USING ALGAE TO CAPTURE CO_2 AND AS A FEEDSTOCK FOR BIOFUEL

by

Brad Archbold

A Thesis: Essay of Distinction
Submitted in partial fulfillment
of the requirements for the degree
Master of Environmental Studies
The Evergreen State College

June 2007

This Thesis for the Master of Environmental Studies Degree

by

Brad Archbold

has been approved for

The Evergreen State College

by

____

Paul Butler, PhD
Member of the Faculty

____

Date

ABSTRACT

Using Algae to Capture CO_2 and as a Feedstock for Biodiesel Fuel

Brad Archbold

World economies require a continuous, inexpensive source of hydrocarbons to power their transportation systems. The fuel of choice is oil, a fuel of finite supply. As the demand for oil increases and/or supply disruptions occur, the acute rise in prices will have extremely detrimental effects on oil-dependent economies. Another negative effect of relying on oil as a fuel source is the release of CO_2 during combustion. CO_2 is a major greenhouse gas and its effect on global climate is of worldwide concern.

There is a need for a new fuel source not based on hydrocarbons, which can be utilized with fewer deleterious effects to the environment. Some feel that the leading candidate for the new fuel economy is the hydrogen fuel cell. The problem is that there is a long lead-time before such a new fuel technology can be implemented.

Until then, a stopgap measure needs to be put in place to fuel the economy without adding large amounts of CO_2 into the atmosphere. One of the most promising options is biofuel. The problem with biofuels is that most are based on oils produced from agricultural crops. Wide-scale use of such fuels may cause further environmental degradation as marginal lands are brought into production to meet demand. In addition, there is concern that increased reliance on these commodities may cause food shortages as food prices rise along with crop prices.

Algae can be used as a source of biodiesel. Algae growth can be fed with CO_2 from power generation plants and then harvested as a source of oil. The algal-biodiesel can be utilized to power world economies until an alternative to hydrocarbons as a source of fuel can be implemented. This truly renewable source of fuel can be raised on non-arable land with wastewater providing the nutrients. This fuel would allow people to use existing transportation technology while reducing their overall carbon footprint.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

I would like to thank Paul Butler, member of The Evergreen State College faculty, for his extensive aid in finishing this thesis. The end product is much clearer because of his help. I would also like to thank members of the U.S. Office of Surface Mining and the Southwest Clean Air Agency for readily sharing information that would have taken a great deal of time to gather myself.

I want to thank my wife, Leigh, for her extensive support during the writing of this thesis. She was repeatedly required to hang out by herself and to pick up my slack in maintaining our home and our life while I was locked away in the study. I would also like to thank my mother for her support through my entire time through the MES program.

INTRODUCTION

The United States is in a position where it will soon need to reduce its reliance on fossil fuels, for both economic and environmental reasons. Fossil fuels are a non-renewable resource, and finite. Alternative fuels need to be developed to protect the U.S. economy from faltering when fossil fuel supplies run low and/or their use becomes environmentally unacceptable.

Besides being of limited supply, fossil fuels release carbon dioxide (CO_2) when burned. The release of CO_2 into the atmosphere as a result of burning fossil fuels is believed to be a major cause of global climate change. Some fear that if industrialized and industrializing countries continue to release large amounts of CO_2 and other greenhouse gases, the atmosphere may be irreversibly changed for the worse. There are many theories on what climate change may entail, but any markets opened up by the new climate conditions will not likely replace the markets disrupted as changes occur.

It is better to follow the precautionary principle and try to change the factors that are the likely cause of global climate change. A first step towards making the needed changes is to find new ways of producing energy, while recycling CO_2. This step is mandatory to slow the release of this greenhouse gas until a new non-hydrocarbon-based fuel economy, such as hydrogen fuels, can be brought on line.

Extensive use of petroleum fuels by the U.S. transportation sector requires the import of large quantities of oil to meet those needs. The utilization of biomass for the production of a transportation biofuel also meets the CO_2 recycling requirement because plants naturally fix CO_2 through the photosynthetic process (Miyamoto, 1997). Biomass can also be produced in the U.S., thus providing a more secure source of fuel.

Many believe that the production of oil in the world has reached its peak and new sources will be harder to find and more expensive to recover (Roberts, 2004). Many sources of oil are in politically unstable regions and require large military expenditures in foreign countries to protect the resource. The countries of the Middle East produce large quantities of the world's oil supply, and recent U.S. policy decisions and actions in that part of the world may cause an increase in instability of future oil supplies.

This thesis investigates the growth of algae as a biomass fuel source by utilizing carbon dioxide from the flue gases of coal-burning power plants and waste streams of other nutrients such as nitrogen. Oils obtained from the algal biomass can then be processed into biodiesel.

The biodiesel produced would then be utilized in the transportation sector to replace the use of petroleum-based diesel. While still emitting CO_2, the use of biodiesel produced from algae releases CO_2 that would have already been released during power production, thus meeting the requirement of recycling CO_2 and reducing overall emissions.

The algae are able to utilize the CO_2 from the flue gases, nitrogen (N) and phosphorous (P) from wastewaters, and energy from sunlight in the photosynthetic process to create carbohydrates. The stored energy in the carbohydrates is utilized to run cell processes that sequester carbon into tissues in the form of proteins and lipids. The lipids are then processed into oils that replace the animal and plant oils that are traditional feedstocks for the biodiesel production process. These feedstocks are refined to produce biofuels. In the U.S., the main biodiesel feedstock sources are soy oils, animal fats from rendering plants, other plant sources, and used cooking oils (Ginder, 2004).

The use of algae to sequester CO_2 and produce biofuel is still relatively new. The processes were originally investigated in the 1980s in the National Renewable Energy Laboratory's Aquatic Species Program (Sheehan et al., 1998a). Successive projects have worked to establish that algae can successfully sequester CO_2 in both open pond and enclosed bioreactor systems. Now, some researchers are working to develop production methods that are economically feasible on a large scale (Kremer, 2006).

This paper also will investigate the feasibility of using photobioreactor technologies to sequester CO_2 from the coal-fueled power plant in Centralia, WA, owned by the Transalta Corporation. The plant has two 702.5 megawatt production facilities that release over 10,000,000 tons[1] of CO_2 per year (Southwest Clean Air Agency, 2005b). To be feasible, an algal sequestration process would need to be economically practicable, fit within the confines of the property available, meet environmental permitting requirements, and have a market for the end product.

CO_2 AND GLOBAL WARMING

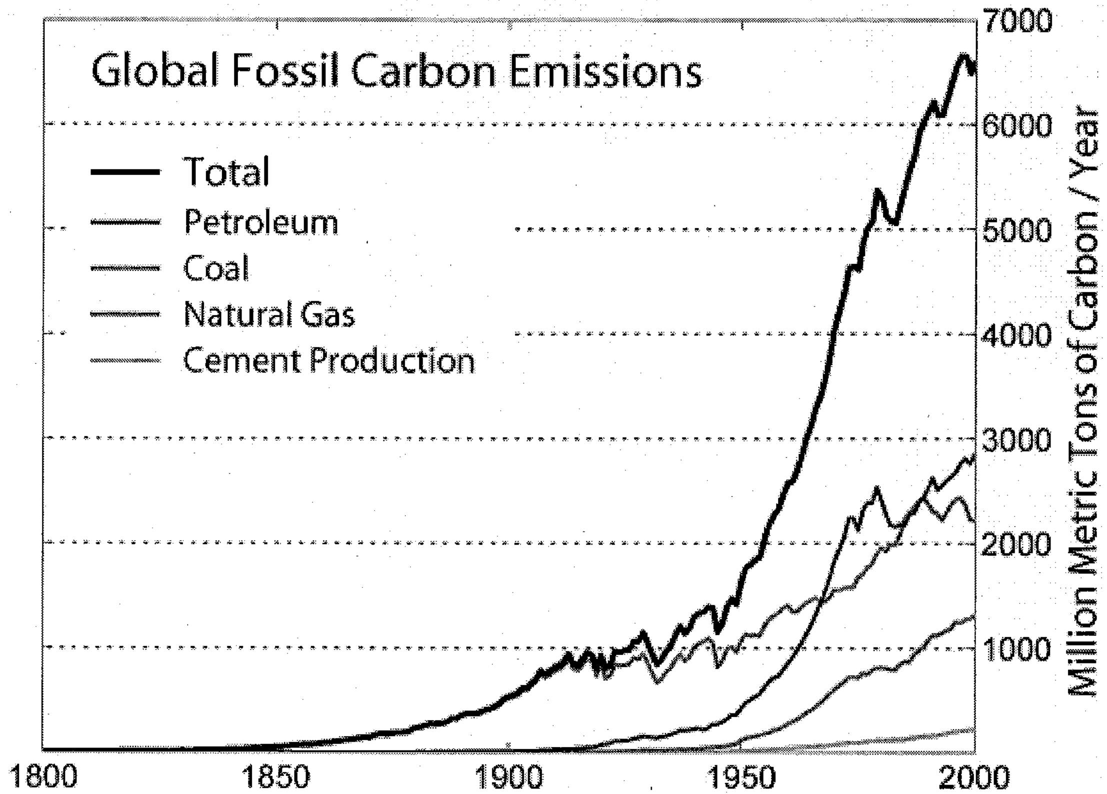
The climate changes associated with the emission of greenhouse gases are beginning to be felt around the world and the theories surrounding the causes, though still repudiated by some, are becoming generally accepted throughout the scientific and political communities.

The main cause of climate change is the release of carbon dioxide from the consumption of non-renewable resources such as fossil fuels. The role of CO_2 in global

[1] I have tried to use metric measurements whenever practicable. For clarity, the use of English units was occasionally deemed more appropriate.

climate change was identified as early as 1979 by the National Academy of Sciences, and a positive correlation between CO_2 in the atmosphere and fossil fuel use has been demonstrated (Speth, 2004; Stepan et al., 2002). These anthropogenic CO_2 emissions have increased sharply in the past 50 years as shown in Figure 1.

Figure 1. – Global CO_2 emissions from fossil fuels and cement production.



Source: Marland, et al, 2003

The most dire temperature-change predictions associated with global warming are that average temperatures will rise between 2.5 to 10.5 degrees Fahrenheit by the end of this century (Speth, 2004). An increase of such magnitude will cause a significant rise in sea level and alter weather patterns, likely resulting in disastrous environmental and societal effects (Speth, 2004).

The rise in both the recorded occurrences of climatic anomalies and an increase in the number of warnings from the international scientific community have brought an increasing awareness of the significance of climate change. Many are calling for reductions of greenhouse gas emissions from industrialized countries. Currently CO_2 levels are approximately 370 ppm, and it is hoped that such reductions would keep atmospheric CO_2 levels from ever reaching 450 ppm. It is believed that beyond this level "dangerous" effects would occur to the planet's ability to support human life, including disastrous increases in sea level and disruption of major ocean currents. Without drastic decreases in current emissions, the 450 ppm-level is projected to be reached by 2030 (Speth, 2004).

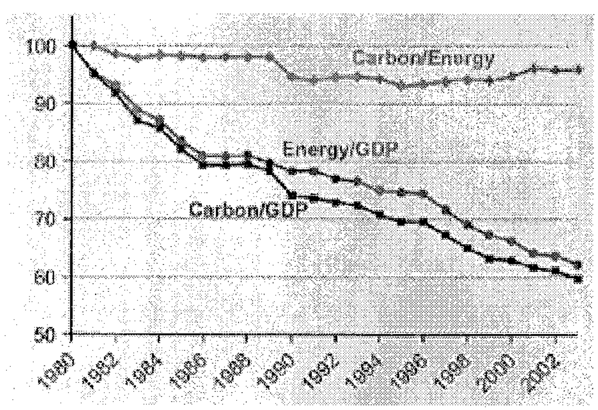
U.S. CO_2 EMISSIONS

The United States is one of the largest emitters of greenhouse gases in the world, averaging around 23 percent of the world's overall output. The country's overall emission rate is growing each year. For example, emissions in 2005 were 17 percent higher than in 1990, despite worldwide calls (e.g. the Kyoto Protocol) for the reduction of emissions by industrialized countries (Energy Information Administration, 2006a).

The yearly increase in rate has continued to decrease with time, but at this time the total amount is still increasing. The yearly increase for 2004 was 0.3 percent compared to the average yearly increase from 1990 to 2004 of 1.2 percent (Energy Information Administration, 2006a). To stem global warming, all industrialized countries need to reduce emissions below their 1990 rates. As the greatest producer of greenhouse gases, the U.S. should take a leading role in reducing emissions.

U.S. increases in energy use, primarily for electricity and transportation, are steadily rising despite the expansion in overall carbon intensity (Energy Information Administration, 2006a). Carbon intensity, the amount of carbon emitted per unit of energy utilized for various uses, is fairly steady or in actual decline through adoption of technologies that are increasingly energy efficient. Figure 2 displays the U.S. carbon intensity over time in the green Carbon/Energy segment. The graph shows that the rate of carbon consumed has dropped by approximately five percent since 1980. This gain is offset by the fact that as people continue to purchase larger homes and fill those homes with an increasing number of electronic goods, the rate of efficiency increase cannot keep up with the increase in demand.

Figure 2. – Intensity ratio of U.S. carbon usage 1980-2005 (1980 = 100%)



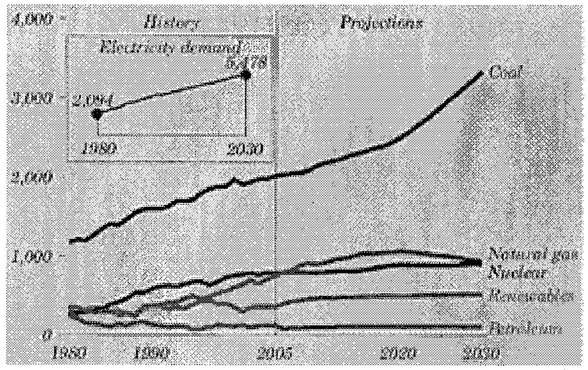
Source: Energy Information Administration, 2006a

The majority of overall U.S. greenhouse gas emissions are in the form of CO_2, making up 84 percent of the total. The largest emitting sectors are the two largest energy sectors, transportation and electricity production. In 2005, 83 percent of U.S. emissions were CO_2 from combustion of coal, petroleum, and natural gas (Energy Information Administration, 2006a). During this year, the actual amount for the transportation sector was 33 percent and the amount for coal-produced electricity was 36 percent (Energy Information Administration, 2006a).

It is projected that natural gas, oil, and coal will grow to 86 percent of the overall energy market, and that this share will stay steady through the year 2030 (Energy Information Administration, 2006b). The increase in the size of this market suggests that CO_2 emissions will continue to expand as the energy market expands, unless steps are taken to reduce emissions. Reduction can come from switching to more carbon-intense fuels, fuels that give more energy per unit of CO_2 emission, cleaning flue or tailpipe emissions, or capturing and sequestering CO_2 as it is released.

The use of fossil fuels for electricity generation is likely to increase as generation from nuclear and other non-fossil fuels are projected to decline, as exhibited in Figure 3 (Energy Information Administration, 2006b; Environmental Protection Agency /Department of Energy, 2000). The major increase in fossil fuel usage for electricity generation will come from coal. All other forms of electric generation from fossil fuels are expected to remain relatively constant, with a slight decrease in the use of natural gas. A significant number of new coal plants are expected to come on line by 2030. By that time, the overall generation level will increase from the current 22.9 quads (quadrillion British thermal units) to 34 quads (Energy Information Administration, 2006b).

Figure 3. - Projected use of fuels for electricity production to 2030 (billion kilowatt hours).



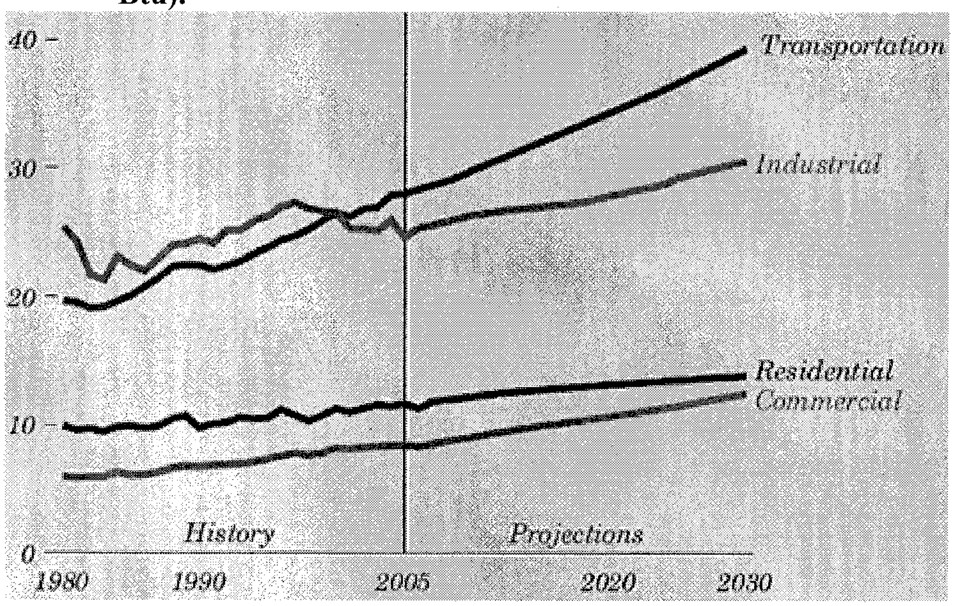
Source: Energy Information Administration, 2006b

The reason for the major increase in coal use is simple; the U.S. has 25 percent of the known coal supply in the world (Sheehan et al., 1998a). Coal is a readily available and relatively cheap source of hydrocarbons for energy production and is likely to remain inexpensive. The price of coal in 2030, adjusted for inflation, is expected to be similar to today's prices (Energy Information Administration, 2006b).

The reliance on coal for an increasing amount of U.S. electricity generation will have negative effects on the environment. Coal has the highest carbon intensity of all the fossil fuels (Energy Information Administration, 2006b). In fact, coal-fired power plants release 80 percent of the CO_2 released during energy production, while only producing 51 percent of the overall electricity output (Environmental Protection Agency/Department of Energy, 2000). In 1999, coal plants produced an average of 1 kilogram of CO_2 per kWh, while the average for all fuels used for energy production was 0.6 kilogram per kWh (Environmental Protection Agency/Department of Energy, 2000). Increased use of coal will drastically raise overall CO_2 output. A decrease in CO_2 released per unit of energy is not likely to occur because CO_2 remediation is prohibitively expensive and CO_2 is not currently regulated under Clean Air Act (Southwest Clean Air Agency, 2007).

While electricity from coal production is expected to increase, this increase will be somewhat tempered by conservation as technology makes electrical devices more energy efficient. On the other hand, consumption of fossil fuels for transportation is expected to rise sharply in contrast to other sectors as shown in Figure 4 (Energy Information Administration, 2006b). The increased use of fossil fuels for transportation means that there will be an increasing market for biofuels.

Figure 4. – Delivered energy consumption by sector, 1980-2030 (quadrillion Btu).



Source: Energy Information Administration, 2006b

CO_2 REDUCTION AND SEQUESTRATION

CO_2 reduction and sequestration schemes need to be implemented immediately if we are to combat the expected global warming that may make life on the planet difficult. The options for reducing CO_2 emissions include: an increase in energy efficiency, a switch to less carbon-intense fuels, a reduction in deforestation, promotion of renewable energy, increased use of nuclear power, and a switch to a non-carbon-based fuel economy (van Harmelen and Oonk, 2006).

For carbon sequestration, there are several options. One option is to capture CO_2 from electricity-production facilities and sequester this CO_2 in oil and gas fields, aquifers, or the ocean. The current cost to sequester a ton of CO_2 is approximately $100 to $300 per ton of emissions avoided (Department of Energy, 2007). The U.S. Department of Energy (DOE) is conducting a research program aimed at finding technologies that will allow CO_2 sequestration at a cost of $10/ton by 2015 (Department of Energy, 2007). Utilization of these techniques is expected to add approximately 10 percent to the cost of electricity (Department of Energy, 2006).

Another option for direct sequestration is biological fixation of CO_2 by plants. Plants utilize CO_2 during photosynthesis and large amounts of that CO_2 are sequestered in plant tissue. The overall rate of sequestration by plants can be enhanced through reforestation, as plants utilize CO_2 directly from the atmosphere. The amount of CO_2 in the atmosphere is approximately 0.036 percent, which means that large areas of land need to be reforested to grow enough plants to sequester a significant amount of CO_2 from low atmospheric levels (Stepan et al., 2002).

A more efficient process of biological fixation is exhibited by algae and cyanobacteria. These aquatic microorganisms can sequester significantly higher rates of CO_2 through direct diffusion from the aqueous solution where they grow. Aqueous solutions can contain much higher rates of CO_2 than the atmosphere (van Harmelen and Oonk, 2006).

Algae biofixation systems have been tested on coal flue gases that were up to 12-13 percent CO_2 (Riesing, no date; Stepan et al., 2002). This percentage of CO_2 can easily be absorbed into the aqueous medium used to grow algae in the biofixation systems. The algae can exhibit growth rates up to 30 times greater than terrestrial plants when such high rates of CO_2 are in the surrounding solution (Sheehan et al., 1998a).

The biofixation systems are comprised of an aqueous solution containing algae that are circulated through an area while CO_2 and nutrients are added. The algae in the system use the CO_2, nutrients, and solar energy in the photosynthesis process. The carbon is sequestered in the algae while oxygen is released. A percentage of the algae is harvested and processed into oils that are used to produce biofuel.

Some strains of algae store the end products of photosynthesis at a higher ratio of lipid content to protein than other strains. The rate of lipid production by algae can also be increased by manipulating the levels of nutrients in the growth medium (Kremer et al, 2006). The lipids are then processed into biodiesel, which can be used to replace petroleum-based diesel. This process has been studied for several decades in both the public and private sectors and will be discussed in depth later in this paper. Prior to that, a history of diesel use and an overview of traditional forms of biodiesel are provided.

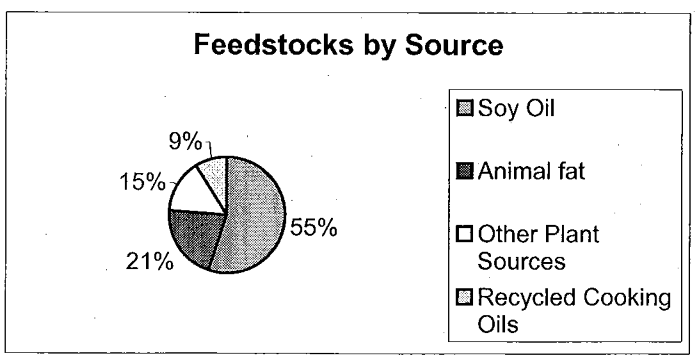
DIESEL USE AND REPLACEMENT

The net U.S. oil imports for transportation needs are projected to increase to 32 percent of total consumption by 2030 from the current rate of 30 percent (Energy Information Administration, 2006b). The amount spent per year on importing petroleum is in between \$110-\$150 billon and accounts for approximately 2/3 of the petroleum used annually in the U.S. (Briggs, 2004). This number is for the cost of the products only and does not include the large expenditures for military bases in foreign countries that protect the flow (Briggs, 2004).

Petroleum fuels (gasoline and diesel) comprise 97 percent of the transportation fuels. Twenty-four percent of the fuel used in the U.S. is diesel, which means an annual import rate of 64 billion barrels (Sazdanoff, 2006). Further steps need to be taken above and beyond the current programs of incentives for producers of alternative fuels, as these fuels are now only projected to replace seven percent of the overall transportation fuels consumed in 2030 (Energy Information Administration, 2006b).

This projection was made based on traditional feedstocks for biofuel production, and includes agricultural products, wood and animal waste. The percentage comprised by each feedstock is shown in Figure 5. New sources for feedstocks, such as algae, need to be investigated and utilized in order to increase the percentage of transportation fuels not manufactured from fossil fuels.

Figure 5. Traditional biodiesel feedstocks.



Source: Ginder, 2004

The biofuel that can be used to replace petrodiesel is biodiesel. Traditional biodiesel is produced from the mono-alkyl esters of fatty acids that are derived from vegetable oils, animal fats, or recycled cooking oil or grease. The oils and fat are commonly referred to as the feedstock for the refining process that produces the fuel.

To produce biodiesel, the feedstock is reacted with an alcohol, most commonly methanol, to produce a compound that is known as fatty acid alkyl ester. The most commonly used catalyst for this reaction is potassium hydroxide and the by-products are a low-quality glycerol, feed quality fat, potassium salts, and methanol. The methanol can be recycled back into the system (Schumaker et al., 2003; Tyson, 2004; Tyson et al., 2004; Van Gerpen, 2004).

The approximate proportions for the conversion process are:

45 kilograms of oil + 4.5 kilograms of methanol = 45 kilograms of biodiesel + 4.5 kilograms of glycerol

or by percentage:

87% oil + 12 % alcohol + 1% catalyst = 86% biodiesel + 9% glycerin + 4% alcohol + 1% fertilizer

A breakdown of the transesterification reaction in the production of biodiesel is the reaction of a triglyceride molecule with an excess of alcohol in the presence of a catalyst to produce glycerin and the mixture of fatty acids known as biodiesel (Figure 6; Tyson et al., 2004; Van Gerpen, 2004).