.

Cadoret JP, Bernard O (2008) Production de bio carburant lipidiqueavec des microalgae: Promesses et defis/Lipid biofuel production with microalgae: Potential and challenges. J Soc Biol 202: 201–211.

Chen L, Liu T, Zhang W, Chen X, Wang J (2012a) Biodiesel production from algae oil high in free fatty acids by two-step catalytic conversion. Bioresource Technology 111: 208–214.

Chen F, Liu Z, Li D, Liu C, Zheng P, Chen S (2012b) Using ammonia for algae harvesting and as nutrient in subsequent cultures. Bioresource Technology 121: 298–303.

Chen M, Liu T, Chen X, Chen L, Zhang W, Wang J, Gao L, Chen Y, Peng X (2012c) Subcritical co-solvents extraction of lipid from wet microalgae pastes of Nannochloropsis sp. European Journal of Lipid Science and Technology 114: 205–212.

Chisti Y (2013) Constraints to commercialization of algal fuels. Journal of Biotechnol 167(3):201-14.

Coustets M, Al-Karablieh N, Thomsen C, Teissie J (2013) Flow process for electroextraction of total proteins from microalgae. J Membr Biol 246: 751–760.

Cheng RL, Feng J, Zhang BX, Huang Y, Cheng J, Zhang CX (2014) Transcriptome and gene expression analysis of an oleaginous diatom under different salinity conditions. Bioenergy Res 7: 192–205.

Coustets M, Joubert-Durigneux V, Hérault J, Schoefs B, Blanckaert V, Garnier JP, Teissié J (2015) Optimization of protein electroextraction from microalgae by a flow process. Bioelectrochemistry 103: 74–81.

Dunahay TG, Jarvis EE, Zeiler KG, Roessler PG, Brown LM (1992) Genetic engineering of microalgae for fuel production: Scientific note. Appl Biochem Biotechnol 34–5: 331–339.

Dunahay TG, Jarvis EE, Dais SS, Roessler PG (1996) Manipulation of microalgal lipid production using genetic engineering. Appl Biochem Biotechnol 57-58:223-31.

Dürre P (1997) Biobutanol: an attractive biofuel. Biotechnol J 2(12):1525-34., 2007 Dec.

Dufey (2006) Biofuels Production, Trade and Sustainable Development: Emerging Issues. London: International Institute for Environment and Development, London.

Demirbas A (2009) Progress and recent trends in biodiesel fuels. Energy Conv Manag 50: 14–34.

Demirbas A (2010) Use of algae as biofuel sources. Energy Conversion and Management 51: 2738–2749.

Demirbas A, Fatih Demirbas M (2011) Importance of algae oil as a source of biodiesel. Energy Conversion and Management 52(1): 163–170.

Davidi L, Katz A, Pick U (2012) Characterization of major lipid droplet proteins from Dunaliella. Planta 236: 19–33.

De Hoop L, De Troch M, Hendriks AJ, De Laender F (2013) Modeling toxic stress by atrazine in a marine consumer-resource system. Environ Toxicol Chem 32: 1088–1095.

Darko E, Heydarizadeh P, Schoefs B, Sabzalian MR (2014) Photosynthesis under artificial light: The shift in primary and secondary metabolism. Philos Trans R Soc B Biol Sci 369: 20130243.

Deipolyi AR, Golberg A, Yarmush ML, Arellano RS, Oklu R (2014) Irreversible electroporation: Evolution of a laboratory technique in interventional oncology. Diagn Interv Radiol 20: 147–154.

Evans JH (1958) The survival of fresh-water algae during dry periods. Part I. An investigation of the algae of 5 small ponds. J Ecol 46 (1): 149–167.

Evans JH (1959a) The survival of fresh-water algae during dry periods. Part II. Drying experiments. J Ecol 47 (1): 55–70.

Evans JH (1959b) The survival of fresh-water algae during dry periods. Part III. Stratification of algae in pond margin litter and mud. J Ecol 47 (1): 55–81.

Evans JH (1960) Further investigations of the algae of pond margins. Hydrobiologia 15 (4): 384–394.

Fisher NS, Schwarzenbach RP (1978) Fatty acid dynamics in Thalassiosira pseudonanabacillariophyceae implications for physiological ecology. J Phycol 14 (2): 143–150.

Frenz J, Largeau C (1989) Casadevall E. Hydrocarbon recovery by extraction with a biocompatible solvent from free and immobilized cultures of Botryococcus braunii. Enzyme Microb Technol 11: 717–724.

Field CB, Behrenfeld MJ, Randerson JT, Falkowski P (1998) Primary production of the biosphere: Integrating terrestrial and oceanic components. Science 281: 237–240.

Frankel EN, Satue-Gracia T, Meyer AS, German JB (2002) Oxidative stability of fish and algae oils containing long-chain polyunsaturated fatty acids in bulk and in oil-in-water emulsions. Journal of Agricultural and Food Chemistry 50(7): 2094–2099.

Guitart R, Guerrero X, Silvestre AM, Gutierrez JM, Mateo R (1996) Organochlorine residues in tissues of striped dolphins affected by the 1990 mediterranean epizootic: relationships with the fatty acid composition. Arch Environ Contam Toxicol 30: 79–83.

Guliyev IS, Feizulayev AA, Huseynov DA (2001) Isotope geochemistry of oils from fields and mud volcanoes in the South Caspian Basin, Azerbaijan. Pet Geosci 7 (2): 201–209.

Ganeva V, Galutzov B, Teissie J (2003) High yield electroextraction of proteins from yeast by a flow process. Anal Biochem 315: 77–84.

Gordon R, Seckbach J (2012) The Science of Algal Fuels: Phycology, Geology, Biophotonics, Genomics and Nanotechnology; Springer: Dordrecht, The Netherlands.

Gerken HG, Donohoe B, Knoshaug EP (2013) Enzymatic cell wall degradation of Chlorella vulgaris and other microalgae for biofuel production. Planta 237: 239–253. https://doi.org/10.1007/s00425-012-1765-0.

Gacheva GV, Gigova LG (2014) Biological activity of microalgae can be enhanced by manipulating the cultivation temperature and irradiance. Cent Eur J Biol 9: 1168–1181.

Ghasemi Naghdi F, Thomas-Hall SR, Durairatnam R, Pratt S, Schenk PM (2014) Comparative effects of biomass pre-treatments for direct and indirect transesterification to enhance microalgal lipid recovery. Front Energy Res 2: 57.

Gillet J-N (2015) Ultrafast molecular dynamics of biofuel extraction for microalgae and bacteria milking: Blocking membrane folding pathways to damaged lipid-bilayer conformations with nanomicelles. J Biomol Struct Dyn 33: 690–705.

Gateau H, Marchand J, Schoefs B (2015) Pulse electric fields allow the biocompatible extraction of molecules from the microalgae Haematococcus pluvialis. In Abstracts, Functional Studies on Model Organisms (EFOR), 6th Annual Meeting, Paris, France; EFOR: Paris, France.

Haller JS Jr (1984) Sampson of the terebinthinates: Medical history of turpentine. South Med J 77: 750–754.

Hamm CE, Merkel R, Springer O, Jurkojc P, Maier C, Prechtel K, Smetacek V (2003) Architecture and material properties of diatom shells provide effective mechanical protection. Nature 421: 841–843.

Hejazi MA, Wijffels RH (2004) Milking of microalgae. Trends Biotechnol 22: 189–194.

Yen H-W et al. (2007) Anaerobic co-digestion of algal sludge and waste paper to produce methane Bioresour Technol.

Hu Q, Sommerfeld M, Jarvis E, Ghirardi M, Posewitz M, Seibert M, Darzins A (2008) Microalgal triacylglycerols as feedstocks for biofuel production: perspectives and advances. Plant J 54 (4): 621–639.

Hildebrand M, Davis AK, Smith SR, Traller JC, Abbriano R (2012) The place of diatoms in the biofuels industry. Biofuels 3: 221–240.

Heydarizadeh P, Poirier I, Loizeau D, Ulmann L, Mimouni V, Schoefs B, Bertrand M (2013) Plastids of marine phytoplankton produce bioactive pigments and lipids. Mar Drugs 11: 3425–3471.

Ho S-H, Ye X, Hasunuma T, Chang J-S, Kondo A (2014) Perspectives on engineering strategies for improving biofuel production from microalgae—A critical review. Biotechnol Adv 32: 1448–1459.

Imahara H, Minami E, Saka S (2006) Thermodynamic study on cloud point of biodiesel with its fatty acid composition. Fuel 85 (12-13): 1666–1670.

Jiang Y, Yoshida T, Quigg A (2012) Photosynthetic performance, lipid production and biomass composition in response to nitrogen limitation in marine microalgae. Plant Physiol Biochem 54: 70e77. http://dx.doi.org/10.1016/j.plaphy.2012.02.012.

Joubert V, Cheype C, Bonnet J, Packan D, Garnier JP, Teissie J, Blanckaert V (2013) Inactivation of Bacillus subtilis var. niger of both spore and vegetative forms by means of corona discharges applied in water. Water Res 47: 1381–1389.

Popp J, Harangi-Rákos M, Gabnai Z, Balogh P, Antal G, Bai A (2016) Biofuels and Their Co-Products as Livestock Feed: Global Economic and Environmental Implications, Molecules, 2016, 21, 285; doi:10.3390/molecules21030285.

Kociolek JP, Stoermer EF (1988) A preliminary investigation of the phylogenetic relationships among the freshwater, apical pore field-bearing cymbelloid and gomphonemoid diatoms (Bacillariophyceae). J Phycol 24: 377–385.

Kociolek JP (2007) Diatoms: Unique eukaryotic extremophiles providing insights into planetary change. Proc Soc Photo-Opt Instrum Eng (SPIE) 6694: 66940S.

Kligerman DC, Bouwer EJ (2015) Prospects for biodiesel production from algae-based wastewater treatment in Brazil: a review. Renewable and Sustainable Energy Reviews 52:1834-46.

Khammee P, Ramaraj R, Whangchai N, Bhuyar P, Unpaprom Y (2020) The immobilization of yeast for fermentation of macroalgae Rhizoclonium sp. for efficient conversion into bioethanol. Biomass Convers Biorefin. https://doi.org/10.1007/s13399-020-00786-y.

León R, Fernández E (2007) Nuclear transformation of eukaryotic microalgae: Historical overview, achievements and problems. Adv Exp Med Biol 616: 1–11.

Ladd C, Venter JC (2010) Big Questions for Maverick Geneticist J. Craig Venter on America's Energy Future. Available online: http://www.popularmechanics.com/blogs/science_news/4275738.html.

Lemoine Y, Schoefs B (2010) Secondary ketocarotenoid astaxanthin biosynthesis in algae: A multifunctional response to stress. Photosynth Res 106: 155–177.

Lam MK, Lee KT (2011) Renewable and sustainable bioenergies production from palm oil mill effluent (POME): wine win strategies toward better environmental protection. Biotechnology Advances 29(1):124-41.

Liu X, Fallon S, Sheng J, Curtiss R III (2011) CO2-limitation-inducible Green Recovery of fatty acids from cyanobacterial biomass. Proc Natl Acad Sci USA 108: 6905–6908.

Liu X, Sheng J, Curtiss R (2011) Fatty acid production in genetically modified cyanobacteria. Proc Natl Acad Sci USA 108: 6899–6904.

Lam MK, Lee KT (2012) Microalgae biofuels: a critical review of issues, problems and the way forward. Biotechnology Advances 30(3):673-90.

Li FJ, Gao DW, Hu HH (2014) High-Efficiency nuclear transformation of the oleaginous marine Nannochloropsis species using PCR product. Biosci Biotechnol Biochem 78: 812–817.

Lane J (2015) Joule's quest for fuels from CO2, sunlight and water. Available online: http://www.biofuelsdigest.com/bdigest/2014/07/03/joules-quest-for-fuels-from-co2-sunlight-and-water.

Munson PJ (1989) Still more on the antiquity of maple sugar and syrup in aboriginal eastern North America. J Ethnobiology 9: 159–170.

Mandal S, Mallick N (2009) Microalga Scenedesmus obliquus as a potential source for biodiesel production. Applied Microbiology and Biotechnology 84(2): 281–291.

Moustafa A, Beszteri B, Maier UG, Bowler C, Valentin K, Bhattacharya D (2009) Genomic footprints of a cryptic plastid endosymbiosis in diatoms. Science 324: 1724–1726.

MB-BigB (2012) Joule Unlimited's bacteria secretes diesel fuel. Available online: http://www.alt-energy.info/biofuel/joule-unlimiteds-bacteria-secretes-diesel-fuel/.

Mimouni V, Ulmann L, Pasquet V, Mathieu M, Picot L, Bougaran G, Cadoret J-P, Morant-Manceau A, Schoefs B (2012) The potential of microalgae for the production of bioactive molecules of pharmaceutical interest. Curr Pharm Biotechnol 13: 2733–2750.

Miyahara M, Aoi M, Inoue-Kashino N, Kashino Y, Ifuku K (2013) Highly efficient transformation of the diatom Phaeodactylum tricornutum by multi-pulse electroporation. Biosci Biotechnol Biochem 77: 874–876.

Masmoudi S, Nguyen-Deroche N, Caruso A, Ayadi H, Morant-Manceau A, Tremblin G, Bertrand M, Schoefs B (2013) Cadmium, copper, sodium and zinc effects on diatoms: From heaven to hell—A review. Cryptogam Algol 34: 185–225.

Maeda Y, Sunaga Y, Yoshino T, Tanaka T (2014) Oleosome-associated protein of the oleaginous diatom Fistulifera solaris contains an endoplasmic reticulum-targeting signal sequence. Mar Drugs 12: 3892–3903.

Nearing H, Nearing S (2000) The Maple Sugar Book: Together with Remarks on Pioneering as a Way of Living in the Twentieth Century; Chelsea Green Publishing: White River Junction, VT, USA.

Nguyen-Deroche TLN, Caruso A, Le TT, Bui TV, Schoefs B, Tremblin G, Morant-Manceau A (2012) Zinc affects differently growth, photosynthesis, antioxidant enzyme activities and phytochelatin synthase expression of four marine diatoms. Sci World J 982957.

Nojima D, Yoshino T, Maeda Y, Tanaka M, Nemoto M, Tanaka T (2013) Proteomics analysis of oil body-associated proteins in the oleaginous diatom. J Proteome Res 12: 5293–5301.

Nautiyal P, Subramanian KA, Dastidar MG (2014a) Production and characterization of biodiesel from algae. Fuel Processing Technology 120: 79–88.

Nautiyal P, Subramanian KA, Dastidar MG (2014b) Kinetic and thermodynamic studies on biodiesel production from Spirulina platensis algae biomass using single stage extraction–transesterification process. Fuel 135: 228–234.

European Commission (2006) An EU Strategy for Biofuels. Communication from the Commission COM34 final, Brussels: 29.

Patil V, Tran KQ, Giselrød HR (2008) Towards sustainable production of biofuels from microalgae. International Journal of Molecular Sciences 9(7):1188-95.

Pittman JK, Dean AP, Osundeko O (2011) The potential of sustainable algal biofuel production using wastewater resources. Bioresour Technol 102(1):17-25.

Patil PD, Gude VG, Mannarswamy A, Deng S, Cooke P, Munson-McGee S, Rhodes I, Lammers P, Nirmalakhandan N (2011) Optimization of direct conversion of wet algae to biodiesel under supercritical methanol conditions. Bioresource Technology 102: 118–122.

Pandey LK, Bergey EA (2016) Exploring the status of motility, lipid bodies, deformities, and size reduction in periphytic diatom community from chronically metal (Cu, Zn) polluted waterbodies as a biomonitoring tool, Sci Total Environ 550: 372-381. https://doi.org/10.1016/j.scitotenv.2015.11.151.

Pandey LK, Han T, Gaur JP (2015) Ecotoxicology, Response of a phytoplanktonic assemblage to copper and zinc enrichment in microcosm. 573-582. https://doi.org/10.1007/s10646-014-1405-5.

Chandra PK, Bhunia B, Bandyopadhyay TK (2023) Carbon dioxide capture and its enhanced utilization using microalgae. Green Sustainable Process for Chemical and Environmental Engineering and Science pages-531-546.

Round FE, Crawford RM, Mann DG (1990) The Diatoms, Biology & Morphology of the Genera; Cambridge University Press: Cambridge, U.K.

Roessler PG, Brown LM, Dunahay TG, Heacox DA, Jarvis EE, Schneider JC, et al. (1994) Genetic-engineering approaches for enhanced production of biodiesel fuel from microalgae. ACS Symp Ser 566:255-70.

Raetz CRH (2001) Biosynthesis, secretion and function of lipid A in Gram-negative bacteria. Glycobiology 11: 872–872.

Robert S, Mansour MP, Blackburn SI (2007) Metolachlor-mediated selection of a microalgal strain producing novel polyunsaturated fatty acids. Mar Biotechnol 9: 146–153.

Ramachandra TV, Mahapatra DM, Karthick B, Gordon R (2009) Milking diatoms for sustainable energy: biochemical engineering versus gasoline-secreting diatom solar panels. Ind Eng Chem Res 48: 8769–8788.

Reppas NB, Ridley CP (2010) Methods and Compositions for the Recombinant Biosynthesis of N-Alkanes. United States Patent 7,794,969.

Robertson DE, Jacobson SA, Morgan F, Berry D, Church GM, Afeyan NB (2011) A new dawn for industrial photosynthesis. Photosynth Res 107: 269–277.

Reep P, Green MP (2012) Procedure for extracting of lipids from algae without cell sacrifice. US Patent 20120040428 A1, 16 February.

Lee RA, Lavoie J-M (2013) From first- to third-generation biofuels: Challenges of producing a commodity from a biomass of increasing complexity. Animal Frontiers Vol. 3, No.2. doi:10.2527/af.2013-0010.

Rickman M, Davis RH, Pellegrino J (2013) Fractionation of organic fuel precursors from electrolytes with membranes. Ind Eng Chem Res 52: 10530–10539.

Roberts GW, Fortier MOP, Sturm BS, Stagg-Williams SM (2013) Promising pathway for algal biofuels through wastewater cultivation and hydrothermal conversion. Energy & Fuels 27(2):857-67.

Rohacek K, Bertrand M, Moreau B, Jacquette B, Caplat C, Morant-Manceau A, Schoefs B (2014) Relaxation of the non-photochemical chlorophyll fluorescence quenching in diatoms: Kinetics, components and mechanisms. Philos Trans R Soc B Biol Sci 369SI: 20130241.

Ramaraj R, Tsai DDW, Chen PH (2015) Biomass of algae growth on natural water medium. J Photochem Photobiol B Biol 142: 124–128. https://doi.org/10.1016/j.jphotobiol.2014.12.007.

Roselló-Soto E, Galanakis CM, Brnčić M, Orlien V, Trujillo FJ, Mawson R, Knoerzer K, Tiwari BK, Barba FJ (2015) Clean recovery of antioxidant compounds from plant foods, by-products and algae assisted by ultrasounds processing. Modeling approaches to optimize processing conditions. Trends Food Sci Technol 42: 134–149.

Carpio RB, De Leon R, Martinez-Goss MR (2015) Growth, lipid content, and lipid profile of the green alga, Chlorella vulgaris Beij., under different concentrations of Fe and CO2 Journal of Engineering Science and Technology Special Issue 6 1/2015, 19 – 30.

Sicko-Goad L, Lazinsky D, Hall J, Simmons MS (1989a) Effects of chlorinated benzenes on diatom fatty acid composition and quantitative morphology. I. 1,2,4-trichlorobenzene. Arch Environ Contam Toxicol 18: 629–663.

Sicko-Goad L, Hall J, Lazinsky D, Simmons MS (1989b) Effects of chlorinated benzenes on diatom fatty acid composition and quantitative morphology. II. 1,3,5-trichlorobenzene. Arch Environ Contam Toxicol 18: 638–646.

Sicko-Goad L, Hall J, Lazinsky D, Simmons MS (1989c) Effects of chlorinated benzenes on diatom fatty acid composition and quantitative morphology. III. 1,2,3-Trichlorobenzene. Arch Environ Contam Toxicol 18 (5): 647–655.

Sicko-Goad L, Evans MS, Lazinsky D, Hall J, Simmons MS (1989d) Effects of chlorinated benzenes on diatom fatty acid composition and quantitative morphology. IV. Pentachlorobenzene and comparison with trichlorobenzene isomers. Arch Environ Contam Toxicol 18: 656–668.

Sixou S, Teissié J (1990) Specific electropermeabilization of leukocytes in a blood sample and application to large volumes of cells. Biochim Biophys Acta 1028: 154–160.

Shay EG (1993) Diesel fuel from vegetable oils: status and opportunities. Biomass and Bioenergy 4(4):227-42.

Sawayama S, Inoue S, Dote Y, Yokoyama S-Y (1995) CO2 fixation and oil production through microalga. Energy Convers Manag 36:729-31.

Sauer T, Galinski EA (1998) Bacterial milking: A novel bioprocess for production of compatible solutes. Biotechnol Bioeng 57: 306–313.

Sheehan J, Dunahay T, Benemann J, Roessler P (1998) A look back at the U.S. Department of Energy's Aquatic Species Programdbiodiesel from algae. Golden, CO: National Renewable Energy Laboratory, Golden, CO.

Sheehan J, Dunahay T, Benemann J, Roessler P (1998) A Look Back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel from Algae, Close-Out Report [NREL/TP-580-24190], National Renewable Energy Laboratory, Golden, CO.

Serdari A, Lois E, Stournas S (1999) Impact of esters of mono-and dicarboxylic acids on diesel fuel quality. Industrial & Engineering Chemistry Research 38(9): 3543–3548.

Spolaore P, Joannis-Cassan C, Duran E, Isambert A (2006) Commercial applications of microalgae. J Biosci Bioeng 101: 87–96.

Sterrenburg FAS, Gordon R, Tiffany MA, Nagy SS (2007) Diatoms: Living in a constructal environment. In Algae and Cyanobacteria in Extreme Environments. Series: Cellular Origin, Life in

Extreme Habitats and Astrobiology, Volume 11; Seckbach J, Ed.; Springer: Dordrecht, The Netherlands, pp. 141–172.

Schenk PM, Thomas-Hall SR, Marx UC, Mussgnug JH, Posten C, Kruse O, Hankamer B (2008) Second generation biofuel: high-efficiency microalgae for biodiesel production. Bioenerg Res 1:20-43.

Sheng J, Vannela R, Rittmann BE (2011) Evaluation of cell-disruption effects of pulsed-electric-field treatment of Synechocystis PCC 6803. Environ Sci Technol 45: 3795–3802.

Sharma KK, Schuhmann H, Schenk PM (2012) High lipid induction in microalgae for biodiesel production. Energies 5: 1532–1553.

Thomas WH, Dodson AN, Reid FMH (1978) Diatom productivity compared to other algae in natural marine phytoplankton assemblages. J Phycol 14: 250–253.

Tsukagoshi N, Yoshida H, Katsurayama M, Udaka S (1983) Uncoupled release of protein and lipid in a protein-secreting bacterium, Bacillus brevis-47. Biochim Biophys Acta 759: 278–285.

Taguchi S, Hirata JA, Laws EA (1987) Silicate deficiency and lipid synthesis of marine diatoms. J Phycol 23: 260–267.

Tsukahara K, Sawayama S (2005) Liquid fuel production using microalgae. J Jpn Pet Inst 48: 251.

Van-Thuoc D, Guzmán H, Quillaguamán J, Hatti-Kaul R (2010) High productivity of ectoines by Halomonas boliviensis using a combined two-step fed-batch culture and milking process. J Biotechnol 147: 46–51.

Velasquez-Orta SB, Lee JGM, Harvey AP (2013) Evaluation of FAME production from wet marine and freshwater microalgae by in situ transesterification. Biochemical Engineering Journal 76: 83–89.

Vinayak V, Gordon R, Gautam S, Rai A (2014) Discovery of a diatom that oozes oil. Adv Sci Lett 20: 1256–1267.

Williams PJleB, Laurens LML (2010) Microalgae as biodiesel & biomass feedstocks: Review & analysis of the biochemistry, energetics & economics. Energy Environ Sci 3: 554–590.

Wald ML (2015) Biotech Company to Patent Fuel-Secreting Bacterium. Available online: http://www.nytimes.com/2010/09/14/science/earth/14fuel.html.

Xiangmeng Ma, Yuei Mi, Chen Zhao, Qun Wei (2022) A comprehensive review on carbon source effect of microalgae lipid accumulation for biofuel production 806: 151387.

Yatsu LY, Jacks TJ, Hensarling TP (1971) Isolation of spherosomes (oleosomes) from onion, cabbage, and cottonseed tissues. Plant Physiol 48: 675–682.

Yeang K (2008) Biofuel from algae. Architectural Design 78: 118–119.

Yadugiri VT (2009) Milking diatoms—A new route to sustainable energy. Curr Sci 97: 748–750.

Zhang XQ, Dubacq JP, Alfsen A (1993) Biochemical and cytological evidence for the stimulation of clathrin-coated (vesicle) formation by exogenous folic acid in Dunaliella salina (Chlorophyta). J Phycol 29: 203–209.

Zhang F, Cheng LH, Xu XH, Zhang L, Chen HL (2011) Screening of biocompatible organic solvents for enhancement of lipid milking from Nannochloropsis sp. Process Biochem 46: 1934–1941.

Zhang CY, Hu HH (2014) High-efficiency nuclear transformation of the diatom Phaeodactylum tricornutum by electroporation. Mar Genom 16: 63–66.

Zhang L, Han JC, Yang GP, Zhu BH, Pan KH (2014) Association of triacylglyceride content and transcript abundance of genes involving in lipid synthesis of nitrogen deficient Phaeodactylum tricornutum. Chin J Oceanol Limnol 32: 397–402.

Author Contributions

S, APS, VKS, LKP and JNM conceived the concept, wrote and approved the manuscript.

Acknowledgements
I (Sangeeta) am thankful to NFSC (National Fellowship for Schedule Caste) for JRF and the Head of the Department of Plant Science, MJP Rohilkhand University, Bareilly, for providing me with laboratory facilities and guidance.

Funding
Not applicable.

Availability of data and materials
Not applicable.

Competing interest
The authors declare no competing interests.

Ethics approval
Not applicable.

Open Access *This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution, and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. Visit for more details http://creativecommons.org/licenses/by/4.0/.*

Citation: Sangeeta, Singh AP, Sinhal VK, Pandey LK and Maurya JN (2025) A Comprehensive Review on the Effect of Climate Change on Algal Biofuel Production. Environmental Science Archives 4(1): 148-166.