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# PRODUCTION AND COMBUSTION ANALYSIS OF MICROALGAE-BASED BIODIESEL


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**A Thesis submitted in partial fulfillment of the requirement for the degree of Bachelor of Science in Mechanical Engineering**


**Department of Mechanical and Production Engineering (MPE)**

**Islamic University of Technology (IUT)**


**May, 2023**

## Candidate's Declaration

This is to certify that the work presented in this thesis, titled, "**Production and Combustion Analysis of Microalgae-based Biodiesel**", is the outcome of the investigation and research carried out by me under the supervision of **Dr. Arafat Ahmed Bhuiyan,** Associate Professor**,** Department of Mechanical and Production Engineering, IUT

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## RECOMMENDATION OF THE BOARD OF SUPERVISORS

The thesis titled "**Production and Combustion Analysis of Microalgae-based Biodiesel**" submitted by A.B.M. Najmul Bari, Student No: 180011107, has been accepted as satisfactory in partial fulfillment of the requirements for the degree of B.Sc. in Mechanical Engineering **on 18th May, 2023.**

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# Abstract

For over the past century, traditional fossil fuel has been the life force of modern society. However, with rising sea-levels and the impending global climate crisis, the entire world and especially tropical countries face impending disasters due to the C2 emissions that accompany the combustion of biodiesel. Therefore, there arises a requirement to discover an alternate bio-energy source. This study examines the production and combustion analysis of microalgae-based biodiesel. Primarily, a culture medium based on a unique Tris buffer solution and Trace Metal Solution were used to amplify growth and a low cost photobioreactor was used to achieve the wet mass. The production of biodiesel from microalgae was conducted by chemically producing biodiesel based on biomass from the microalgal strain *C. Vulgaris*. The produced biodiesel was then characterized for acid value, kinematic viscosity, density, flash point, and cetane number which are some of its physicochemical parameters. The combustion analysis was conducted using an Internal Combustion engine, which measured the engine performance parameters. Thus, this study indicates the feasibility of utilizing microalgae-based biodiesel as a replacement fuel for internal combustion engines.

# Chapter 1: Introduction

## 1.1 Introduction to Biodiesel:

### 1.1.1 The Global Energy Crisis

The world is facing an energy crisis and fuel shortage due to increased demand, limited resources, and inefficient use. Since the 1970s, global energy consumption has more than doubled and is forecast to climb further over the next two decades[1],[2]. According to the International Energy Agency, worldwide energy demand will increase by more than 50% over the next 20 years. At the same time, the world's proven stocks of oil, natural gas, and coal are finite and will be insufficient to supply this expanding demand[3]. As a result, to satisfy its energy demands, the globe has increasingly resorted to renewable energy sources such as solar, wind, and hydropower. These supplies, however, are limited and cannot meet demand. Furthermore, the world's energy infrastructure is inefficient and wastes a significant quantity of energy. According to the International Energy Agency, approximately two-thirds of all energy generated globally is lost owing to energy system inefficiencies [4]. As a result, to decrease energy waste, the world is progressively turning to more efficient energy sources and technologies. There is also a global gasoline scarcity. The supply of gasoline is not keeping up with the rising demand. This is especially true for automobile fuels like gasoline, diesel, and jet fuel. As a result, the world's transportation needs are increasingly being met by alternative fuels such as biofuels, natural gas, and electricity. Finally, the world is facing a climate crisis due to the emissions of greenhouse gases, the main culprit of which is $CO_2$ which accounts for 53% of all greenhouse emissions [5]. The burning of fossil fuels is the leading cause of global warming and climate change. As a result, the world is increasingly turning to renewable energy sources and technologies to reduce emissions and mitigate climate change. Overall, the world is facing an energy crisis and fuel shortage due to increased demand, limited resources, and inefficient use. Renewable energy sources, carbon-neutral energy sources, alternative fuels, and energy efficiency technologies are key to addressing this crisis and ensuring a sustainable energy future for the world [6]–[8].

Subsequently, global energy research has significantly shifted towards finding environment friendly solutions. One particular field of interest is the reduction of greenhouse gases in the form of CO2, via technology such as capture of carbon from large sources [9]–[13].

### 1.1.2 Biofuel Production

At it's core, Biodiesels 32 are defined as any sort of combustible fuels that are derived from organic biomass that result in little to no $CO_2$ emission during production via both chemical and chemical processes [14], [15]. Biodiesel is usually derived by primarily by the formation of biomass from biologically renewable sources. Biomass refers to any organic material that has the potential to store chemical energy in organic form that is formed via the process of photosynthesis [16]. Microalgae are microscopic organisms which are capable of converting sunlight into biomass, and this biomass can then be converted into biodiesel [17].

### 1.1.3 Biodiesel

Biodiesel from microalgae is 56 a promising alternative to traditional fossil fuels due to its renewable and sustainable nature, as well as its higher energy efficiency. Biodiesel from microalgae has the potential to revolutionize the way we produce, store and use energy. It is a renewable, sustainable, and ecologically benign alternative to traditional fossil fuels, and its superior energy efficiency makes it a compelling option for powering automobiles and other energy-intensive applications. Algal biorefining is a technique that involves cultivating and collecting microalgae, extracting lipids, and trans esterifying these lipids into biodiesel to manufacture biodiesel from microalgae [18]. When compared to typical oil refineries, this procedure is quite straightforward and can be carried out on a considerably smaller scale. As a result, microalgae-based biodiesel is less expensive and easier to generate than standard biodiesel. Furthermore, microalgae-based biodiesel emits less CO2 and other pollutants, making it 30 a more sustainable and ecologically friendly alternative to traditional fossil fuels[19]. It is expensive to create and maintain the extensive and sophisticated infrastructure needed to produce biodiesel from microalgae. Furthermore, it can be challenging and time-consuming to collect and extract lipids from microalgae. Additionally, a catalyst must be used during the transesterification process, which might raise the cost of manufacture. The promise of microalgae-based biodiesel is clear, notwithstanding these difficulties. It has the ability to lessen reliance on fossil fuels and offer a more ecologically friendly and sustainable energy source. It is a desirable alternative for running autos and other applications due to its increased energy efficiency. In the future, a range of vehicles, such as automobiles, buses, and even airplanes, may be powered by microalgae-based biodiesel. Additionally, it can be used to power other energy-consuming applications, such as generators and industrial machinery.

Furthermore, microalgae-based biodiesel may be used to make bioplastics, which are biodegradable and less harmful to the environment than regular plastics. Furthermore, biodiesel derived from microalgae may be utilized to create bioproducts such as fertilizers and animal feed. Microalgae-based biodiesel research and development are now underway. 41 More research is needed to increase the efficiency of the manufacturing process and lower production costs in order to exploit the promise of this developing technology. In addition, novel ways of collecting and extracting lipids from microalgae, as well as new transesterification catalysts, require development. In addition, research is needed to develop new uses for microalgae-based biodiesel, such as bioplastics, bioproducts, and other energy-intensive applications. It can also be used to power other energy-consuming applications like generators and industrial machines. Furthermore, microalgae-based biodiesel may be used to make bioplastics, which are biodegradable and less harmful to the environment than regular plastics. Furthermore, biodiesel derived from microalgae may be utilized to create bioproducts such as fertilizers and animal feed. Finally, it is crucial to remember that biodiesel derived from microalgae is not the only sustainable energy source accessible. Solar and wind energy, for example, have the ability to supply clean and sustainable energy as well [20], [21]. As a result, 52 it is critical to examine the potential of all renewable energy sources and select the best alternative for every specific application. Finally, microalgae-based biodiesel has the potential to transform the way we generate, store, and consume energy. It is a renewable, sustainable, and ecologically benign alternative to traditional fossil fuels, and its superior energy efficiency makes it a compelling option for powering automobiles and other energy-intensive applications. Despite the difficulties in producing it, the promise of microalgae-based biodiesel is obvious. More research and development are required to realize the full potential of this developing technology and to find new uses for microalgae-based biodiesel. Ultimately, microalgae-based biodiesel has the potential to reduce dependence on fossil fuels and provide a more sustainable and environmentally friendly energy source.

## 1.2 Microalgae Production

### 1.2.1 Microalgae:

Microalgae are an eclectic collection of microscopic aquatic creatures that play an important part in the health of our planet. They may be found in fresh, salt, and brackish water, and their sizes range from a few micrometers to several millimeters. Microalgae are photosynthetic, which means they can make their own food by absorbing light energy from the sun. As a result, they are a vital source of food for other aquatic animals and contribute significantly to the global carbon cycle[22].

Microalgae are employed in a number of industrial and commercial applications, in addition to their ecological relevance. For example, they are used in biofuel production, wastewater treatment, and cosmetics. More recently, they have also been used to develop nutritional supplements and health products, as well as to create natural dyes and other products. Microalgae have also been used to create biodegradable plastics, and to produce biomolecules such as omega-3 fatty acids [23].

The potential applications of microalgae are vast and far-reaching, as they are capable of producing a wide range of products in a sustainable and environmentally friendly manner. As technology advances and our understanding of microalgae continues to grow, the potential applications of these organisms will likely only increase.

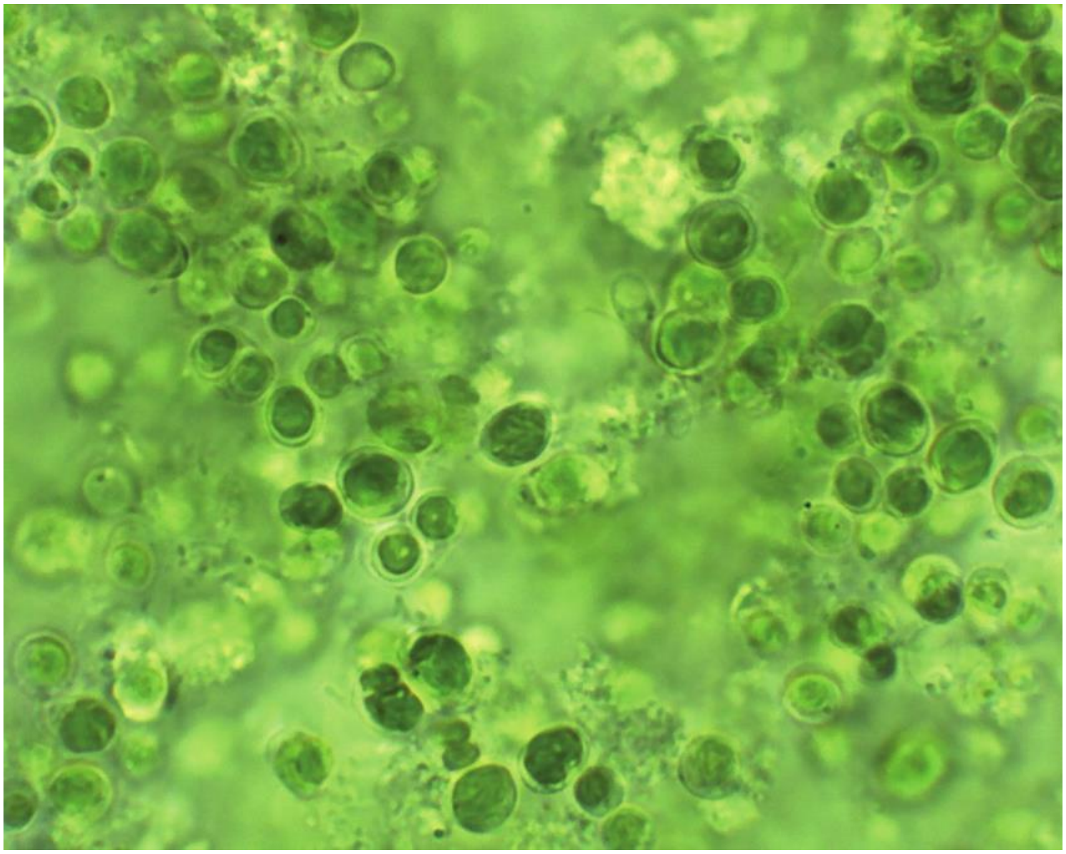

Figure 1: A 400X magnified microscopic image of a strain of *Chlorella Vulgaris* micro-algae strain [24].

Several characteristics of algal physiology are crucial for determining how successfully microalgae could be incorporated into applications for renewable biofuels. These characteristics can be encapsulated as follows: Algae, unlike terrestrial plants, (i) are naturally more efficient at converting solar energy into usable forms of energy (3–8% more effective than terrestrial; (ii) do not need pretreatments to break down cellular products due to a lack of intractable biopolymers; and iii) are better sources of energy since their ecological and metabolic diversity allows for the selection of taxa that are suited for growth in locally available resources [25]–[27].

### 1.2.2 Photobioreactor

Because just basic ingredients are needed, microalgae production seems to be rather simple. Most studies on microalgae production have focused on growing algae in sterile but expensive photobioreactors or in open ponds, which cost less to maintain but are more susceptible to contamination [28].

A photobioreactor (PBR) is a device that uses light to grow photosynthetic microorganisms and other organisms, such as algae [29]. It is a closed system, which is sealed from the environment and maintains the desired physiological conditions and operating parameters for the organisms. PBRs use light for the production of biomass, chemical feedstock, and energy. They are used in various fields, such as wastewater treatment, biotechnology, pharmaceuticals, production of biofuels, bioplastics, and biochemicals. PBRs are becoming increasingly popular, as they are cost-effective and efficient, while offering an environmentally friendly, sustainable solution. The main advantages of a photobioreactor are that it can be used for large-scale production of target compounds, it can be used for continuous or batch operations, and it can be operated using a wide range of light sources, including artificial and natural light. PBRs are very simple to utilize and scale up, making them an appealing alternative for industrial manufacturing.

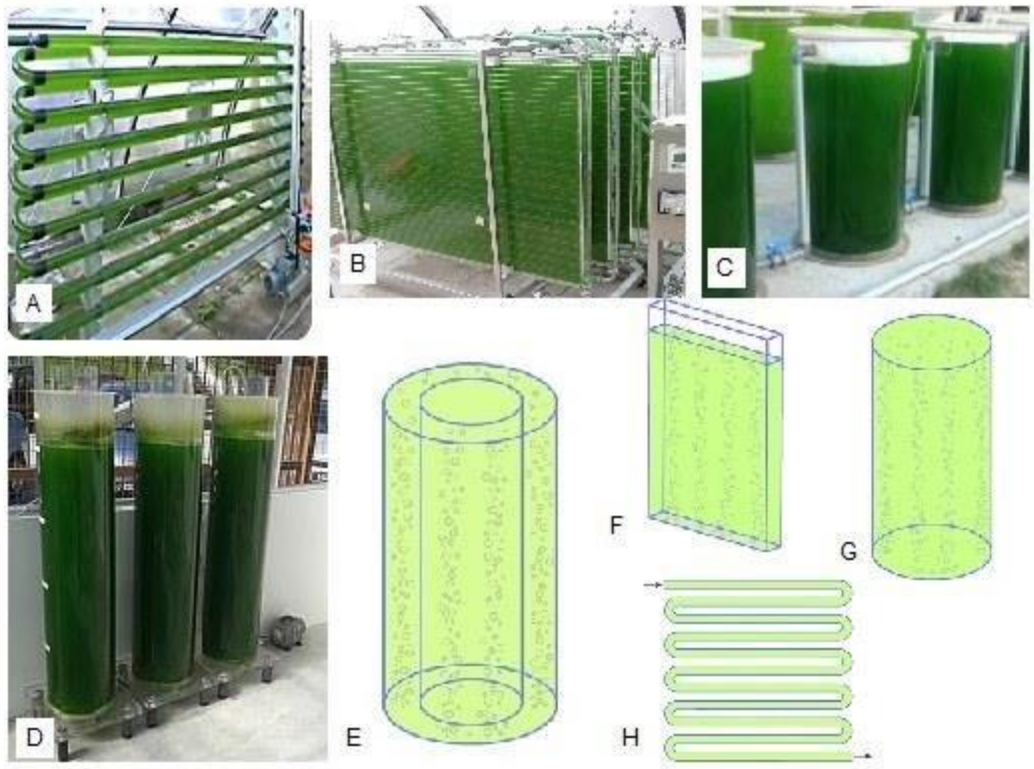


Figure 2: different type of Photobioreactors for algal cultivation, A. Tubular, B. Plate , C. Column, D. Annular, E-H. Diagrammatic representation of photobioreactors, E. Annular, F. Plate, G. Column, H. Tubular [30].

## 1.3 Biodiesel Extraction

### 1.3.1 Transesterification

Large, branching triglycerides are transformed into smaller, linear molecules—molecules more akin to those found in diesel fuel—through the transesterification process. A greater ratio is frequently used to increase the generation of biodiesel, but a three-to-one molar ratio of alcohol to triglyceride is necessary for this. The three processes involved in the process are the conversion of TG to diacylglycerol (DG) and one fatty acid ester, DG to monoacylglycerol (MG) and another fatty acid ester, and MG to glycerol and the final fatty acid ester. The hydrolysis of TGs, which results in the production of fatty acids and glycerol as a byproduct, requires a catalyst [31], [32]. The resultant biodiesel and glycerol must next be refined, typically by repeatedly washing with distilled water to remove the catalyst. It is imperative to highlight that the catalyst selected has a significant impact on the process' performance.

## 1.4 Biodiesel Combustion in IC Engine

### 1.4.1 Combustion of Biodiesel

Biodiesel is a renewable and sustainable fuel derived from natural sources such as vegetable oils, animal fats, and waste cooking oils. It has the potential to reduce emissions from diesel engines and is an important alternative to petroleum-based diesel fuel. When biodiesel is used as a fuel in an internal combustion (IC) engine, it is burned in the same way as diesel fuel. Biodiesel, on the other hand, burns cleaner and more effectively due to its increased oxygen content, resulting in less pollutants such as carbon monoxide, unburned hydrocarbons, and particulate matter[33]. In addition, biodiesel emits less sulfur dioxide, a primary contributor to acid rain. Furthermore, biodiesel is biodegradable, non-toxic, and reasonably easy to work with. As a result, it is an appealing alternative to fossil fuels.

Biodiesel combustion in IC engines is more efficient than petroleum-based diesel fuel combustion [34]. Biodiesel, for example, has a greater cetane number, which enhances the rate at which the fuel is burned, resulting in a more thorough combustion. Furthermore, because biodiesel has a greater flash point than diesel fuel, it lowers the danger of engine fires and explosions. Furthermore, biodiesel contains more energy than diesel fuel, resulting in improved power output.

The use of biodiesel in IC engines has environmental benefits as well. Biodiesel emits less CO2 and other greenhouse gases than petroleum-based diesel fuel, hence lowering its environmental effect. Because biodiesel is not generated from petroleum, it does not need drilling or refining. Thus, biodiesel may be utilized to minimize reliance on fossil fuels and contribute to the development of a more sustainable energy system.

Overall, biodiesel is a safe and efficient fuel that may be utilized in internal combustion engines. Biodiesel is a safer and more efficient fuel than petroleum-based diesel fuel due to its greater oxygen content and flash point [35]. Furthermore, its biodegradability and low emissions make it a more sustainable fuel source than petroleum-based diesel.

As a result, biodiesel is an appealing option to petroleum-based diesel fuel, both in terms of efficiency and environmental impact.

## 1.5 Scopes

The scopes for the research conducted can be summarized via the following:

1. Production of *Chlorella Vulgaris* and *Chlorella Sorokiniana* Microalgae based biomass in different geographical conditions

2. Extraction and examination of microalgae-based biofuel from aforementioned biomass.

3. Chemical analysis of acquired biodiesel from *Chlorella Vulgaris* biomass.

4. Analytical simulation of the combustion of biomass acquired through experimentation.

## 1.6 Objectives

The objectives of the conducted experimental research and the following analytical simulation were to primarily explore the aforementioned scopes. Therefore, the objectives of the paper can be summarized as:

1. To produce of *Chlorella Vulgaris* and *Chlorella Sorokiniana* Microalgae based biomass in tropical conditions.
2. To extract and physically examine microalgae-based biodiesel from aforementioned biomass
3. To perform chemical analysis on the biofuel extracted from the aforementioned biomass.
4. To simulate the flow of biodiesel extracted via experimentation
5. To analyze the combustion characteristics of the biodiesel within an Internal Combustion Engine.
6. To firmly establish microalgae based biodiesel as a viable alternative to traditional fossil fuel in Bangladesh.

To achieve these objectives, an experimental setup including a photobioreactor was created at Bangabandhu Sheikh Mujibur Rahman Agriculture University (BSMRAU) premises for the production of *Chlorella Vulgaris* based biomass. Local environmental factors such as seasonal air humidity, microalgae growth considerations, temperature and air pressure play a big part in the lipid content of microalgae sample.

Furthermore, methods of biodiesel extraction from biomass gathered via experimentation were also explored. Finally, analytical simulation was done taking into account the chemical properties of extracted biofuel.

# Chapter 2: Literature Review

As atmospheric pollution grows dangerously as a result of an increase in atmospheric $CO_2$ concentration, fossil fuel stocks are being rapidly depleted, leading to chaotic conditions that are driving fossil fuels to the edge of depletion. Utilizing algal biomass is beneficial for the atmospheric fixation of $CO_2$ as well as the production of biodiesel, which is safe for both the environment and people. Since it may be utilized for transportation and has less of an impact on the growth of biodiesel crops than it does on the growth of vegetable crops that can improve human welfare, biodiesel produced from an algal source can aid in the preservation of the environment [36].

According to research by Eyasu Shumbulo Shubaa and Demeke Kifleb, microalgal biofuels are a promising replacement for fossil fuels because of the inherent efficiency of microalgae to convert solar energy into chemical energy and their significantly higher potential yield of oils suitable for biofuel production than terrestrial crops. Over the past few years, there have been numerous developments in the genetic and metabolic engineering of algae strains to reduce production costs [37]. There have also been advancements in a variety of technical fields related to the production of algal biomass and methods for converting biomass into biofuels. Interest in microalgal biofuels is rising globally as concerns about fossil fuels, energy security, greenhouse gas emissions, and the potential for alternative biofuel feedstocks to compete for scarce agricultural resources grow. The abundance of sunlight and positively high temperatures in the tropics may be helpful for the low-cost production of hydrogen in a closed photobioreactor [38].

According to studies by Jassinnee Milano and Hwai Chyuan Ong, biomass obtained from microalgae can be used to make biofuels, which could eventually displace fossil fuels and reduce global $CO_2$ emissions. Microalgae fuels can be utilized in place of fossil fuels for transportation since their chemical makeup is comparable to that of gasoline and diesel. Microalgae have quick growth rates and high lipid concentrations, making them a viable choice for $CO_2$ fixation and biodiesel production. Now that the difficulties of commercializing the production on a large scale have been addressed, microalgae have a great potential to create biofuels and replace fossil fuel in the generation of energy. The following are some of the difficulties: (a) the low market demand for biofuels because fossil fuel is so inexpensive; (b) the high cost of producing biofuels from microalgae; and (c) the demand for an energy ratio greater than unity. Oil extraction from dried microalgae and low-cost, highly effective, low-contamination harvesting techniques are two issues that have been resolved. Natural flocculants can be used to solve these issues because they are less expensive and biodegradable than mineral flocculants. Despite the high lipid content of the microalgae being known, oil extraction is not going as planned. As a result, making biofuels from microalgae biomass is costly and has a low rate of return on investment. However, as governments put out more incentives and investment in recent technologies increases, it can be hoped that microalgae based biodiesel will soon become financially viable [39].

Studies conducted by Phukan, Chutia and Konwar describe microalgae are desired biomass species because they grow quickly and can fix more CO2 than terrestrial plants. Due to their high oil content and quick biomass synthesis, microalgae have long been recognized as a dependable source for the generation of biofuels. Within this research, it was concluded that the Chlorella species of microalgae shows desirable characteristics for future use and as a source of bioenergy. Microalgae of this species show high growth rate in expensive mediums and high biomass productivity [40].

AK Anwar conducted in depth studies about the combustion of non specialized biodiesel within an Internal Combustion (IC) engine and came to the conclusion that the use of biodiesel can significantly reduce greenhouse emissions. The author also conducted a combustion analysis, wear test and economic analysis which all point to the potential of biodiesel in increasing engine performance while remaining affordable [41].

# Chapter 3: Methodology

## 3.1 Species Selection

Prior to beginning the production process, specific species must first be chosen. The chosen species ought to have a few distinctive traits. it must be simple to locate in the natural world within the setup's geographical vicinity. It must have a rapid pace of growth. It must also have a substantial quantity of lipids. We choose to use two species in this example based on the aforementioned traits. They are *C. sorokiniana* and *C. vulgaris.*

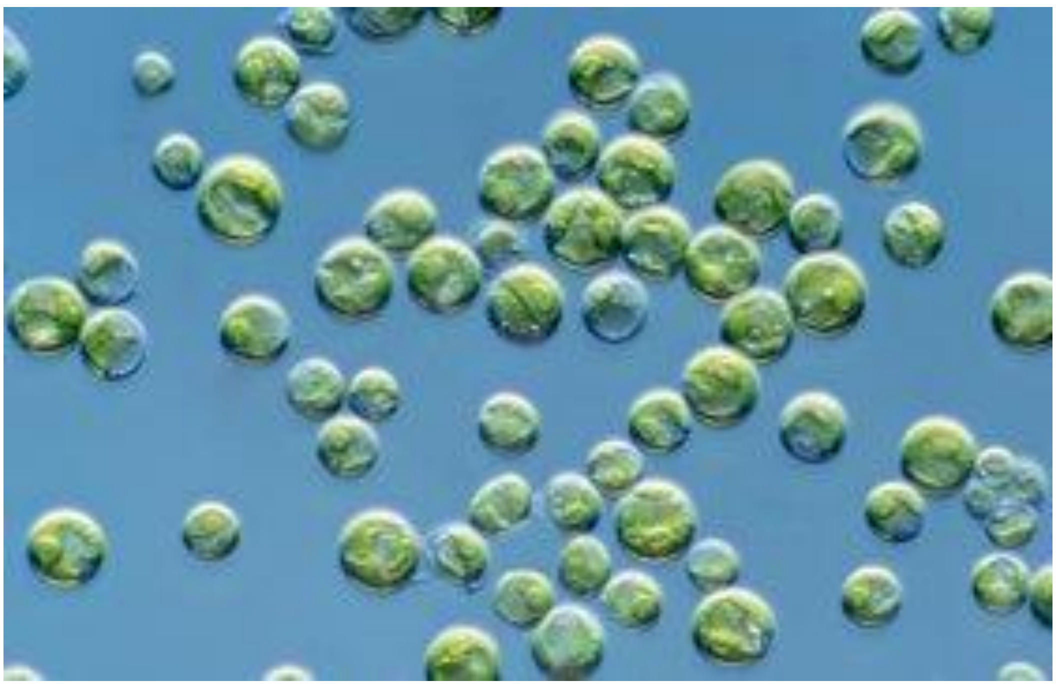

Figure 3: Enhanced and magnified image of *Chlorella Vulgaris* [42].

*Chlorella Vulgaris* is a single-celled green algae that is widely studied for its potential as a source of food, nutrition, and bioactive compounds. It is a fast-growing species of microalgae that has a high photosynthetic efficiency and rich nutritional content. C. Vulgaris has a high concentration of vital fatty acids, proteins, vitamins, minerals, and colors. It also includes phytochemicals that may have health advantages such as antioxidant and anti-inflammatory properties. It is also a potential biofuel source, and its capacity to absorb enormous volumes of $CO_2$ makes it a viable carbon sequestration technology[42].

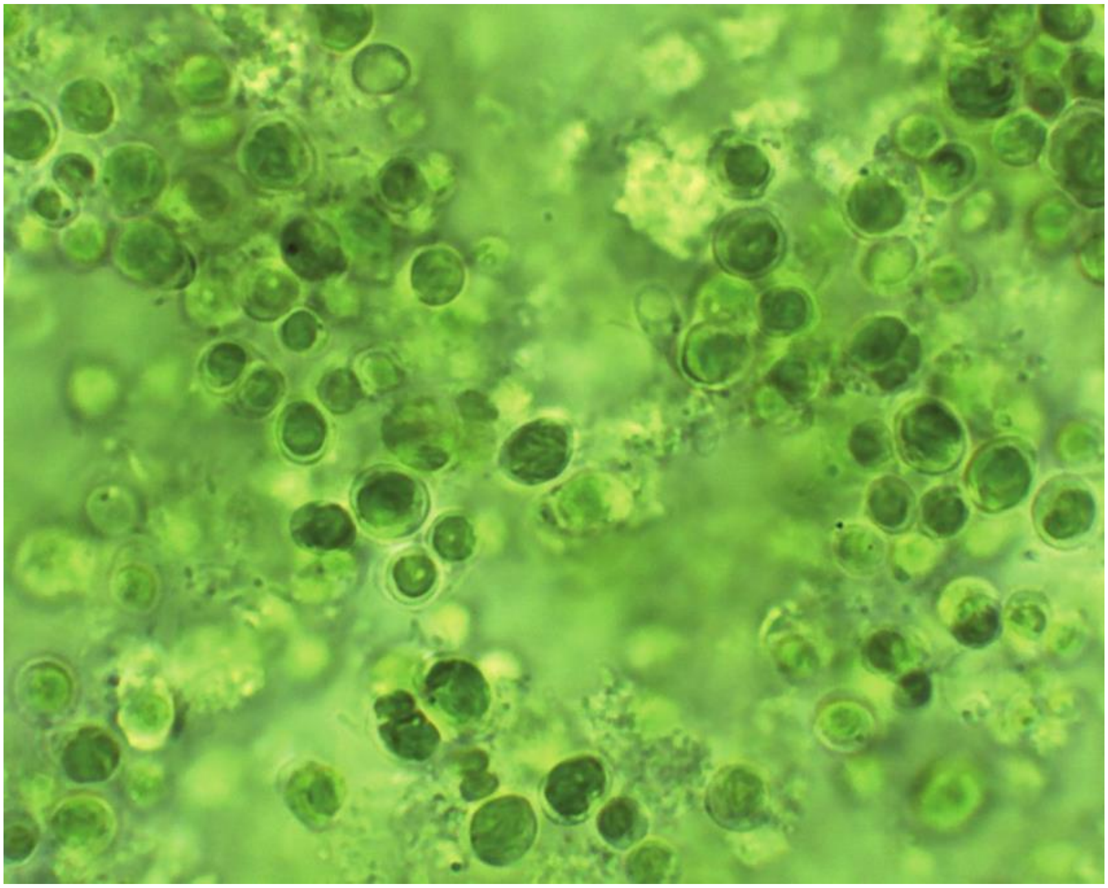

Figure 4: *Chlorella Sorokinia* under 1000X Magnification [43].

*Chlorella sorokiniana is a unicellular photosynthetic alga in the Chlorellaceae family. It is a single-celled, tiny green alga with a diameter of around 2-8 m. It is a eukaryotic creature with cellulose and other polysaccharides in its cell wall. It has the ability to fix nitrogen and can be utilized in wastewater treatment. Chlorella sorokiniana grows quickly, with a doubling period of 12-24 hours depending on the environment. It is also known to be resistant to a wide range of environmental conditions and to thrive in a variety of temperatures and salinities*. It is also known to be a good source of proteins, lipids, carbohydrates, and vitamins [44].

## 3.2 Creating Culture Medium and Providing Anti-Contaminant

The trace metal solution and the tris buffer solution are combined to form the culture medium. It is the medium in which the nutrients are distributed to encourage the seeds of microalgae to grow quickly. The nutrients in the seeds are tris buffer solution and trace metal solution. In this instance, the culture media contained 10 trace metals. The culture media is first applied in a flask or beaker. At first, different solutions for each of the ten trace elements were placed in each of the ten flasks. Size variations exist in the culture media. The container could be anything from a little beaker to a big drum, depending on the manufacturing. Large ponds serve as the cultural medium for commercial production. Then, a pipet was used to remove 2 ml of each solution from there and add them to the beaker that was chosen to serve as the culture medium. After that, a certain quantity of each ingredient was added to another to create tris buffer solution in a jar.

**Table 1: Solution Breakdown**

| **Tris Buffer Solution** | | **Trace Metal Solution** | |
|---|---|---|---|
| **Chemicals** | **Amount (mg/L)** | **Chemicals** | **Amount (mg/L)** |
| 1.Tris (hydroxymethyl) aminomethane | 2,420 | **1.** $Na_2EDTA$ | 50 |
| 2. $NH_4Cl$ | 400 | 2.$ZnSO_4 \cdot 7H_2O$ | 22 |
| 3. $K_2HPO_4$ | 108 | 3. $H_3BO_3$ | 11.4 |
| 4. $MgSO_4 \cdot 7H_2O$ | 100 | 4. KOH | 16 |
| 5. $KH_2PO_4$ | 56 | 5.$MnCl_2 . 4H_2O$ | 5.06 |
| 6. $CaCl_2 . 2H_2O$ | 50 | 6.$FeSO_4 \cdot 7H_2O$ | 4.99 |
| 7.Glacial Acetic Acid | 1 ml | 7. $CoCl_2 . 6H_2O$ | 1.61 |
| | | 8.$CuSO_4 \cdot 5H_2O$ | 1.57 |
| | | 9.$(NH_4)6Mo_7O_{24} . 4H_2O$ | 1.10 |
| | | 10. $CaCl_2 . 2H_2O$ | 0.05 |

Figure 5: Culture Medium

The tris buffer solution should be carefully combined with the glacial acetic acid due to the foul odor and severe skin damage it causes. The mixture then needs to be swirled for a while to combine the ingredients completely. When stirring a small beaker, you can do so by swishing it about in your palm. Once it has been fully blended, it is prepared to be added to the culture medium's trace metal solution. Contamination during microalgae production is problematic because it can lead to the growth of bacteria, fungi, and other microorganisms that can cause the microalgae to become contaminated with toxins or other harmful compounds. Contamination can also lead to the production of biofilms, which can interfere with the growth of the microalgae and make them more difficult to separate and harvest. In addition to the negative effects of contamination on the quality of the microalgae, it can also have a negative impact on the overall production process. Contamination can lead to decreased yields, as contaminated microalgae can be difficult to separate and harvest. Contamination can also lead to increased costs associated with additional water treatment, disposal of contaminated material, and replacement of contaminated equipment. Finally, contamination can lead to slower growth rates, which can further reduce the production yield. All of these factors can have a negative impact on the overall efficiency and profitability of microalgae production [45].

Figure 6: Bacterial Attack

The culture medium has been polluted if a visible white or red layer of bacteria is present on top of it. It might not be readily noticeable from the outside if there hasn't been a significant bacterial attack. There is a distinct method of identification in that situation. Since the beginning of mass production, the culture media has a tendency to get greener. If nothing has changed after a few days, we must conclude that bacteria have attacked it.

The aforementioned effects are visible in Fig. 6. We must use anti-contaminant to address this problem. Penicillin and amoxicillin were used as antibacterial drugs in this case. Amoxicillin 250 mg/L and penicillin 500 mg/L were used, respectively. Before being introduced to the culture medium, these two antibacterial solutions were mixed together in a different container. contamination cannot now enter the culturing media.

## 3.3 Setting up the Low-cost Photobioreactor

After creating the culture medium and integrating the antibacterial agents, it must be placed in a photobioreactor system to ensure that the seeds develop quickly in the culture medium. Natural sunlight cannot be used in this situation since it is not accessible 24 hours a day. As a result, an artificial setup must be put in place. We present a photobioreactor that we designed in response to the exorbitant pricing of photobioreactors on the market. This configuration is inexpensive to build. In order to make this setup the following items are needed:

1. Flood light of 100 W
2. Air pump
3. Carbon dioxide cylinder
4. Plastic box
5. Rubber pipes

In this setup, a rubber pipe is taken where in one end it is connected to an air pump and another end of the pipe will be inside the culture medium. A plastic box was used to store the pump. In order to ensure proper sunlight, a flood light was place in the culture medium. After positioning the culture media correctly, necessary amount of carbon dioxide is provided from the cylinder to the plastic box.

Figure 7: Lowcost Photobioreactor setup

The $CO_2$ will be pumped into the culture medium via the rubber pipes by the air pump within. The $CO_2$ from the cylinder must be pumped several times every 3/4 hour. The procedure must be repeated for the next two weeks. Microalgae growth will be at its height during this time period. Within this period, the moist mass can be removed from the culture media.

## 3.4 Production of Wet Mass

Figure 8: Experimental setup at the day of production

This diagram depicts the situation on the day of production. The culture media is virtually white in color. This is the result of combining every ingredient in the culture medium. This figure also depicts the photobioreactor arrangement. To make the culture medium more contaminant-proof, we utilized aluminum foil as the cover.

Figure 9: Experimental Setup two weeks after production

Two weeks after production, The color of the four cultural media has changed to a dark green as shown in this figure. This signifies that we had a really good output from this batch. Microalgae have colonized the whole culture media. From here, we must remove the undesirable water and collect the moist bulk.

## 3.5 Retrieval of the Wet Mass

To harvest the moist material from the culture medium, we must first remove the undesired water. We must utilize a flocculant for this reason. Flocculants are substances that aid in particle clumping in water. The flocculant was aluminum chloride. It aids in the formation of a moist mass sediment at the bottom of the culture media.

Figure 10: Sediment of the wet mass

Aluminium Chloride was utilized as a flocculant at a rate of 0.5 gm/L. The water from the top is then evacuated using a syphon until just the moist substance remains. The wet mass is then extracted from the medium to determine the dry mass.

## 3.6 Producing Biomass/ Dry Mass from the Wet Mass

After collecting the wet mass, the microalgae should be dried to obtain the necessary dry mass or biomass. The drying of the moist bulk takes place in an oven. The gathered moist material must be placed in an oven at 70-80°C for one day. The dry mass may then be calculated from there.

Figure 11: The desired biomass

A large amount of dry mass may be obtained via mass manufacturing, and from there the oil processing operations can proceed.

## 3.7 Combustion Analysis

72 For the combustion of biodiesel derived from microalgae source, all the thermal parameters are derived from the experimental work of Conversion of Biodiesel from Microalgae source which is listed in Table 2. During the combustion of biodiesel, various chemical reactions take place in the presence of $O_2$. The fundamental reaction for this is given in equation 1.

To simulate the whole combustion of biodiesel, a generalized eddy-dissipation model was employed. The biodiesel chemical reaction equation is-

$C_{17}H_{34}O_2 + 24.5O_2 \rightarrow 17CO_2 + 17H_2O + \Delta H$ (1)

Molecular weight of the biodiesel is as follows:

Weight of Carbon 17*12= 204

Weight of Hydrogen 34*1= 34

Weight of Oxygen 16*2= 32

Total Molecular Weight of Biodiesel $MW_r$ = 204 + 34 + 32 = 270. The empirical relationship used to compute 1 the average molecular weight of biodiesel is

$MW_e$ = 14.027C -2.016d +2.016 *1 + 31.998

= 14.027*17 - 2.016*1 + 31.9988 = 268.4578

Where, C is the number of carbon present 37 in the biodiesel and d is the amount of double bonds in a hydrocarbon.

**Table 2: A comparison of the parameters of diesel and biodiesel**

| **Property Name** | **Unit** | **Biodiesel** | **Diesel** |
|---|---|---|---|
| Kinematic Viscosity | Cst | 4.8 | 3.6 |
| Density | $kg/m^3$ | 845-900 | 825 |
| Cetane Number | - | 58.4(47-60) | 51.5 |
| Calorific Value | kJ/kg | 39340-43759.5 | 44,000 |
| Specific Heat | J/kg-K | 1900-2050 | 1750 |
| Stoichiometric A/F Ratio | - | 12.525 | 15 |
| Molecular Weight | - | 270 | ≈ 200 |
| Auto Ignition Temp. | K | 700 | 483 |
| Flash Point | °C | 88-170 | 76 |
| Calorific Value | MJ/kg | 39.8 | 45 |
| Ignition Delay | Angle to crankshaft | 9.39 | 10.56 |

### 3.7.1 A/F ratio for biodiesel combustion

Figure 12 illustrates the stoichiometric combustion reaction in which the fuel's hydrocarbon reactant (in this case, biodiesel) must produce heat, $CO_2$, and water as byproducts of combustion. Here the value of z symbolizes the stoichiometric coefficient of air.

$z = x + (y/4); z = 17 + (34/4) = 25.5$

A/F ratio = mass of air/mass of fuel inlet

= z*4.76*29/ (molecular mass of fuel* no. of moles)

= 12.53 kg

So in the chemical reaction of the combustion of 1kg biodiesel, 12.53kg of air is required.

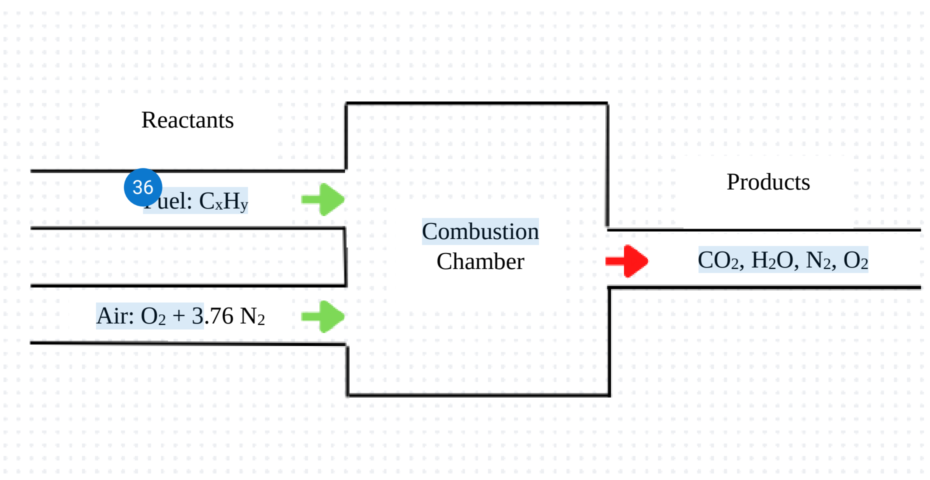


Fig. 12: Schematic of reaction from combustion chamber

### 3.7.2 Modeling of the problem

Fig. 4 depicts the cylindrical combustion chamber under consideration. In this study, the flame is a turbulent diffusion flame. Through a small nozzle in the middle, biodiesel enters the cylinder at 50 m/s, while ambient air enters at 0.5 m/s coaxially. The equivalency ratio is 0.76 (about 28% additional air). Because the injection speed for biodiesel is rapid, the cylinder's outer wall offers less resistance, allowing it to expand quickly and blend with the intake air of the cylinder.

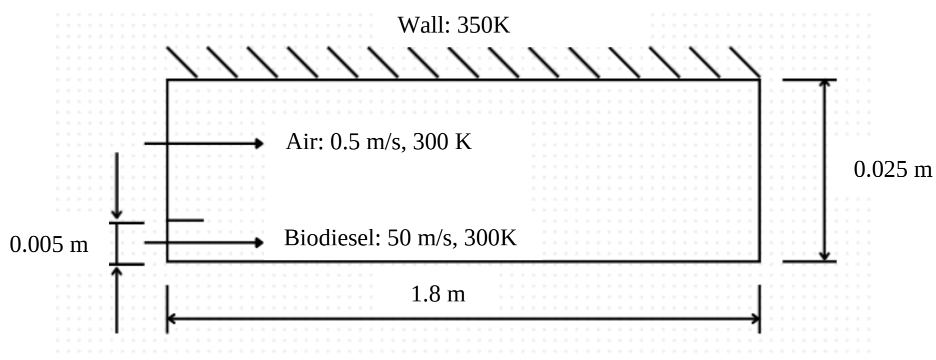


Fig. 13: Analysis of a cylinder combustor schematic

### 3.7.3 CFD Modelling of biodiesel combustion using ANSYS

The study of the combustion process to improve efficiency and reduce emissions is known as combustion analysis. It may be done using a variety of methods, the most common of which being computational fluid dynamics (CFD) software. CFD software may be used by engineers to simulate fluid movement, heat transfer, and chemical reactions in a combustion chamber. This data is then utilized to improve the combustion chamber architecture in order to enhance the combustion process. Ansys fluent was used for combustion analysis, and the design was imported as a.CAD file from SolidWorks. The following are the actions taken to complete the simulation:

**3.7.3.A Creating the geometry:** The combustion chamber geometry was created in SolidWorks and then imported into Ansys Fluent for analysis. It is critical to verify that the geometry is clean and watertight before importing it into Fluent. This preparatory step is critical because it guarantees that the combustion chamber geometry is appropriately transferred into the Fluent program for further analysis and assessment.

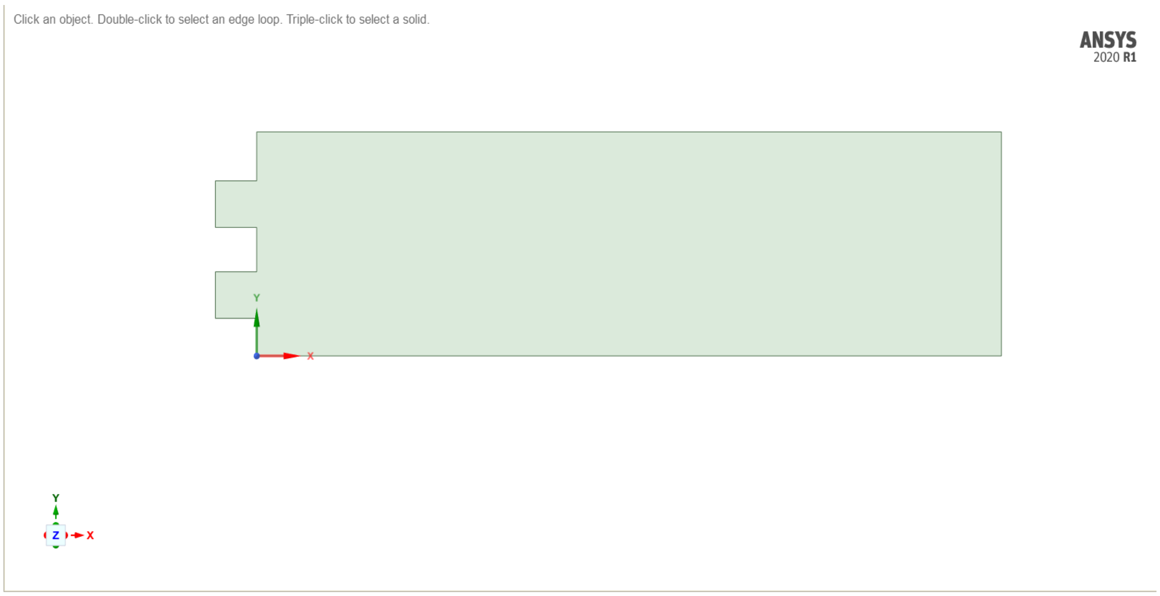


Fig 14: Simulation Geometry

**3.7.3.B Specifying boundary conditions:** It is vital to completely and exactly specify the simulation's boundary conditions. These conditions include the fluid flow's intake and exit parameters, as well as the boundary conditions for combustion and radiation. Table 2 specifically indicates the simulation's needed boundary conditions. Boundary conditions are used as a crucial component to appropriately reflect the convection load. The careful selection and definition of these boundary conditions is critical in allowing for an accurate and trustworthy simulation of the desired occurrence.

**3.7.3.C Mesh generation:** To solve equations, a computational mesh is developed to effectively discretize the geometry. In this situation, the structured mesh generating tools included with the program are used. Through the use of geometry-based fine mesh production methods, the whole domain is discretized. This procedure guarantees that the domain is partitioned into smaller pieces, which allows for more precise and efficient computations. The computational mesh is meticulously created to fit the needs of the analysis and enable the resolution of equations inside the prescribed geometry by leveraging the in-built structured mesh generating tools.

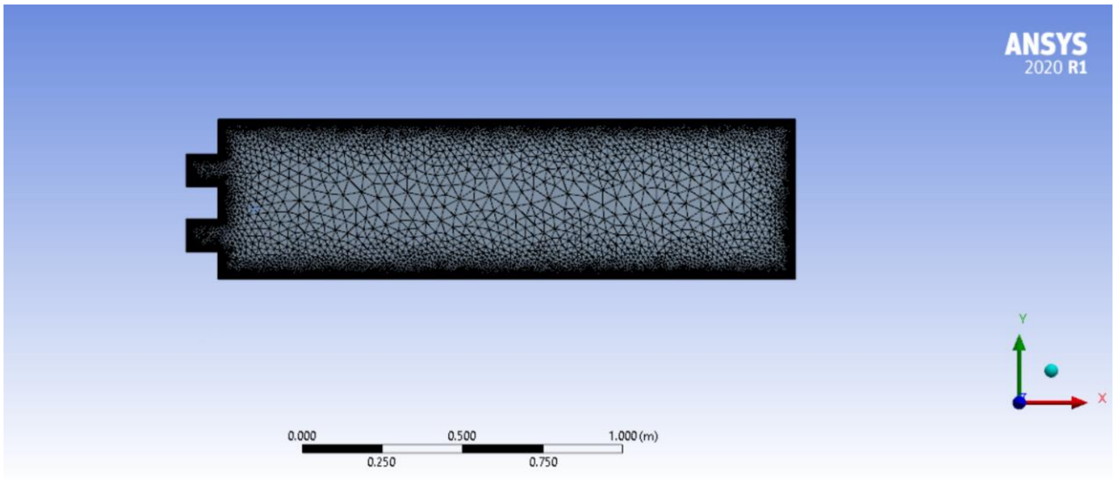


Fig 15: Mesh Generation

**3.7.3.D Modeling and Simulation:** The simulation may be run after specifying the issue and creating the mesh. Ansys Fluent solves the equations using iterative solution methods, allowing the user to watch the simulation's progress and judge the convergence of the result. The ST-Model is an excellent choice for analyzing chemical processes since it allows for complete examination. The eddy dissipation model, on the other hand, is useful for studying quick responses and turbulent flow phenomena. Ansys Fluent supports accurate and informative simulations by using these appropriate models, adapting to varied scenarios and addressing a wide variety of research objectives.

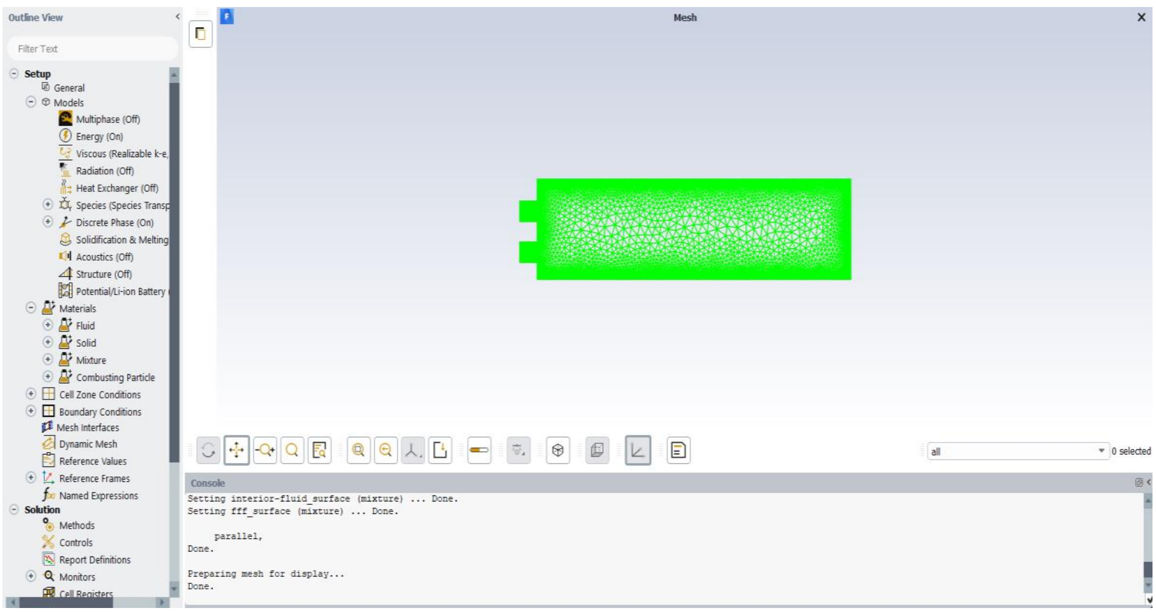


Fig 16: Simulation

**3.7.3.E Post-processing result:** Following simulation completion, the results are post-processed and visualized using the integrated capabilities in Ansys Fluent. This includes the creation of graphical representations such as contour plots, vector fields, and cross-sectional slices that exhibit the solution variables in depth. Animations may also be used to efficiently depict temporal fluctuations. These built-in post-processing tools allow researchers to examine and interpret simulation data, allowing them to extract useful insights and get a better knowledge of the phenomena under inquiry.

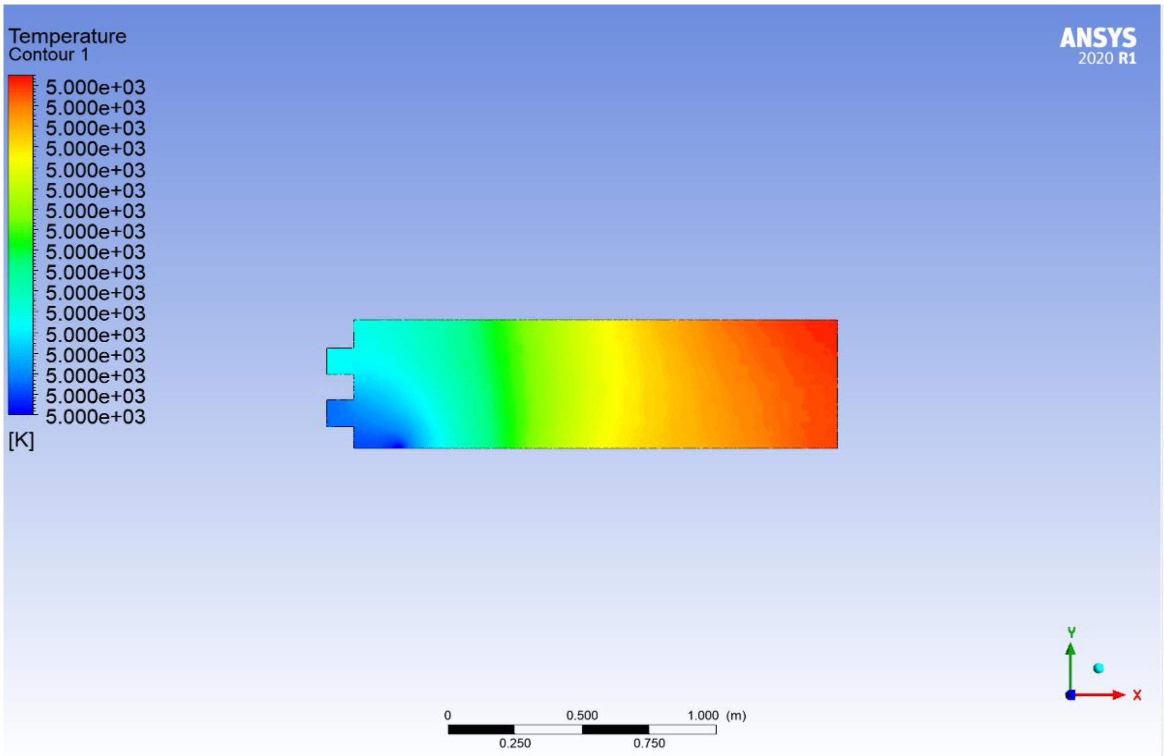


Fig 17: Post Processing Results

The following is a consolidated analytical step and boundary condition:

**Table 3: Consolidated Analytical Steps and Boundary Conditions**

| **Analysis Steps** | **Boundary Condition** |
|---|---|
| a) Import .cad file in Ansys Fluent | • Fuel: 50 m/s from the nozzle at a temperature of 350°C |
| b) Discretize the entire geometry into fine meshes | |
| c) Choose Energy and then the ON option | • Air: At a speed of 0.5 m/s and a temperature of 300 K, the species mass fraction is 0.76. |
| d) As the $k$-$\varepsilon$(2eqn) turbulence model, use the viscous model. | |
| e) Species transport is used to transport the species. | • Walls: Constant at 350°C |
| f) Material and feed boundary conditions must be chosen. | |
| g) Solve the temperature and exhaust output reaction. | |
| h) NOx is chosen once more in Models for Computing NOx | |
| i) Resolve it for exhaust. | |

# Chapter 4. Results

## 4.1. Microalgae-to-Biodiesel Conversion

This research provides a complete and formal investigation of the microalgae-to-biodiesel conversion process, with the goal of determining its efficiency and feasibility for long-term biofuel production. We concentrated on third-generation biodiesel synthesis using microalgae as a renewable feedstock. The growth and usage of selected species of microalgae with higher lipid production and other desired features for biodiesel production is referred to as third-generation microalgae synthesis. These microalgae strains are usually genetically engineered or carefully grown to have a greater oil content, quicker growth rates, better resistance to environmental conditions, and higher nutrient absorption efficiency. The goal of third-generation microalgae synthesis is to enhance biodiesel yield and efficiency while reducing environmental effect. This innovative method has enormous promise for producing sustainable and economically viable biodiesel, making it a promising option for the future of renewable energy. The investigation included crucial topics and produced significant discoveries that would help enhance biodiesel manufacturing technology.

First, the lipid content of the chosen microalgae strain was rigorously evaluated, as it has a direct influence on biodiesel output. The quantity of lipids, or fatty acids, found in these microscopic aquatic creatures is referred to as the lipid content of microalgae. Lipids play an important function in microalgae as an energy storage mechanism, just like fats do in vertebrates. Microalgae lipid content varies greatly depending on the species, growing circumstances, and cultivation methods used. Some microalgae species have a high lipid content that exceeds 50% of their dry weight. Because lipids may be turned into biodiesel by processes such as transesterification, these lipid-rich microalgae strains are particularly appealing for biodiesel production. Because of their increased energy density and potential for higher biodiesel yields, microalgae with higher lipid content are regarded promising feedstocks for biodiesel synthesis. Microalgae lipid content can be controlled by a variety of parameters such as nutrition availability, light intensity, temperature, and carbon dioxide concentration. Optimizing these growing conditions, as well as using genetic engineering or selective breeding techniques, can increase the lipid content of microalgae strains, resulting in higher oil yields and enhanced biodiesel production efficiency.

Accurate lipid content assessment is critical in microalgae research and industrial applications. To evaluate the lipid content of microalgae, methods such as gravimetric analysis, solvent extraction, and lipid staining techniques are routinely utilized. Furthermore, sophisticated analytical techniques such as gas chromatography and lipid profiling may offer extensive information on the exact fatty acid content of the lipids, allowing researchers to assess the quality and appropriateness of microalgae strains for biodiesel generation. Understanding and improving microalgae lipid content is critical for developing efficient and sustainable biodiesel production systems. Researchers and industry personnel may work toward exploiting the full potential of these minuscule organisms as a renewable energy source by choosing and producing microalgae strains with greater lipid content. The analysis verified a particularly high lipid content, indicating that microalgae has a promising future as a feedstock for biodiesel synthesis.

Following that, several extraction procedures, such as solvent extraction, supercritical fluid extraction, and in situ transesterification, were thoroughly compared. By removing the requirement for a separate extraction phase, in-situ transesterification streamlines the biodiesel synthesis process. This decreases the complexity of the process, energy consumption, and capital investment. For the extraction of lipids from microalgae biomass, solvent extraction and supercritical fluid extraction technologies require additional processes and equipment, resulting in greater operational costs and complexity. Another advantage of in-situ transesterification is the capacity to produce more biodiesel. This approach reduces lipid loss and possible degradation by directly converting lipids inside the microalgae biomass. Solvent and supercritical fluid extraction may leave some lipids in residual biomass or result in loss during the extraction process, resulting in decreased biodiesel yields.

In-situ transesterification is also more time efficient. Because there is no separate extraction phase, the procedure may be finished in less time than solvent and supercritical fluid extraction techniques, which require additional time for lipid extraction and separation. Furthermore, in-situ transesterification lowers the need for solvents or supercritical fluids, which are frequently connected with safety and environmental problems. Organic solvents are used in solvent extraction, which might pose health and safety issues and necessitate additional precautions for proper disposal. Because supercritical fluid extraction necessitates the use of costly and energy-intensive equipment, it is less cost-effective and ecologically friendly than in-situ transesterification. The results showed that the in-situ transesterification approach was more efficient, simplifying the process and successfully lowering overall expenses.

Furthermore, extensive optimization attempts were made to improve the transesterification reaction. Using experimental procedures and statistical approaches, variables such as reaction duration, temperature, and catalyst concentration were thoroughly investigated. The ideal conditions were identified using this rigorous technique, resulting in considerably higher conversion efficiency and excellent biodiesel quality.

The findings of this thorough investigation highlight the excellent prospects of microalgae-to-biodiesel conversion as a sustainable alternative to biofuel generation. The exceptional lipid content of microalgae, together with effective extraction procedures and optimum transesterification conditions, all contribute to this conversion process's practicality and viability. Furthermore, the biodiesel generated has been shown to be of high quality, making it an ecologically beneficial alternative to regular diesel fuel.

## 4.2. Combustion of Microalgae-Derived Biodiesel using Ansys Fluent

The combustion parameters of microalgae-derived biodiesel were examined in this work using Ansys Fluent, a popular computational fluid dynamics (CFD) program. The goal was to evaluate the emissions, combustion efficiency, and thermal characteristics of microalgae-derived biodiesel as a fuel alternative. The combustion simulations were performed to get insight into the fuel's behaviour during the combustion process.

The results demonstrated that biodiesel generated from microalgae had good combustion characteristics. The simulations revealed a consistent and efficient combustion process comparable to that of regular diesel fuel. Microalgae-derived biodiesel was shown to have acceptable combustion efficiency, meaning that it has the potential to be a viable and efficient fuel source.

Emission study using Ansys Fluent yielded encouraging findings. When compared to fossil diesel fuel, the microalgae-derived biodiesel had reduced amounts of particulate matter, carbon monoxide, and sulphur compounds. These findings point to the environmental benefits of utilizing microalgae-derived biodiesel, which helps to reduce air pollution and improve air quality.

Furthermore, Ansys Fluent thermal study confirmed the favourable combustion characteristics of microalgae-derived biodiesel. The fuel had a shorter ignition delay and combustion duration, resulting in more efficient energy conversion and enhanced engine performance. Because of these properties, microalgae-derived biodiesel is a viable sustainable energy source.

The combustion simulations performed with Ansys Fluent revealed important information on the behaviour of microalgae-derived biodiesel throughout the combustion process. It was feasible to assess the fuel's potential as a sustainable fuel alternative by correctly modelling and studying its combustion behaviour. When compared to fossil diesel, the combustion of microalgae-derived biodiesel yielded lower amounts of hazardous emissions. NOx emissions were greatly decreased, owing to the lower nitrogen content of the biodiesel fuel. Furthermore, because microalgae-derived biodiesel includes insignificant quantities of sulphur compounds, burning of biodiesel resulted in decreased levels of sulphur dioxide ($SO_2$) emissions.

Particulate matter (PM) emissions were also reduced during the burning of microalgae-derived biodiesel, according to the calculations. The biodiesel fuel performed better in terms of atomization and vaporization, resulting in a cleaner and more thorough combustion process. Reduced particulate matter emissions lead to enhanced air quality and fewer health hazards associated with particulate matter exposure. The combustion properties of biodiesel obtained from microalgae were found to be equivalent to or somewhat different from regular diesel fuel. The flame temperature, peak pressure, and heat release rates were all within acceptable limits, showing that the combustion process was stable and efficient. The simulations also demonstrated the need of tweaking the combustion parameters for microalgae-derived biodiesel in order to get the highest performance. Modifying fuel injection time, spray characteristics, and combustion chamber design can improve combustion efficiency and lower emissions even further.

Overall, the Ansys Fluent combustion simulation findings indicate the feasibility and practicality of microalgae-derived biodiesel as an ecologically benign and efficient fuel choice. The models showed steady combustion, decreased emissions, and favourable thermal characteristics, showing the promise of microalgae-derived biodiesel in lowering greenhouse gas emissions and reliance on fossil fuels. The findings of the ANSYS Fluent simulations show that microalgae-derived biodiesel has the potential to be a profitable and ecologically benign alternative to fossil fuel. It is a viable renewable fuel source for a variety of uses, including transportation and power production, because to its good combustion properties, low emissions, and similar performance. More experimental validation and optimization research is required to corroborate these findings and enhance the combustion process for higher efficiency and fewer emissions.

# Chapter 5. Conclusion

The conversion of microalgae to biodiesel is a very promising and feasible technology for producing sustainable and renewable energy. The process of extracting oil from microalgae and turning it into biodiesel offers a number of benefits that make it a viable alternative to traditional fossil fuels.

Microalgae contain a lot of oil, often more than 50% of their dry weight. Because of their high oil content and rapid growth rate, they may produce enormous volumes of oil in relatively short periods of cultivation. As a result, microalgae are a very efficient feedstock for biodiesel production, capable of providing significant amounts of energy.

Furthermore, because microalgae farming is adaptable to non-arable soil and non-potable water sources, it reduces competition with food crops and demand for freshwater resources. Microalgae may be produced in a range of settings, including open ponds, closed photobioreactors, and even wastewater treatment plants, allowing them to make use of land and water resources that would otherwise go unused or viewed as waste.

Furthermore, producing microalgae has environmental benefits. These bacteria have a remarkable ability to repair carbon dioxide ($CO_2$), which aids in the reduction of greenhouse gas emissions. Notably, microalgae absorb more $CO_2$ per unit of biomass than terrestrial plants, making them a useful asset in attempts to collect and sequester carbon. Microbes aid in the reduction of greenhouse gas emissions through methods such as carbon sequestration and methanotrophism. Photosynthesis allows microbes, particularly photosynthetic organisms like cyanobacteria and algae, to absorb carbon dioxide ($CO_2$). They convert atmospheric $CO_2$ into organic molecules and store carbon in their biomass. This process, known as carbon sequestration, helps to remove $CO_2$ from the atmosphere, therefore lowering the greenhouse effect.

Microbes also play an essential role in methanotrophic methane ($CH_4$) emissions reduction. Methane is a strong greenhouse gas with significantly more warming potential than $CO_2$. Methanotrophs are microorganisms that have the rare ability to generate energy from methane. They convert methane to carbon dioxide, reducing its greenhouse gas impacts.

Furthermore, in addition to biodiesel, microalgae have the potential to yield large co-products.. Other substances produced by the oil extraction process include proteins, carbohydrates, and pigments, which have uses in a variety of sectors such as animal feed, dietary supplements, and medicines. This multi-product method improves the economic feasibility of microalgae culture and contributes to the process's overall sustainability.

Nonetheless, overcoming some obstacles is required for widespread adoption of microalgae to biodiesel conversion. These difficulties include developing cost-effective growing systems, optimizing oil extraction processes, and increasing the efficiency of the conversion process. Furthermore, commercializing microalgae-based biodiesel on a big scale necessitates further research, development, and investment.

The conversion of microalgae to biodiesel is a highly promising path for producing sustainable energy. It provides a chance to minimize dependency on scarce fossil fuel supplies, alleviate climate change through effective carbon sequestration, and generate valuable by-products. Microalgae-based biodiesel has the potential [40] to play an important role in the future energy landscape, contributing to a more ecologically friendly and sustainable society via continued research and development.

# Chapter 6. Future Scopes

To secure future fuel supplies, biofuels have emerged as a critical option, accounting for approximately 66% of global energy consumption [46]. The world's increasing energy demands, coupled with concerns about climate change and the finite nature of fossil fuel resources, have driven the exploration of alternative fuel sources. Among the various biofuel systems, micro-algal biofuels stand out as a promising solution, capable of delivering clean and sustainable fuels while addressing concerns associated with first-generation biofuels and lignocellulosic processes based on wood feedstocks.

One of the notable advantages of microalgal biofuels is their potential to eliminate the contentious debate between food production and fuel production. First-generation biofuels, such as ethanol produced from corn or sugarcane, have faced criticism for diverting agricultural land and resources away from food production, potentially exacerbating food security issues. In contrast, microalgal biofuels offer a distinct advantage as they can be cultivated using non-arable land and do not compete directly with food crops. Furthermore, unlike traditional crop-based biofuels, microalgae cultivation does not need large areas of land, making it a more effective use of resources.

According to statistics, microalgal biodiesel has gotten a lot of interest because of its technological feasibility and potential to totally replace petroleum-derived liquid fuels[47]. Biodiesel derived from microalgae has qualities comparable to normal diesel fuel, allowing it to be used in current diesel engines without modification. This compatibility and potential for complete displacement of petroleum-based fuels make microalgal biodiesel an attractive option in the transition to a renewable energy future.

However, one of the key challenges that needs to be overcome is the improvement of the economics of microalgal biodiesel production. Currently, the cost of producing microalgal biodiesel is higher compared to conventional Petro diesel, which limits its commercial viability. In-depth economic feasibility studies have indicated that microalgal production systems possess considerable economic potential, not just for fuel production but also for the development of food supplements to cater to the needs of a rapidly increasing global population [48].

To make microalgal biodiesel more economically competitive, substantial improvements to algal biology through genetic and metabolic engineering are required. By manipulating the genetic makeup and metabolic pathways of microalgae, researchers can enhance their lipid content and overall productivity, thereby increasing the yield of biodiesel. Furthermore, advancements in photobioreactor engineering, which involve optimizing the design and operation of cultivation systems, can contribute to lowering production costs by increasing efficiency and scalability.

Microalgal production systems have the potential to produce other useful co-products in addition to biodiesel. Proteins, carbohydrates, and a variety of bioactive compounds found in microalgae can be used to make food supplements, animal feed, cosmetics, and pharmaceuticals. The overall economics of microalgal production can be enhanced by implementing the biorefinery concept, which entails extracting numerous high-value products from microalgae. Microalgal biofuel systems may be more economically viable if their revenue streams are diversified through the production of a variety of goods.

Considering these technological advancements and the economic potential of microalgal production systems, they are poised to offer significant benefits to communities in the near term. The maturation of a stand-alone microalgal biofuel industry is a foreseeable development over the next decade, with the potential to not only address the demand for renewable fuels but also contribute to food security and sustainable development goals.

Microalgal production systems have the potential to produce other useful co-products in addition to biodiesel. Proteins, carbohydrates, and a variety of bioactive compounds found in microalgae can be used to make food supplements, animal feed, cosmetics, and pharmaceuticals. Implementing the biorefinery idea, which comprises extracting several high-value products from microalgae, can improve the overall economics of microalgal production. Microalgal biofuel systems may be more economically feasible if their income streams are diversified by producing a wide range of commodities.

Furthermore, microalgae's promise goes beyond fuel and food. These adaptable microbes have been used in a variety of sectors, including wastewater treatment, carbon capture, and high-value chemical manufacturing. Statistics show, for example, that microalgae have been successfully used in wastewater treatment systems, where they absorb nutrients and contaminants, resulting in cost-effective and ecologically favorable solutions. [49]. Furthermore, microalgae can collect and consume carbon dioxide (CO2) during photosynthesis, making them excellent candidates for reducing greenhouse gas emissions from industrial sources [50].

The transition to a sustainable and renewable energy future requires not only technological advancements but also the support of policymakers, investors, and the wider community. Governments around the world have recognized the importance of biofuels as a key component of their energy strategies and have implemented policies to incentivize their production and use. For instance, a recent study reported that over 100 countries have implemented renewable fuel mandates or targets to promote the use of biofuels [51]. Financial investments and research initiatives focused on improving the economics and efficiency of microalgal biofuel production have further accelerated the development of this industry.

To sum up, microalgal biofuels have enormous potential to secure future fuel supplies and solve problems caused by traditional fossil fuels. Microalgae differ from other biofuel systems in that they can generate sustainable and clean fuels while reducing issues with deforestation and food production. Improvements in algal biology, genetic and metabolic engineering, the use of biorefinery principles, and photobioreactor engineering are all required to increase the economic viability of microalgal biodiesel production.

By utilizing these developments, the microalgal biofuel industry can mature and provide not only renewable fuels but also support the development of a wide range of high-value products as well as food security and environmental sustainability. Microalgal biofuels have been made possible by the ongoing assistance and cooperation of researchers, decision-makers, and industry participants.

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