# Czech University of Life Sciences Prague

## Faculty of Engineering

# Energy and Environment: *Case Study on Biomass Sources of Energy*

**Diploma Thesis**

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**Declaration**

I declare that I have elaborated my diploma thesis aimed at "Energy and Environment: *Case Study on Biomass Sources of Energy*" independently and that I have used only the sources quoted in the "References".

In Prague, 28 April 2009 Signature: …………………..………..

Tarekegn Kebede GODOBE

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## Abstract

The main questions of the study are whether the utilization of biomass sources of energy has impacts (positive or negative) on our environment and whether these sources of energy can give answer to current international concerns in regard to global warming, climate change, and air and water pollution due to emissions from the production, processing and utilization of biomass energy. In order to evaluate the cases and to answer those questions, assessment of the Life Cycle of biodiesel was carried out in this thesis. And the results of the assessment were compared with that of petroleum source of energy, petroleum diesel.

The results of the assessment have shown that, for petroleum diesel, $CO^2$ emitted from the tailpipe represents 86.54% of the total $CO^2$ emitted across the entire life cycle of the fuel while most remaining $CO^2$ comes from emissions at the oil refinery, which contribute 9.6% of the total $CO^2$ emissions. For biodiesel, 84.43% of the $CO^2$ emissions occur at the tailpipe. At the tailpipe, biodiesel emits 4.7% more $CO^2$ than petroleum diesel. Biodiesel generates 573.96 g/bhp-h $CO^2$ compared to 548.02 g/bhp-h $CO^2$ for petroleum diesel. The overall life cycle emissions of $CO^2$ from B100 are 78.45% lower than those of petroleum diesel. The reduction is a direct result of carbon recycling in soybean plants. B20 reduces net $CO^2$ emissions by 15.66%. B100 increases total hydrocarbon, THC, emissions by 36%. Thus, increases in HCs for B20 are around 7%. The THC includes $CH_4$. Carbon monoxide, CO, emissions for petroleum diesel, B20, and B100 show dramatic differences in life cycle emissions. B100 has lower emissions of CO on a life cycle basis. TPM drop 32.41% for B100 compared to petroleum diesel. B100 reduces SOx emissions compared to petroleum diesel. Biodiesel increases NOx emissions in diesel engines unless adjustments are made to the engine, such as retarding of engine timing. Therefore, from these points, it is clear that biomass sources of energy are much more benign in view of ecological and impact on human health due to emissions.

*Keywords:* Energy; Biomass Energy; Biodiesel; Petroleum diesel; Global warming; Pollution; Biomass energy analysis; Life cycle analysis (LCA); Soybean.

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# 1. INTRODUCTION

Since recent decades, the energy needs of the globe are rising swiftly. The decreasing in fossil fuels supply, growing of emission pollutions caused by them and the current mounting fuel prices give biomass energy sources more attention. Accordingly, biomass energy has attracted steadily increasing attention as a promising renewable energy [1].

As studies indicated, the potential environmental benefits from biomass energy utilization are numerous. It can dramatically decrease in the amount of carbon dioxide released from fossil fuel consumption, can mitigate sulfur and nitrogen oxide emission, and can be used to cope with global warming due to GHG emissions from fossil fuels. Additionally, biomass sources of energy can minimize the total particulate matter emitted to the environment [2]. Currently, such benefits have increased in energy demand of biomass sources and decrease in oil reserves and have focused attention on biofuels exploitation [3].

This biodiesel source of energy is one of the renewable and clean alternative fuels for vehicles. It can be derived from plant's fruit, seed (soybeans), latex, animal fats, wasted oil, frying oil, etc [3] by transesterification with methanol or ethanol. Results from many studies have shown that compared with petroleum diesel, biodiesel has better degradation characteristic and lower hydrocarbon (HC), carbon monoxide (CO), particulate matter (PM), sulfur oxides ($SO_x$) emissions, and $CO_2$ emissions, but higher nitrogen oxides ($NO_x$) emissions [4]. However, these sources of energy may also have some negative effects on the environment. Thus, this case study serves to answer some of the questions most often raised in regards to biomass sources of energy utilization: what are the net $CO_2$ emissions? What is the energy utilization of the integrated system? Which substances are emitted at the highest rates? What parts of the system (production, processing, and utilization) are responsible for these emissions? How far these alternatives are more important over petroleum sources of fuel, diesel fuel?

To provide answers to these questions and more to mitigate an impact, it is more helpful to assess the whole life cycle of the system through the implementation of Life Cycle Assessment tools. Life cycle assessment (LCA) is a method to define and reduce the environmental burdens from a product, process or activity by identifying and quantifying energy and materials usage and waste discharges, assessing the impacts of the wastes on the environment and evaluating opportunities for environmental improvements over the whole life cycle [5]. LCA has become an important decision-making tool for promoting alternative fuels because it is very important to study the fuel life cycle systematically in terms of energy efficiencies and environmental impacts before implementing a fuel policy. Many LCA studies have been carried out on alternative fuels such as biodiesel, methanol, ethanol, and fuel cell, etc. [6]. A few life cycle inventory data, especially on biodiesel, have been compiled by different countries. Almost all of the earlier biodiesel studies were focused on the power, fuel economy and exhaust emissions performance of biodiesel fueled engines. The main objective of this case study is to carry out an assessment based on the previously compiled inventory data in regards to environment impact indicators of soybean sources of biodiesel and to compare this biodiesel with petroleum diesel and, eventually, to understand the advantages and disadvantages in biodiesel implementation in city bus.

# 2. BACKGROUND

## 2.1. Energy and Civilization

Energy plays a fundamental role in shaping the human condition. People's need for energy is essential for survival, so it is not surprising that energy production and consumption are some of the most important activities of human life. In fact, it has been argued that energy is the key to the advance of civilization, that the evolution of human societies is dependent on the conversion of various forms energy for human use. [7].

## 2.2. Sources of Energy

All forms of energy are stored in different ways, in the energy sources that we use every day. These sources are categorized into two main groups. These are renewable - an energy source that can be replenished in a short period of time and nonrenewable - an energy source that we are using up and cannot recreate in a short period of time. Both forms of energy sources can be used to produce secondary energy sources including electricity and hydrogen. These different forms of energy have been harnessed for different purposes that are beneficiary human life advancement. [8]

Renewable energy is an energy generated from natural resources - such as sunlight, wind, biomass, hydropower and ocean/tidal energy from water, and geothermal heat - which are renewable. Renewable energy sources produce electricity, thermal energy (steam or heat) or transportation fuels without depleting resources; they are replenished through natural processes or through sustainable management practices. [8]

However, we get most of our energy from nonrenewable energy sources, which include the fossil fuels -- oil, natural gas, and coal. They're called fossil fuels because they were formed over millions and millions of years by the action of heat from the Earth's core and pressure from rock and soil on the remains (or "fossils") of dead plants and animals. Another nonrenewable energy source is the element uranium, whose atoms we split (through a process called nuclear fission) to create heat and ultimately electricity.

## 2.3. Biomass Energy Development

Before the start of the industrial revolution, biomass energy was the world's dominant and the oldest energy source having been used for thousands of years, ever since people began to burn wood to cook food, to space heating, and cooking keep warm and for other functions. It is still important, accounting for ~7% of world primary energy consumption in 2000 [9], or about one-third of the energy from sources other than fossil fuels [10]

Today, biomass energy resources are not only used for cooking and heating but also to fuel vehicles (ethanol and biodiesel), currently comprise only 2% of world biomass energy [11], and increasingly to generate electricity and heat for industrial processes [8], particularly in the forestry and paper industries [12]. In developing countries, still biomass energy is the backbone for the sources of energy for cooking and warming purpose.

In spite of the fact that fossil fuels have largely replaced biomass as the major sources of energy in industrialized countries as well as in some of developing countries and its development progress has been declining since industrial revolution, still biomass energy is among the most promising, hyped and subsidized renewable energy sources [13]. They have real potential to heighten energy security in nations without abundant fossil fuel reserves, to increase supplies of liquid transportation fuels and to decrease net emissions of carbon into the atmosphere per unit of energy delivered. [14]

Recently, many external forces have influenced the development of biomass energy systems and many opportunities for expansion of biomass energy are developing due to rapid increasing of world energy demand along with alarming global population growth, environmental problems such as global warming, and economic case like soaring of fossil fuel price and the concerns have been encouraging governments, industries and consumers to explore alternatives to fossil fuels, including renewable sources such as biomass. [15]

### 2.3.1. Increasing World Energy Demand

#### 2.3.1.1. History: consumption and production

It is clear that over the millennia, humankind has moved from such dependence on renewable resources ; biomass, geothermal, solar energy, and wind energy, to the present depletable resources, that is, typically fossil fuels. [16]. There has been an enormous growth in total fossil fuel consumption worldwide since 1965 when we compare with the insignificant value of renewable energy, particularly bioenergy (Figure 2.1) [17]. Meanwhile, the world's total output or production has been steeping up year by year, Figure 2.2. In last ten years, the world's total output of primary energy - petroleum, natural gas, coal, and electric power (hydro, nuclear, geothermal, solar, wind, and wood and waste) - increased at an average annual rate of 2.3 percent and "World production increased from 373 quadrillion Btu in 1996 to 469 quadrillion Btu in 2006" [18]

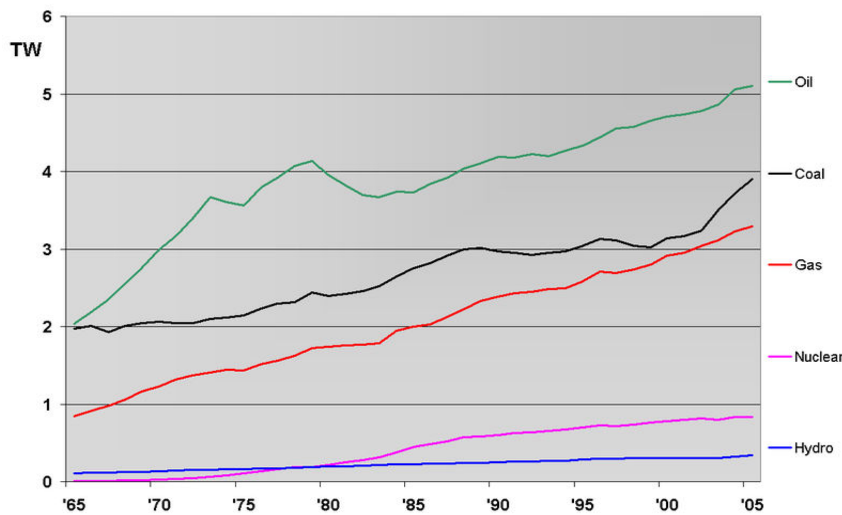


Figure 2.1: Rate of world energy consumption in terawatts (TW), 1965-2005
Source: [19]

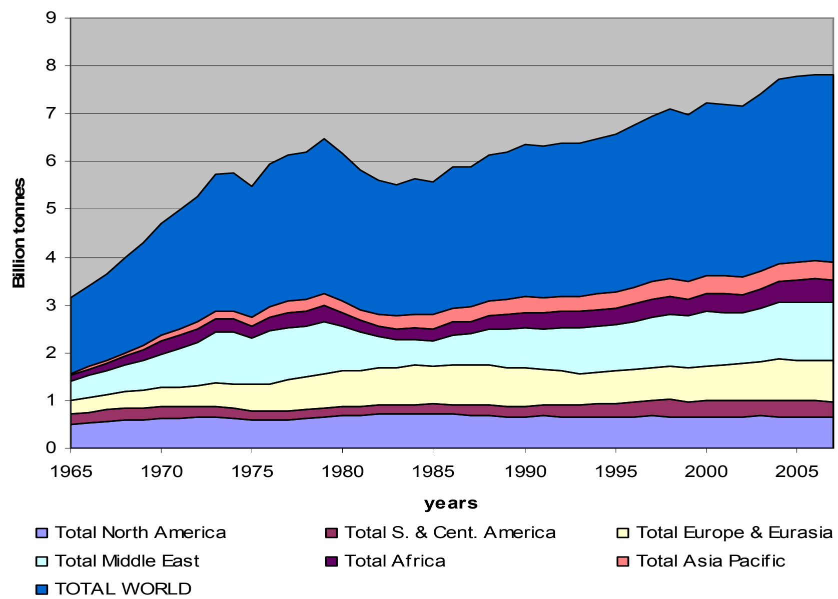


Figure 2.2: World Primary Energy Production Trends, 1965 – 2007

Sources: [19]

#### 2.3.1.2. Projection: Consumption

According to Energy Information Administration, EIA, World energy consumption is projected to expand by 50 percent from 2005 to 2030 in the IEO2008 reference case projection (Figure 2.3 and 2.4). Although high prices for oil and natural gas, which are expected to continue throughout the period, are likely to slow the growth of energy demand in the long term, world energy consumption is projected to continue increasing strongly as a result of robust economic growth and expanding populations in the world's developing countries. OECD member countries are, for the most part, more advanced energy consumers. Energy demand in the OECD economies is expected to grow slowly over the projection period, at an average annual rate of 0.7 percent, whereas energy consumption in the emerging economies of non-OECD countries is expected to expand by an average of 2.5 percent per year. [20]

The use of all energy sources increases over the time frame of the IEO2008 reference case (Figure 2.3). Given expectations that world oil prices will remain relatively high throughout the projection, liquid fuels are the world's slowest growing source of energy; liquids consumption increases at an average annual rate of 1.2 percent from 2005 to 2030. Renewable energy and coal are the fastest growing energy sources, with consumption increasing by 2.1 percent and 2.0 percent, respectively. Projected high prices for oil and natural gas, as well as rising concern about the environmental impacts of fossil fuel use, improve prospects for renewable energy sources. Coal's costs are comparatively low relative to the costs of liquids and natural gas, and abundant resources in large energy-consuming countries (including China, India, and the United States) make coal an economical fuel choice [20].

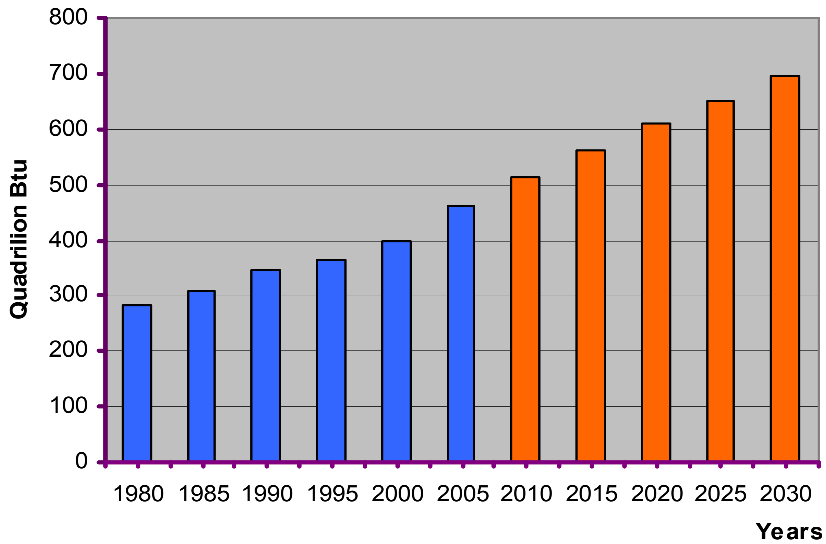


Figure: 2.3: History and Projection of World Marketed Energy Consumption, 1980 – 2030

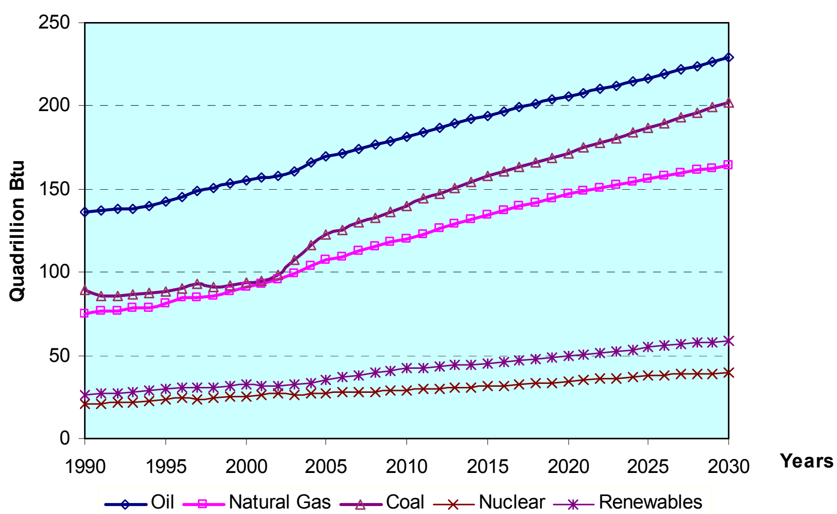


Figure: 2.4: History and Projection of World Marketed Energy Consumption, 1980 – 2030

Sources: History: [21]

#### 2.3.1.3. Delivered Energy Consumption by Sectoral Trends

The transport and power-generation sectors will absorb a growing share of global energy over the projection period, in line with past trends. Together, their share will reach over 60% in 2030, compared with 54% now. Demand for mobility and electricity-related services will continue to grow broadly in line with GDP, but at a slower rate than in the past. Inputs to power stations worldwide will grow by 2% per year between 2002 and 2030 [22].

Energy use in final sectors – transport, industry, households, services, agriculture and non-energy uses – will grow by 1.6% per year through to 2030. This is roughly the same rate as for primary energy demand. As a result, the share of final consumption in primary demand will hold steady at 68%. Transport demand will grow quickest, at 2.1% per year. Residential and services consumption will grow at an average annual rate of 1.5%, as will industrial demand [22]. As indicated below, for the coming decade, the transport sector will take more than half of total oil expected to be produced.

### 2.3.2. Global Warming and Climate Change

Although there has been advancement in the consumption of fossil fuel for existence, it should come as no surprise that the type, method and extent mankind has been using it is at the heart of many of the serious environmental problems that have emerged in recent years. The most obvious environmental effects are the physical impacts of mining for coal and drilling for oil and gas, and distributing the resultant fuels to the point of use. [17] However, increasingly it is the use of these fossil fuels - to generate electricity, to provide heat, and to provide transport - that presents the major problems globally as a main source of highly influential anthropogenic greenhouse gas emissions and other wastes, which have serious environmental impacts like the confronting climate change, global warming, and other pollutions - in the form of dust, smog and acid rain. [23].

#### 2.3.2.1. Background on Global Warming and Climate Change

The sheer scale of human technological activities and progress in utilization of fossil fuels and development put an increasing stress on the natural environment to the extent that it cannot absorb our wastes, while our extravagant daily life lead us increasingly to exploit such limited resources of our planet [17]. One of the upshots of the impacts are the current earth's climate change and global warming typically as a result of human activities that alters the concentration of atmospheric greenhouse gases due to the burning of fossil fuels. This human activities result in emissions of four long-lived GHGs: CO2, methane (CH4), nitrous oxide (N2O) and halocarbons (a group of gases containing fluorine, chlorine or bromine). Atmospheric concentrations of GHGs increase when emissions are larger than removal processes [23].

These GHGs have an impact in the atmosphere and have an ability to absorb and emit radiation within the thermal infrared range that warms the globe, that is, GHGs trap heat radiation and inhibit its release back into space, thus, leading to the global climate change [25]. This process is the fundamental cause of the greenhouse effect. "The heart of the climate change problem is that the Earth's capacity to absorb carbon dioxide (CO2) and other greenhouse gases is being overwhelmed. Humanity is living beyond its environmental means and running up ecological debts that future generations will be unable to repay" [24]

The primary heat-trapping greenhouse gases are CO2, methane (CH4), and nitrous oxide (N2O) [23]. "CO2 and methane (CH4) are two of the most potent gases that contribute to global warming. Fossil fuels are major contributors to global warming, producing large amounts of CO2" [26]. As indicated in the table below, CO2 has the highest radiative force that contributes to the global warming much more than other GHGs. Increased carbon dioxide levels are thought to exacerbate the heating effects of the Greenhouse Effect (GHE) by reducing the re-radiation of heat from the sun and, therefore, increasing the temperature contained in the atmosphere. As the ability of the atmosphere to capture and recycle energy emitted by the Earth's surface is essential to a stable climate, this heightened temperature may introduce a de-stabilising influence and potentially affect global weather patterns and, eventually, long-term climate change.

Table 2.1: Main GHG and their increment since pre-industrial era along with radiative forcing

| Gas | Preindustrial Level | Current Level | Increase since 1750 | Radiative forcing ($W/m^2$) |
|---|---|---|---|---|
| Carbon dioxide | 280 ppm | 387ppm | 104 ppm | 1.46 |
| Methane | 700 ppb | 1,745 ppb | 1,045 ppb | 0.48 |
| Nitrous oxide | 270 ppb | 314 ppb | 44 ppb | 0.15 |
| CFC-12 | 0 | 533 ppt | 533 ppt | 0.17 |

Source: [25]

#### 2.3.2.2. Greenhouse Gas Emission Trends and Its Global Impacts

As study shows, , since pre-industrial era, greenhouse gas emissions have globally grown up with an increment of 70% between 1970 and 2004 due to the influence of human activities. [27]. The largest growth in GHG emissions between 1970 and 2004 has come from energy supply, transport and industry, while residential and commercial buildings, forestry (including deforestation) and agriculture sectors have been growing at a lower rate [27]. And it is true that burning biomass emits CO2 but renewably grown biomass leads to a net zero increase in atmospheric CO2, because reestablished trees absorb the biogenic CO2 released during biomass combustion.

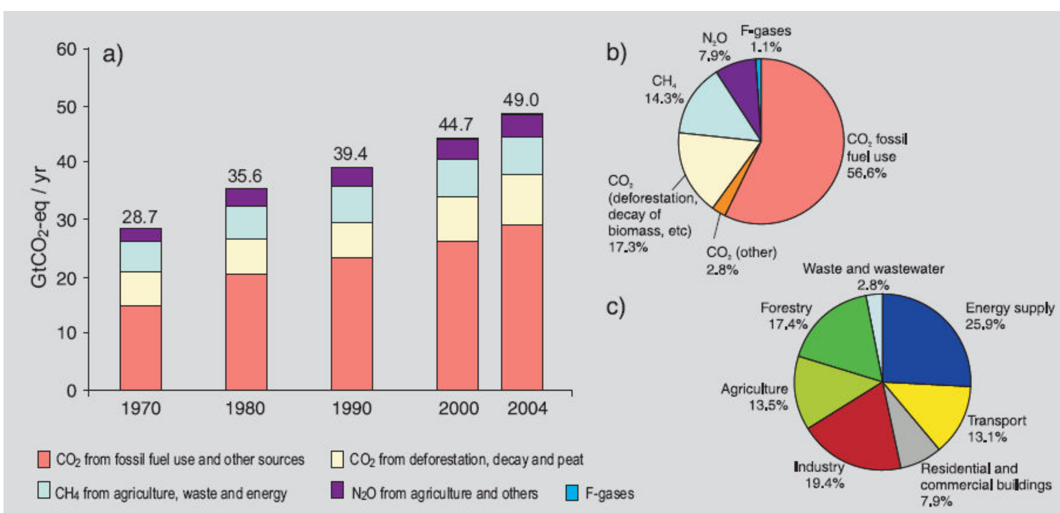


**Figure 2.4:** (a) Global annual emissions of anthropogenic GHGs from 1970 to 2004.5 (b) Share of different anthropogenic GHGs in total emissions in 2004 in terms of CO2-eq. (c) Share of different sectors in total anthropogenic GHG emissions in 2004 in terms of CO2-eq. (Forestry includes deforestation.)

Source: [27]

The IPCC reports that global greenhouse gas (GHG) emissions have grown since pre-industrial times, with an increase of 70% between 1970 and 2004. Since pre-industrial times, increasing emissions of GHGs due to human activities have led to a marked increase in atmospheric GHG concentrations. The largest growth in global GHG emissions between 1970 and 2004 has come from the energy supply sector (an increase of 145%). The growth in direct emissions in this period from transport was 120%, industry 65% and land use, land use change, and forestry 40%. Between 1970 and 1990 direct emissions from agriculture grew by 27% and from buildings by 26%, and the latter remained at approximately at 1990 levels thereafter. However, the buildings sector has a high level of electricity use and hence the total of direct and indirect emissions in this sector is much higher (75%) than direct emissions [28].

With current climate change mitigation policies and related sustainable development practices, global GHG emissions will continue to grow over the next few decades. In the IPPC modelling where little is done to reduce emissions (such as our current global practice), fossil fuels are projected to maintain their dominant position in the global energy mix to 2030 and beyond. Carbon dioxide emissions between 2000 and 2030 from energy use will grow 45 to 110% over that period. [28].

Human activities have an impact upon the levels of greenhouse gases in the atmosphere, which has other effects upon the system, with their own possible repercussions. The most recent assessment report compiled by the IPCC observed that "changes in atmospheric concentrations of greenhouse gases and aerosols, land cover and solar radiation alter the energy balance of the climate system" [28]., and concluded that "increases in anthropogenic greenhouse gas concentrations is very likely to have caused most of the increases in global average temperatures since the mid-20th century" [28].

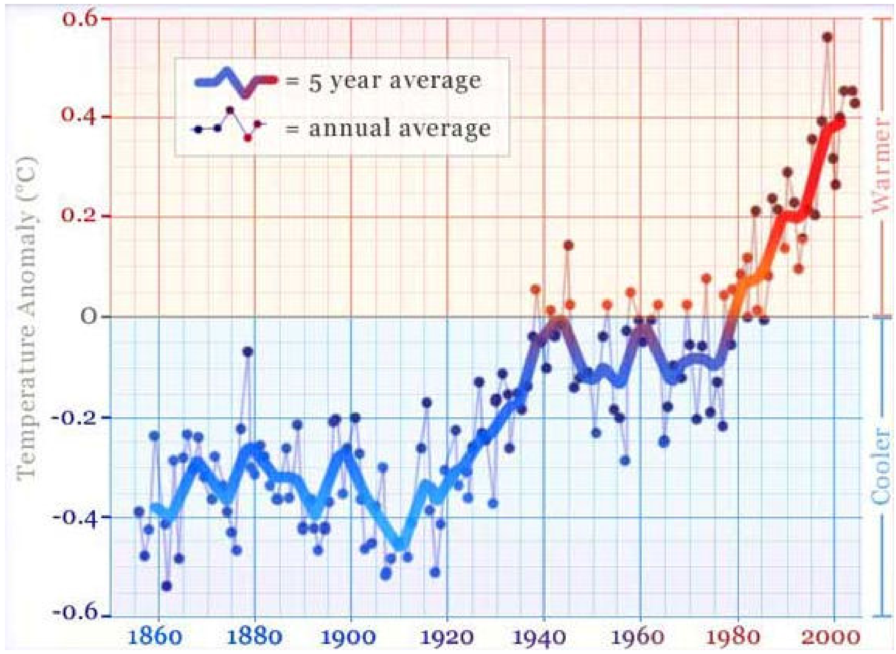


Figure 2.5: Global Temperature Trend
Source: [29]

Global mean surface temperatures have increased 0.3 to 0.6 degrees Celsius since the beginning of the industrial revolution, end of the 19th Century. The 10 warmest years in the entire 20th Century occurred in the last 15 years, with 1998 being the warmest year on record [**30**]. The snow cover in the Northern Hemisphere and floating ice in the Arctic Ocean are both decreasing. Any reduction in the extent of Arctic sea ice and snow cover reduces the albedo, or reflectivity, of the land or ocean surface and allows more solar radiation to be absorbed [31]. Therefore, this effect can be regarded as a positive feedback mechanism for continued warming. Global sea levels have risen 10 to 25 cm over the past century. Global warming has already increased worldwide precipitation over land by 1 percent producing severe flooding around the world [31]. Increasing concentrations of greenhouse gases are expected to accelerate the rate of climate change. Scientists expect that the average global surface temperature could rise up to 6 degrees Celsius by 2100 [32].

#### 2.3.2.3. Main Causes of Climate Change: Human-induced Global Warming

Since industrialization, deforestation and the burning of fossil fuels have dramatically increased the concentrations of greenhouse gases in the atmosphere. These concentrations are now far greater than concentrations for at least the past 800 000 years. Intuitively, such a massive increase in these greenhouse gases must have an impact on the world's climate. Not surprisingly, scientists have been worried about the potential for human-induced global warming since the 1800s [33].

Over the last hundred years humans have become more dependent upon fossil fuels for the majority of their energy production. Oil derivatives used to operate automobiles and trucks, heat homes and businesses, power industrial factories, as well as burning coal primarily for electric power production are responsible for roughly 80 percent of society's carbon dioxide emissions, roughly 15 percent of its methane emissions, and roughly 20 percent of global nitrous oxide emissions. Increased rates of artificially based agriculture, deforestation, landfills, industrial production, and mining operations for the extraction of coal also contribute to increasing emissions of greenhouse gases [34].

## 2.4. Biomass Energy Production

### 2.4.1. Biomass Energy Definition and Sources

The term biomass energy can refer to any source of energy produced from non-fossil biological materials. Biomass energy ranges from firewood to ethanol produced from corn or sugarcane to methane captured from landfills [13]. This bioenergy can be derived from a wide range of materials of different origin and with different properties. It can come from ocean and freshwater habitats as well as from land. But the most important bioenergy fuels are forest products, agricultural residues and wastes, energy crops, and municipal solid waste (MSW) [35].

### 2.4.2. Advantages of Biomass Energy

The use of bioenergy can have many environmental benefits over fossil fuels if the resource is produced and used in a sustainable way. If the land from which bioenergy is produced is replanted, bioenergy is used sustainably and the carbon released will be recycled into the next generation of growing plants. Substituting fossil fuels with bioenergy means the carbon from the displaced fossil fuels remains in the ground and is not discharged into the atmosphere That is, it does not increase atmospheric levels of carbon dioxide, a primary greenhouse gas, because of the cycles of re-growth for plants and trees. The extent to which bioenergy can displace net emissions of $CO_2$ will depend on the efficiency with which it can be produced and used. Bioenergy plants have lower emissions of $SO_2$ than do coal and oil plants. They may produce, however, more particulate matter than oil- and gas-fired plants. These emissions are in generally controllable but they increase generating costs [35].

In broadly speaking, biomass energy is increasingly popular as an alternative energy source for a variety of reasons:

- Biomass is far more widely available than fossil fuels and, with good management practices, can be produced renewably.
- Modernized biomass energy can provide a basis for rural development and employment in developing countries, thereby helping curb urban migration
- In developing countries, growing biomass for energy on deforested and otherwise degraded lands might provide a mechanism for financing the restoration of these lands.
- In industrialized countries, growing biomass for energy on excess croplands can provide a new livelihood for farmers who might otherwise abandon farming because of food crop overproduction.
- If biomass is grown sustainable, its production and use leads to net zero buildup of ($CO_2$) in the atmosphere, because the $CO_2$ released in combustion is offset by the $CO_2$ extracted from the atmosphere during photosynthesis. It can help provide answers to the global warming and climate change issue.
- It is a renewable resource and it is promising for the future sustainable energy supply.
- It results in less waste being sent to landfills.

- The use of biomass can also decrease the amount of methane, another greenhouse gas, which is emitted from decaying organic matter.
- It can be converted into several forms of energy. For example, wood can be processed and converted to gas. Landfills can produce methane, and corn, wheat and other materials can be used to manufacture liquid fuel ethanol.

### 2.4.3. Conversion Technologies: Biomass to Biomass Energy

The old way of converting biomass to energy, practiced for thousands of years, is simply to burn it to produce heat. The heat can be used directly, for heating, cooking, and industrial processes, or indirectly, to produce electricity. The problems with burning biomass are that much of the energy is wasted and that it can cause some pollution if it is not carefully controlled [36].

In general, any biomass resources are converted to useful energy in three primary ways [37]. The first and oldest way is thermal method. This can be used directly for heating, cooking and industrial processes, or indirectly to generate electricity. At biomass power plants, biomass is burned in a boiler to produce high-pressure steam, which, in turn drives a turbine to generate electricity. The next one is thermo-chemical that involves heating (but not burning) plant matter, it is possible to break down biomass into gases, liquids and solids, which can be further processed into gas and liquid fuels like methane and alcohol. Biomass reactors heat biomass in a low-oxygen environment to produce a fuel gas (mostly methane), which can then fuel steam generators, combustion turbines, combined cycle technologies or fuel cells. Finally, Biochemical is the method that requires adding bacteria, yeasts and enzymes to biomass liquids causing biomass materials to ferment and change into alcohol. A similar process is used to turn agricultural products into ethanol (grain alcohol), which is then mixed with gasoline to make an ethanol-gasoline blend. And when bacteria are used to break down biomass, methane is produced and can be captured from landfills and sewage treatment plants to produce fuel for heat and power.

### 2.4.4. Potential Environmental Impacts: Production And Utilization

#### 2.4.4.1. Overview

The extraction, conversion, and utilization of various forms of energy are recognized as one of the major contributors to environmental degradation at the global as well as at the local level. This can be due to GHG emissions and local air pollution due to combustion of fossil fuels, submergence of forests by hydroelectric power projects, or forest degradation due to firewood use. Furthermore, change of farm land use in terms of expansion and intensive utilization for biomass production contribute great negative impact on environment [38].

I n a recent study undertaken to ensure the early incorporation of environmental considerations in decisions concerning biomass-to-energy systems, a number of issues emerged indicating the need for early attention to environmental, socio-economic and health concerns. Both production of biomass as well as conversion can lead to environmental impact, and although most impacts will be site-specific, some generic effects can be identified [39].

In general case, it is necessary to understand the environmental implications of biomass use as an energy source via[38], :

- Atmospheric pollution from emissions of greenhouse gases during combustion of wood, deforestation, and utilization of fossil fuel while producing and transporting of biomass, with its implications for climate change;
- Contributions to deforestation, forest degradation, and increasing monoculture, leading to loss of biodiversity and soil degradation;
- Loss of nutrients due to combustion of cattle dung and crop residues in case of developing countries;
- land-use-change during the production of biomass feedstock;
- Water Resources Depletion and Pollution
- Soil Erosion and Nutrient Loss
- Introduction of Invasive Plant Species

#### 2.4.4.2. Biomass Production: land-use-change

One of the most commonly noted environmental impacts of biofuel production is land-use change. The amount of biofuel produced per unit area of cultivated land differs noticeably among feedstocks [40]. Given the rising demand for biofuels globally and that this demand is expected to continue to increase over the next ten years , increasing amounts of land will likely be devoted to biofuel production. For example it is estimated that a 10% substitution of petrol and diesel fuel would require that 43% and 38% of current cropland in the United States and Europe, respectively, be devoted to feedstock production [41], or that the production of feedstocks increases overseas. The choice of feedstock, the place where it is grown and the cultivation practices used all play a significant role in determining if the production of a certain biofuel will have negative or positive impacts on the environment, and the magnitude of those impacts.

#### 2.4.4.3. Impacts on Biodiversity and Deforestation

Habitat loss is one of the major causes of biodiversity decline globally [42]. The increasing demand for bioenergy could lead to both direct and indirect expansions of cultivated areas, resulting in further habitat loss and negative impacts on biodiversity, especially if forest, grassland, peatland and wetlands are used for feedstock production and if large monoculture plantations are created. It has been noted that, in some Organisation for Economic Co-operation and Development (OECD) member countries, the increasing demand for oilseed has already begun to put pressure on areas designated for conservation [42]. Similarly the rising demand for palm oil has contributed to extensive deforestation in parts of South-East Asia [43].

Further, if management practices are not changed to avoid the leaching and emission of eutrophicating nutrients, the increased use of fertilizers could also result in increased eutrophication of terrestrial and aquatic ecosystems, as well as the increased dry deposition of reactive nitrogen, both leading to a loss of biodiversity [44]. The increased use of pesticides would also have adverse impacts on biodiversity and the increased use of agrichemicals generally could create health hazards for communities living near areas where feedstocks are being produced [43].

### 2.4.4.4. Greenhouse Gas Emission and Air Pollution

Land use change associated with the production of energy crops would also affect carbon dioxide emissions. If energy crop plantations are established on forested land or carbon rich soils any reduction achieved through the use of biofuels could be negated or even greatly out-weighed by the release of greenhouse gases stemming from land-use change and the production of feedstocks. Processes such as draining wetlands and clearing land with fire are particularly detrimental with regard to greenhouse gas emissions and air quality [45]. For example it is estimated that the drainage of peatlands in South-East Asia can results in the release of up to 100 tonnes of carbon dioxide per hectare per year and if peatland soils are burned the amount of carbon dioxide released could be double or triple this value [46]. The drainage and burning or peatlands in South-East Asia between 1997 and 2006 resulted in carbon dioxide emissions of, on average, 2,000 megatonnes per year [46]. Such practices would also result in a loss of above- and below-ground biodiversity.

Two issues need to be addressed before the efficacy of biofuels can be assessed: the net reduction in fossil fuel carbon emissions (avoided emissions) arising from the use of agriculturally derived first generation biofuels and the effect of alternative land-use strategies on carbon stores in the biosphere [47]. Taking these factors into account, a study found that converting rainforests, peatlands, savannas, or grasslands to produce food-based biofuels in Brazil, South-East Asia, and the United States creates a biomass carbon debt by releasing 17 to 420 times more carbon dioxide than the annual greenhouse gas (GHG) reductions these biofuels provide by displacing fossil fuel use [48].

The release of nitrogen from soils, resulting from the application of industrial fertilizers, is the largest single source of nitrous oxide emissions globally [46]. Nitrous oxide has a global warming potential 296 times larger than that of carbon dioxide. Therefore, if the production of biofuel feedstocks requires increased fertilizer use, there could be additional detrimental climate change effects if the application of nitrogen is not managed appropriately.

Some forms of bioenergy can help improve air quality during the use phase, depending on feedstocks and combustion methods. Just a 20% blend of biodiesel can reduce asthma causing particulate matter by 30% and acid-rain forming sulphur dioxide by virtually 100%.However, during the production of some forms of bioenergy, air pollution can be increased. The burning of cane fields for harvesting and the burning of crop wastes, for example, can increase local air pollution.

On the other hand, the open air burning of biomass has a potential of polluting troposphere air, for example, by releasing of particulates to air while burning of cane fields for harvesting and the burning of crop wastes, which is harmful for human breathing system and health [49].

#### 2.4.4.5. Water Resources Depletion

In addition to the potential effects of land use change, the production of energy crops can also have impacts on water availability and quality. Agriculture accounts for more than 70% of total water used in most countries, so cultivating energy crops can put further pressure on scarce water resources. Farmers may pump 250 billion litres of underground water to raise the corn feedstock for an ethanol production facility. If managed poorly, energy crops can lower sub-surface water tables, as well as rivers and lakes, particularly if these crops are irrigated. Besides, Considerable amounts of water are also required to convert bioenergy feedstocks into fuels. For instance, a 200 million-litre ethanol plant might use 600 million-litres of water to make fuel - more water than some small towns use in a developed country. [49].

#### 2.4.4.6. Introduction of Invasive Plant Species

Another concern with regard to the production of feedstocks for biofuels is the potential introduction and establishment of alien invasive species [50]. Several grasses and woody species which are potential candidates for future biofuel production also have traits which are commonly found in invasive species. These traits include rapid growth, high water-use efficiency and long canopy duration. It is feared that should such crops be introduced they could become invasive and displace indigenous species and result in a decrease in biodiversity. For example Jatropha curcas, a potential feedstock for biofuels, is considered weedy in several countries, including India and many South American states [51]. Similar warnings have also been raised with regard to species of Miscanthus and switchgrass (Panicum virgatum). Other biofuel crops such as Sorghum halepense (Johnson grass), Arundo donax (giant reed), Phalaris arundinacea (reed canary grass) are already known to be invasive in the United States.

#### 2.4.4.7. Impact Categories and Scale of Impacts

As listed above, the production as well as the utilization of biomass energy has many problems which can be categorized according to their impacts and the scale of influence on ecology and human being's health in one way or another.

As indicated by study [52], the land-use-change has Global impacts on land availability that need global cooperation to act on it. The change of this land-use can also lead to the loss of biodiversity that eventually may have local to global influences on the number of species plants as well as on species of birds and animal those are living on specific plant species for their survival. Furthermore, the emission of GHGs due to the land-use-change, production of energy crops and utilization of biomass energy have global problem that has been categorized as having huge problem on global warming and climate change, which has become getting great attention across the world. These emissions also have remarkable global impacts on human health due to the total releases to air, water, and soil as GHGs and particulate matters. In addition, these emissions have acidification impact, for instance as acid rain, at the regional and local level and eutrophication influence on local level. Soil erosion and nutrient loss are also another regional and local impact on the environment as a result of the production of energy crops and deforestation for land use purpose [52].

## 2.5. Statement of the Problems of the Case Study

- The possibility of increasing concentration of Greenhouse Gas in the atmosphere due to increase of more emission;
- The risk of loss of biodiversity due to monoculture, chemical application, invasive species, and others;
- The possibility of deforestation that leads to more emission;
- There is risk of water, soil and air pollution and depletion of water resources;
- Land-use change associated with food-crop-land utilization;

## 2.6. Controversial ideal and the need of assessment tools

With the rising of use of bioenergy has also come debate regarding the potential positive and/or negative impacts of the utilization of the products and in the productions system. While proponents of biomass energy point to the potential for cleaner fuels, greater economic opportunities for farmers and rural communities, and a renewable source of energy, the other group argue that biomass energy risk damaging biodiversity, marginalizing indigenous and local communities, creating more greenhouse gas emissions than they prevent, creating more pollutants rather than avoiding, and other things. This debate is complicated by the fact that numerous types of biomass (or feedstocks) can be used in the production of bioenergies [39]. On the other hand, consumption of fossil fuel is putting the world to face a common global problem like global warming and climate change.

In order to quantify the extent and the type of environmental impacts of production and utilization of biomass energy and to bring in to consensus the arguments on the impact of biomass energy and to understand the effect of bioenergy on overall consumption of petroleum and other fossil fuels, it is crucial to investigate and quantify the problems through the context of system's "life cycle".

## 2.7. Background: Life Cycle Assessment Description

### 2.7.1. Concept and definition of a Life Cycle Assessment (LCA)

The complexity of identifying environmental pollution sources and the magnitude of complex pollution effects on the international community demands a broader focus. Previously, product and process analysis simply included the production and generation of products and energy at local point source. However, in order to evaluate the increasing complex environmental impacts of internationally produced and traded goods, it necessary to assess the whole chain; from the extraction of raw materials to the end use consumer; Life Cycle Assessment.

Life-Cycle Assessment (LCA) is both a concept and methodology for auditing and evaluating environmental performance of products, processes, and activities over their entire lifetime 'from cradle to grave'. The aim of this holistic approach is to identify and quantify all factors/variables in the system relevant to resource consumption and environmental impact. The entire life cycle includes crude material extraction, manufacturing, transport and distribution, product use, service and maintenance, recycling and final waste handling. In order to assess the energy and environmental expenses along the life cycle chain, a mathematical computer model is designed to show a representative picture of the environmental impacts of the real system [53].

An LCA can help decision-makers select the product or process that result in the least impact to the environment. This information can be used with other factors, such as cost and performance data to select a product or process [52].

The LCA process is a systematic, phased approach and consists of four components: goal definition and scoping, inventory analysis, impact assessment, and interpretation as illustrated in figure 2.8 [52]:

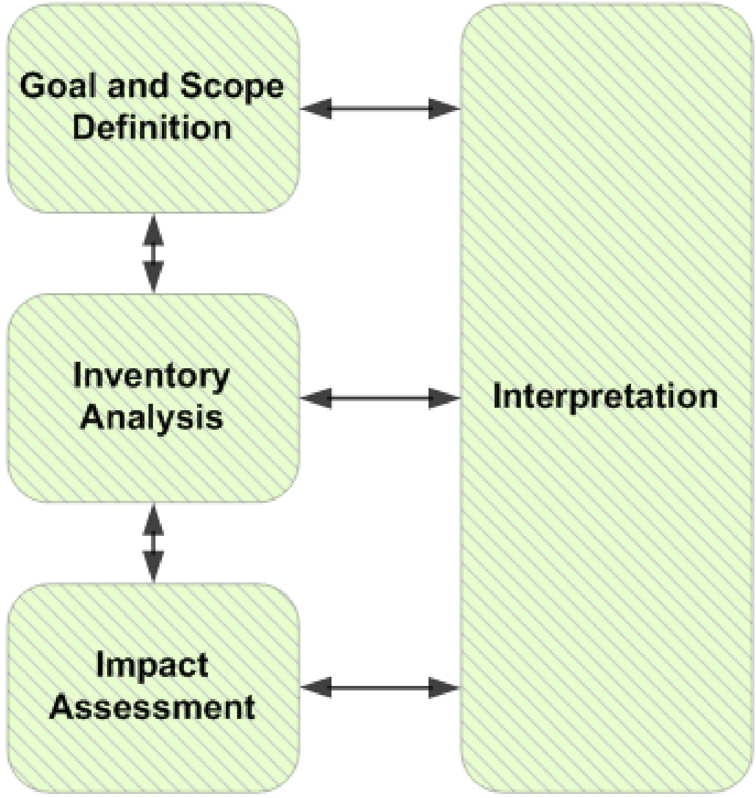


**Figure 2.8: Phases of an LCA and its frame work**

### 2.7.2. Description of the Components

In the Life Cycle Assessment, there are main components those describe the assessment for the required purpose [54]. The Goal Definition and Scoping defines and describe the product, process or activity in the system. This also establishes the context in which the assessment is to be made and identify the boundaries and environmental effects to be reviewed for the assessment. The Inventory Analysis part identifies and quantifies energy, water and materials usage and environmental releases (e.g., air emissions, solid waste disposal, waste water discharges). Impact Assessment assesses the potential human and environmental effects of energy, water, and material usage and the environmental releases identified in the inventory analysis.

# 3. OBJECTIVE OF THE STUDY:

**General objective:**

- to assess the impact of utilization of biomass source of energy on the environment and on the future of human being's life;

**Specific objectives:**

- to assess and analysis, to the extent possible, the impact of utilization of biodiesel energy on our environment;
- to assess environmental benefits of biodiesel over petroleum diesel sources of energy;
- to identify and quantify the advantages of biodiesel as a substitute for petroleum diesel
- to suggest an environmentally friendly source(s) of energy;

# 4. METHODOLOGY

## 4.1. Overview

In this case study, in order to judge the impacts of utilization of energy, particularly bioenergy, on our environment and human's health, Life Cycle Assessment has been used and the implementation of "life cycle" assessment has focused on the production system of biofuel, especially biodiesel from "source to wheel" in-line with the investigation of the influence of production system of petroleum diesel from "well to wheel". The benefits related to biodiesel energy balance, its effect on emissions of greenhouse gases, and its effects on the generation of air, water and solid waste pollutants have been analyzed through this assessment.

It is clear that the impact of production and utilization of biomass energy on our environment is greatly influenced by the types of biomass and the conversion technologies used to convert the biomass to useful energy, . It is also known that biomass energy resources are widely varied in forms, energy potential and length of during of growth of biomass that determine the overall energy potential of the biomass. So that, it is important to concentrate on specific energy source of biomass and conversion technology in order to assess the environmental impacts of the biomass sources of energy. Therefore, in this case study, taking in to account the aforementioned problems, a biofuel derived from soybean oil has been selected to examine the life cycle impact of the system while weighing against the life cycle of the petroleum diesel. Furthermore, because of the high effect of the fuels' end uses, that are affected by the conversion technology, on the life cycle flows assessment, the end uses evaluation on urban bus has been chosen due the availability of the data on engine performance.

## 4.2. Life Cycle Assessment: Goal Definition and Scoping

### 4.2.1. Goal Definition

The purpose of this study is to assess the impact of bioenergy on the existing environment at the first position. To the particular points, the case study is going to explore and compute the influence of consuming of biofuel, especially biodiesel, on the environment at local, regional, national and international level. Furthermore, this research points out the significances of consumption of biomass sources of energy, biodiesel, over the fossil fuel sources of energy, diesel. That is, it is to quantify and compare the comprehensive sets of environmental flow (to and from the environment) associated with both biodiesel and petroleum-based diesel, over their entire life cycles. Finally, it puts forward suggestions on the environmentally benign sources of energy depending on the final result of the study. In addition to the purpose stated, this study was intended to provide the necessary information that could be used to answer the questions have been raised by many environmentalists and researchers with regards to the impact of energy on our environment.

### 4.2.2. Scope

#### 4.2.2.1. System description and boundaries

The system boundaries for any LCA should be drawn as broadly as possible. In addition to counting the material and energy flows of the primary process of interest, those processes involved in the extraction of raw materials and production of intermediate feedstock (e.g., the fertilizer needed to grow biomass) must be included into the consideration [54].

System boundaries define the relevant processes to be included or excluded from the LCA. The common ones that are generally considered are construction and disposition stages, the flows associated with producing the inputs consumed in life cycle stages, accounting for duplicate stages common to both life cycles, and the rules for allocating life cycle contributions between co-products of production processes.

Fuel life cycle boundary in this study is from the source of fuel to fuel combustion in vehicle engines, i.e., the source-to-wheel (StW) process. It includes stages of feedstock, fuel production, and fuel use. Feedstock and fuel production together is also known as the source-to-tank (StT) stage while fuel use as the tank-to-wheel (TtW) stage. As illustrated schematically by Fig. 4.1, the primary material, energy, emission flows and pollutants were tracked from the field production of soybeans up to the utilization of the oil in biodiesel bus engine in the case of biodiesel fuel system boundaries and in the case of petroleum diesel system, the major operational boundary was traced from the extraction of crude oil from the ground to the use of the fuel in a diesel bus engine.

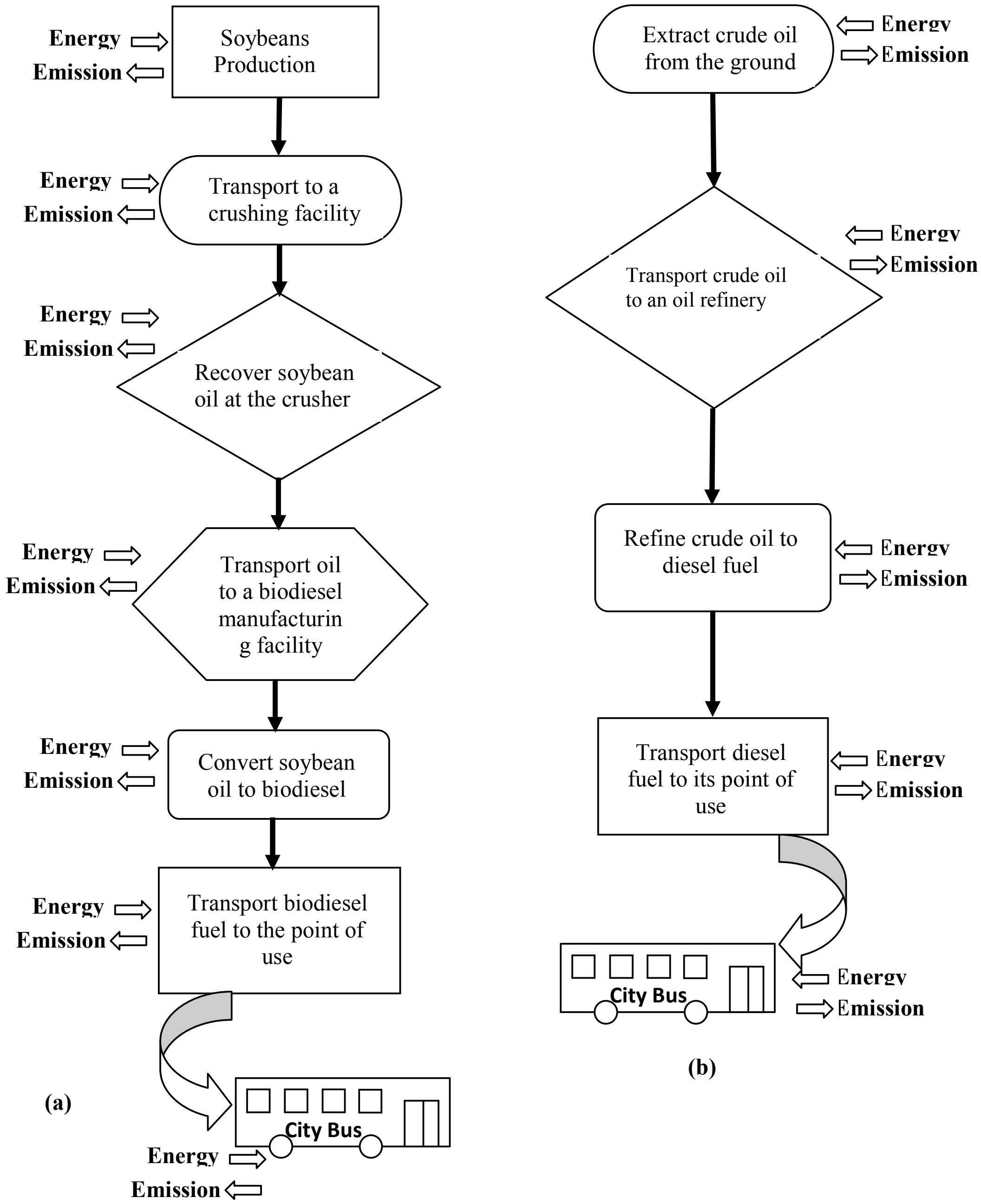


Figure 4.1: Flowchart showing the life cycle of major operations within the boundaries of the biodiesel (a) and petroleum diesel (b) systems

#### 4.2.2.2. Functional unit

Common sense dictates that two fuels should be compared on the same basis. So the service that the fuels provide, in this case study, the work that the bus engine provides, is the unit of comparison. Thus, the functional unit (FU) selected to allow an objective basis for determination of LCA and for comparison purpose is units per brake horsepower hour (hp hr) of diesel engine service for all the inputs and outflows associated with each step in the Life Cycle data. That is, for heavy-duty diesel engines, the common unit of work is a brake-horsepower hour (bhp-h) unlike that of light-duty vehicles, like automobiles, where the service provided by the fuel is a one mile distances it propels the vehicle. Once this shared function is defined, a comparison of fuel life cycles for diesel engines characterizes all life cycle flows per bhp-h of diesel bus service [55].

## 4.3. Life Cycle Inventory

This part of the LCA gives the details of the process by quantifying energy and raw material required for the process, atmospheric emissions, waterborne emissions, solid wastes pollutants, and other releases for the entire life cycle of a product, process, or activity [54]. In this phase of the LCA, all relevant data is collected and organized. An inventory analysis produces a list containing the quantities of pollutants released to the environment and the amount of energy and material consumed. Without an LCI, no basis exists to evaluate comparative environmental impacts or potential improvements.

As stated above, this second phase inventory involves data collection and modeling of the product system, as well as description and verification of data. This encompasses all data related to environmental (e.g., $CO_2$) and technical (e.g., intermediate chemicals) quantities for all relevant unit processes within the study boundaries that compose the product system. Examples of inputs and outputs quantities include inputs of materials, energy, chemicals and other - and outputs in the form of air emissions, water emissions or solid waste. Other types of exchanges or interventions such as radiation or land use can also be included.

### 4.3.1. Key Assumptions of the LCI

These key assumptions were used while collecting and processing data for LCI analysis. The general key assumptions considered so as to appreciate the data are: national average distances were used to describe the transportation distances for all feedstocks, intermediate products, and fuels and both fuels were assumed to be used in engines calibrated to meet 1994 EPA regulations for diesel exhaust when operated on low-sulfur petroleum diesel [55].

**Other assumptions were as under listed** [55]:

**Diesel fuel assumptions include:**

- Sources of crude oil, domestic and foreign, were split almost evenly,
- Publicly available refinery data were used to model a generic refinery,
- Engine emissions from petroleum diesel are taken from published 1994 engine certification data.

**Biodiesel assumptions include:**

- Emissions were based on actual engine data for biodiesel emissions that were then modeled as changes in the oxygen content in the fuel.
- Energy efficiencies of biodiesel-fueled engines were identical to those of petroleum diesel-fueled engines.
- Biomass-derived carbon dioxide ($CO_2$) in the fuel emissions is recycled in soybean production.
- Soybean crushing and soy oil esterification data were based on published data and engineering models.

### 4.3.2. Researching LCI information

Information used in this study is obtained from different sources. Due to the availability and quality of the data of the inventory depend on different factors – geographical location, soil type, technology and etc - those inventory data produced in United States and in Europe have been more considered for this case study in order to conduct the assessment as much as possible to give clear view of impact of energy on our environment.

In this case study, the assessment and analyses of output of various inventory data [55] that were carried out using dedicated software packages by previous studies of only Life Cycle Assessment inventories and modeling of biofuel and fossil fuel has been investigated so as to get views of the extent of impacts of bioenergy on our environment and human health with comparison of fossil sources of energy.

### 4.3.3. Case of Biodiesel Fuel Modeling and Impacts Information

As listed in Figure 4.1 above, the processing system of the biodiesel fuel has its own life cycle phases that include produce soybeans, transport soybeans to a soy crushing facility, recover soybean oil at the crusher, transport soybean oil to a biodiesel manufacturing facility, convert soybean oil to biodiesel, and transport biodiesel fuel to the point of use. So as to get an overview of each phase of the life cycle of biodiesel in-line with activities involved, emission and energy flow, it is important to describe each of them as under.

#### 4.3.3.1. Soybean Agriculture

The agriculture part of this LCI study involves identifying the complete environmental flows associated with soybean production. This includes the amounts of chemicals and fuels used on the farm and their associated emissions, as well as the manufacturing, packaging, and processing of the inputs used to grow soybeans. For example, the energy required to mine, process, and transport potash fertilizer to the field is estimated. Also, the environmental flows and energy requirements involved in making and transporting pesticides, seed, and all other farm inputs are accounted for

##### 4.3.3.1.1. General Assumption

In production model of soybean, it was assumed that $CO^2$ uptake by the soybean plant is released back to the environment through decomposition of plant residue, left in the field after harvesting, or through the combustion of biodiesel made from soybeans. Thus, the net biomass-derived $CO^2$ balance for growing and burning soybean biodiesel is zero. $CO^2$ sequestered in the beans is carried through the LCA as $CO^2$ (biomass) versus $CO^2$ (fossil), which results from the combustion of petroleum resources, such as the methanol component of the biodiesel

### 4.3.3.1.2. Energy Use and Energy Emission

Energy inputs for soybean production include gasoline, diesel fuel, liquefied petroleum gas (LPG), natural gas, and electricity. These energy sources are required for field equipment (e.g., tractors and combines), as well as such activities as pumping irrigation water to soybean fields [55].

Taking in to account the general assumption given above, the emissions associated with the production of soybean are due to the utilization of fossil sources of fuel in the farm equipment like farm tractors, trucks, and etc. The emissions from the two types of tractors are shown in Table 4.1 and Table 4.2 [55].

Table 4.1: Emission Factors for Diesel Fuel Combustion in a Farming Tractor

| Tractor type | Emission Factors (g/MJ diesel fuel burned) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Hydrocarbons | CO | $NO_x$ | PM10 | $SO_2$ | $CH_4$ | $N_2O$ | $CO_2$ |
| Diesel | 0.085 | 0.32 | 0.89 | 0.041 | 0.12 | 0.0042 | 0.0019 | 75.5 |

Table 4.2: Emission Factors for Gasoline Combustion in a Farming Tractor

| Tractor type | Emission Factors (g/MJ diesel fuel burned) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Hydrocarbons | CO | $NO_x$ | PM10 | $SO_2$ | $CH_4$ | $N_2O$ | $CO_2$ |
| Gasoline | 0.20 | 1.14 | 0.63 | 0.0074 | 0.0046 | 0.032 | 0.0019 | 67.7 |

#### 4.3.3.1.3. Field Emissions

Although farmers generally use soil tests to avoid over-fertilization and to determine precise fertilizer application rates that ensure good yields, not all the fertilizer is used by the plants. Unused fertilizer will degrade in the soil and some will completely dissipate. Some attaches to soil particles and moves off the field through soil erosion. Also, some of the applied fertilizer transforms into gases such as N2O and NOx and enters the atmosphere.

#### 4.3.3.1.4. $NO_x$ and $N_2O$ Emissions from Soil

It is possible for the nitrogen applied to soil as fertilizer to be released into the atmosphere as $N_2O$, and $NO_x$ ($NO + NO_2 = NO_x$). Although soybeans don't generally need nitrogen fertilizer (10 lb of nitrogen/acre compared to 123 lb/acre for corn), they contribute to nitrogen emissions indirectly. Soybean production systems produce soybeans and nitrogen fertilizer for the next growing season through nitrogen fixation. That nitrogen fixation leads to nitrogen emissions in the following year when decomposition occurs [55].

### 4.3.3.2. Soybean Transport to Crusher

The energy consumption and the possible emission during the transportation of soybeans from the field to the crusher are based on existing practices in the soybean farming system and soybean crushing sectors. Besides, the mode of transportation determines the extent of emission while transporting soybean to crushing area.

### 4.3.3.3. Soybean Crushing: Energy Inputs and Emission from the Process

According to the Ecobalance model, the different forms of energy inputs to the soybean crushing facility are as indicated in the Table 4.3 [55].

Table 4.3: Energy Inputs to Soybean Crushing Process

| Energy Source | Energy per Metric Ton of Beans Delivered | Energy per Metric Ton of Oil Produced |
|---|---|---|
| Electricity (kWh) | 69.66 | 410.45 |
| Natural Gas (kcal) | 266,275 | 1,568,858.71 |
| Steam (kcal) | 220,020 | 1,296,331.52 |

In the crushing process, air and water emissions are the main concerning part in-line with the impact of environment. In air emissions, hexane emissions come from vent losses in meal processing and solvent recovery. Emissions from combustion are associated with combustion of natural gas to produce steam and hot air for drying. The added flow of water is due to the use of steam injected directly into the process streams. This steam condenses and ultimately ends up as wastewater. For more information, refer Table 4.4 and 4.5 [55].

Table 4.4: Air Emissions from Soybean Crushing Facility (Excluding Combustion)

| Component | Hourly Flow (kg/h) | kg per Metric Ton of Beans Delivered | kg per Metric Ton of Oil Produced |
|---|---|---|---|
| Moisture | 6,561 | 69.28 | 408.19 |
| Air | 317 | 3.35 | 19.73 |
| Hexane | 163 | 1.72 | 10.15 |

Table 4.5: Water Emissions from a Soybean Crushing Facility

| Component | Wastewater kg/h | kg per Metric Ton of Beans Delivered | kg per Metric Ton of Soybean Oil Produced |
|---|---|---|---|
| Total Wastewater | 7,358.26 | 77.70 | 457.77 |
| Soybean Oil | 80.77 | 0.85 | 5.02 |
| Triglycerides | 78.96 | 0.83 | 4.91 |
| Phosphatides | 0.02 | 0.0002 | 0.00 |
| Unsaponifiable Matter | 1.21 | 0.01 | 0.08 |
| Free Fatty Acids | 0.58 | 0.01 | 0.04 |
| Moisture | 7,277.50 | 76.85 | 452.75 |

#### 4.3.3.4. Soybean Oil Transport

In this phase of process, the main concerns are the energy demand and fugitive Emissions from storage and handling of soybeans. The major problem here is the decision on modes of transportation and distance to be transported and where to locate the conversion facilities.

#### 4.3.3.5. Soybean Oil Conversion: Energy Inputs and Emission from the Process

In modeling biodiesel production, the heart of the process for converting soybean oil to biodiesel is assumed to be a reaction known as transesterification. In this reaction, a simple alcohol such as methanol is reacted with the triglycerides in soybean oil to produce a fatty acid methyl ester (biodiesel) and glycerol [55, 56].

Energy requirements for the conversion of soybean oil to biodiesel include steam and electricity. Steam is assumed to be produced using a natural gas-fired industrial boiler. Steam demand is greatest for glycerine recovery. Both the methanol and glycerine columns separate and recover methanol from the aqueous reactor product streams. When the energy of glycerine recovery is included with the energy requirements for methanol recovery, recycle of methanol represents 64% of the total energy demand for the conversion facility.

Table 4.6: Water and Solid Waste Emissions from a Biodiesel Production Facility

| Classification | Component | Hourly Flow (kg/h) | Normalized Flow (kg/metric ton biodiesel) |
|---|---|---|---|
| Solid Waste | Oil and Grease | 122.55 | 11.667 |
| Liquid Waste | Total Wastewater | 4,003.96 | 381.200 |
| | Methanol | 9.00 | 0.8572 |
| | Water | 3,660.03 | 348.457 |
| | Phosphatides | 2.16 | 0.20541 |
| | Unsaponifiable Matter | 161.82 | 15.4058 |
| | Soap | 160.39 | 15.2701 |
| | Glycerides | 10.56 | 1.00539 |

Source: [55]

#### 4.3.3.6. Biodiesel Transport: Energy and Fugitive Emissions

In addition to the energy requirements and subsequent emissions from the actual modes of transportation (truck diesel use and emissions), energy and emissions are also created while loading and unloading the biodiesel.

### 4.3.4. Case of Petroleum Fuel Modeling and Impacts Inventory

#### 4.3.4.1. Crude Oil Extraction

In order to investigate the overall activities in the crude oil extraction, it can be possible to observe three separate types of processes. The three processes are onshore production, offshore production, and enhanced recovery. Enhanced recovery entails the underground injection of steam (produced by natural gas boilers) and $CO_2$ to force the crude oil to the surface. Out of the three methods, the onshore shares the prominent part.

#### 4.3.4.1.1. Process Emissions: Onshore Extraction

Air, water, and solid waste emissions are emitted from conventional onshore crude oil extraction. Water effluents are based on the amount of wastewater produced and its estimated average composition. As estimated [55], about 0.7 L of wastewater is produced for every kg of crude oil produced by conventional onshore crude oil extraction. The total wastewater produced is actually higher than this estimate, but only 0.7 L are released to the environment. The rest is treated on site through reinjection, evaporation, etc.

Air emissions from conventional onshore crude oil extraction come from the combustion of natural gas in the crude oil/natural gas separators, venting and flaring of natural gas, and from volatilization (fugitive) emissions of crude oil. Based on the amount of gas produced, these proportions can be used to estimate a constant factor for kilogram of natural gas flared and vented per kilogram of crude oil extracted [55].

The extracted crude oil must undergo an additional step before it is ready to be shipped to refineries; it must be separated from the natural gas and water. These field separators are assumed to operate on natural gas produced at the site, as explained in the previous sections. The combustion of natural gas leads to air emissions as indicated in the table below [55].

Table 4.7: VOC Emissions for Onshore Crude Oil Wells

| **Component** | **Emission Factor (g/well-yr.)** |
|---|---:|
| Fugitive Emissions | 180,000 |
| Crude Oil Sumps | 4,000 |
| Crude Oil Pits | 4,000 |
| **Total** | **188,000** |

#### 4.3.4.2. Crude Oil Transport to Refinery: Energy and Fugitive Emissions

In addition to the energy requirements and subsequent emissions from the actual modes of transportation (e.g., truck diesel use and emissions, pipeline electricity requirements, and emissions from electricity production), energy and emissions are also created during the loading and unloading of the crude oil.

The loading and unloading of crude oil is assumed to require electricity for pumping. The amount of electricity used is based on the electricity required for pipeline transport. Pipelines are assumed to require 5.8 x 10-5 MJ of electricity per 1 kg transported 1 km [55].

#### 4.3.4.3. Crude Oil Refining

##### 4.3.4.3.1. Energy Requirement: Energy and Process Emissions

Emissions from crude oil refining include air emissions, water effluents, and solid waste. The following sections describe how each is modeled from crude oil refining.

Air emissions from crude oil refining are assumed to come from three sources:

- Fuel combustion
- Process emissions
- Fugitive emissions.

Fuel combustion emissions are based on the amount and types of fuels consumed and emission factors for specific combustion devices [56]. All the fuels used in the refinery are assumed to be combusted in industrial boilers. The emissions for electricity production are based on Ecobalance's database DEAM for the standard U.S. electricity grid [55]. Emissions for purchased steam production are based on Ecobalance's database DEAM for the production of steam from natural gas. Process emissions for a petroleum refinery are based on emission factors published in EPA AP-42 fifth edition [55]. The emission factors for petroleum refining processes are shown in Table 4.8.

Table 4.8: Petroleum Refining Process Emissions

| Process | Emission Factors | | | | | |
|---|---|---|---|---|---|---|
| | Particulate | $SO_2$ | CO | Non-Methane Hydrocarbons | $NO_2$ | $CO_2$ |
| Catalytic Cracking (g/L crackers feed) | 0.052 | 0.79 | -- | -- | 0.11 | 40.7 |
| Fluid Coking (g/L cokers feed) | 1.5 | -- | -- | -- | -- | -- |
| Vapor Recovery/Flare (g/L refinery feed) | -- | 0.077 | 0.012 | 0.002 | 0.054 | -- |
| Sulfur Recovery (g/kg sulfur produced) | -- | 29 | -- | -- | -- | -- |

**Source:** 55

#### 4.3.4.4. Diesel Fuel Transport

In addition to the energy requirements and subsequent emissions from the actual modes of transportation (e.g., truck diesel use and emissions, pipeline electricity requirements, and emissions from electricity production), energy and emissions are also caused by loading and unloading the diesel fuel. Also, fugitive tank emissions from diesel fuel storage at the urban bus refueling location are assumed to be negligible.

### 4.3.5. Urban Bus Operation and Impacts

#### 4.3.5.1. Biodiesel Fuel Combustion: Tailpipe Emissions

The LCI modeling of biodiesel combustion in an urban bus is based on the amount of biodiesel required to supply the functional unit of this study (1 bhp-h), and the emissions from the tailpipe of the bus. The amount of biodiesel required is dependent on the fuel economy of the bus engine, and the emissions are dependent on many factors, including the type of engine.

Figure 4.2 and Figure 4.3 show how biodiesel emissions of $NO_x$ and PM10 change with blend level in four-stroke engines while Figure 4.4 and Figure 4.5 show the effect of biodiesel on CO and NMHC emissions in four-stroke engines [55].

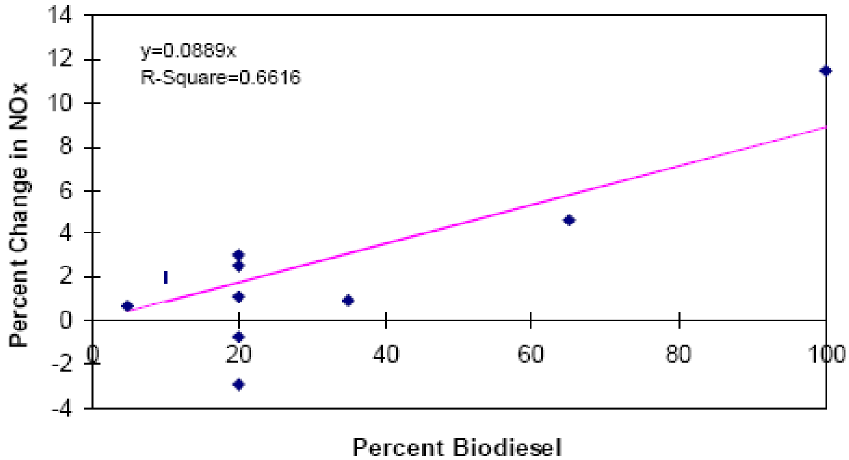


Figure 4.2: Effect of Biodiesel Blend Level on NOx Emissions for Four-Stroke Diesel Engines

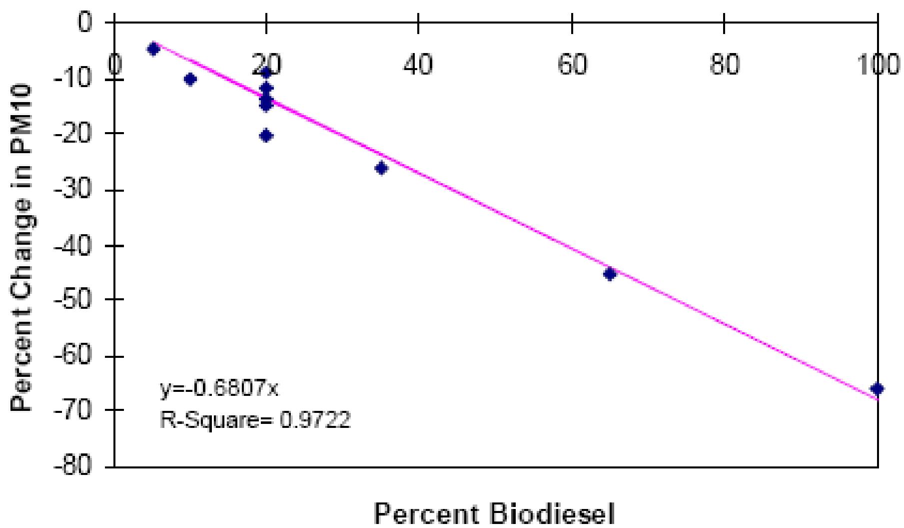


Figure 4.3: Effect of Biodiesel Blend Level on PM10 Emissions for Four-Stroke Engines

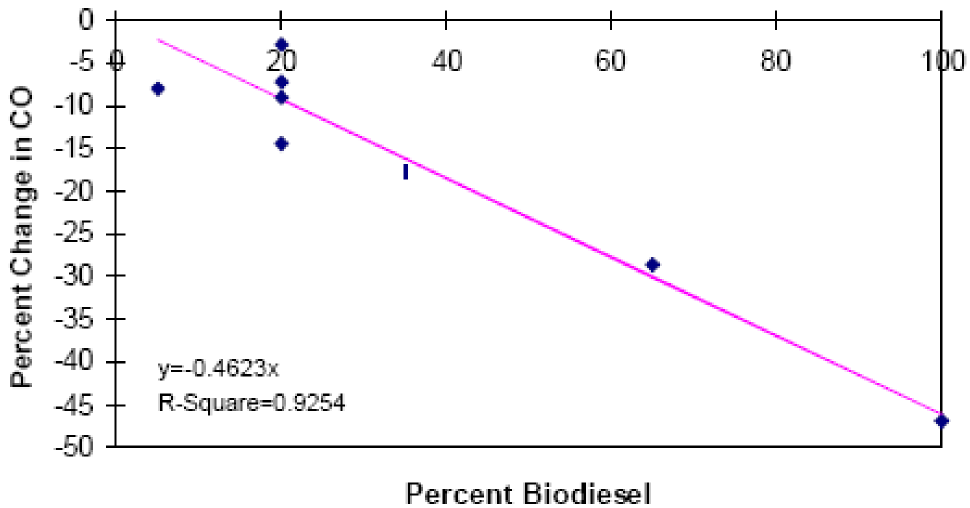


Figure 4.4: Effect of Biodiesel Blend Level on CO Emissions for Four-Stroke Engines

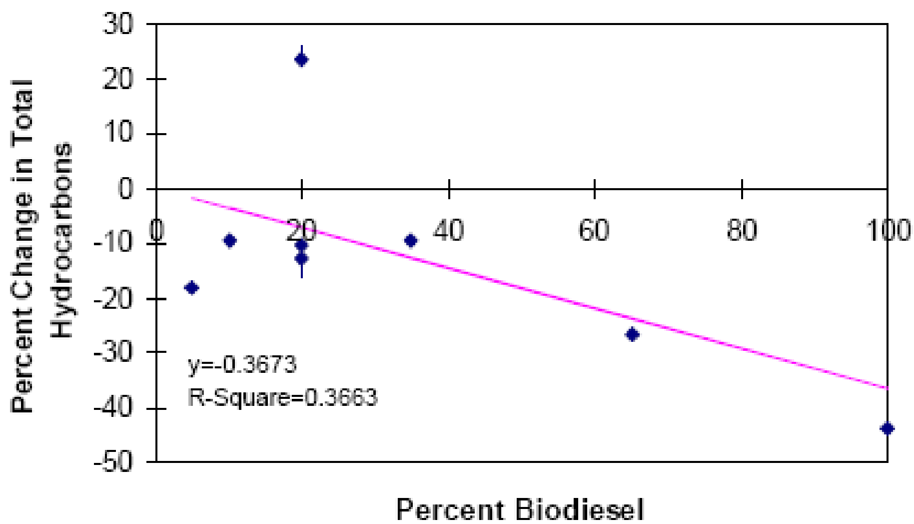


Figure 4.5: Effect of Biodiesel Blend Level on NMHC for Four-Stroke Engines

The distinction is important in identifying the amount of $CO_2$ derived from biomass. This portion of the $CO_2$ emissions does not contribute to total $CO_2$ in the atmosphere because of its recycle in the production of soybean oil. As discussed in the section describing biodiesel production, biodiesel contains 73.2% biomass carbon and 4% fossil-derived carbon. Thus, 73.2% of the total $CO_2$ emitted at the tailpipe is recycled in the agriculture step of the life cycle for biodiesel [55].

As illustrated below, Table 4.9 shows estimates from the LCI model for emissions from petroleum diesel and biodiesel blends based on the linear models described. The change in tailpipe emissions resulting from the biodiesel use is assumed to be linear.

Table 4.9: Effect of Biodiesel on Tailpipe Emissions (g/bhp-h)

| **Emission** | **Diesel Fuel Baseline** | **20% Biodiesel Blend** | **100% Neat Biodiesel** |
|---|---|---|---|
| Carbon Dioxide (fossil) | 633.28 7 | 534.10 | 136.45 |
| Carbon Dioxide (biomass) | 0 | 108.7 | 543.34 |
| Carbon Monoxide | 1.2 | 1.089 | 0.6452 |
| Hydrocarbons | 0.1 | 0.09265 | 0.06327 |
| Particulate Matter (PM10) | 0.08 | 0.0691 | 0.02554 |
| Sulfur Oxides (as SO2) | 0.17 | 0.14 | 0 |
| Nitrogen Oxides (as NO2) | 4.8 | 4.885 | 5.22 |

Source: [55]

#### 4.3.5.2. Diesel Fuel Combustion: Tailpipe Emissions

In this case study, the LCI modeling of combustion of diesel fuel in an urban bus is composed of the amount of diesel fuel required to supply 1 bhp-h, and the emissions from the tailpipe of the bus. It is true that the amount of diesel fuel required depends on the fuel economy of the bus engine. The emissions depend on many factors, including the type of engine, but in this study it has been assumed that they equal the EPA standards for diesel emissions from heavy duty vehicles [55, 56].

# 5. RESULTS OF ASSESSMENT AND DISCUSSION

In this particular study, the main purpose of the results and discussion part is that it allows a side-by-side comparison of biodiesel and petroleum diesel sources of fuels in line with their environmental impact indicators like hydrocarbon, HC, carbon monoxide, CO, particulate matter smaller than 10 microns, PM10, nitrogen oxides $NO_x$, Sulfur oxide, $So_x$, and carbon dioxide, $CO_2$, emissions. Source - to - wheel, StW, mission (g/bhp-h) is defined as the amount of emissions per unit of fuel output in the whole life cycle. It was calculated as the sum of the emissions per unit of fuel output at each stage during the fuel life cycle.

## 5.1. $CO_2$ Emission

### 5.1.1. Biomass-Derived Carbon Contribution

Biomass-derived fuels reduce the net atmospheric carbon in two ways. First, they participate in the relatively rapid biological cycling of carbon to the atmosphere (via engine tailpipe emissions) and from the atmosphere (via photosynthesis). Second, they displace fossil fuels. Fossil fuel combustion releases carbon that took millions of years to be removed from the atmosphere; combustion of biomass fuels participates in a process that allows $CO_2$ to be rapidly recycled to fuel. The net effect of shifting from fossil fuels to biomass-derived fuels is thus to reduce the amount of $CO_2$ in the atmosphere.

The material balance shows all the biomass carbon flows associated with the delivery of 1 bhp-h of engine work (Table 4.10). For illustration, only the case of 100% biodiesel is shown. Lower blend rates proportionately lower the amount of biomass carbon credited as part of the recycled $CO_2$.

Glycerol is removed from the triglycerides as a by-product. Fatty acids are removed as soaps and waste. Finally, carbon released in combustion ends up as $CO_2$, CO, THC, and TPM. As indicated in the Table 4.10, of the 169.34 grams of carbon absorbed in the soybean agriculture stage, only 148.39 grams end up in biodiesel. After accounting for carbon that ends up in other combustion products, 148.05 grams of carbon end up as 543.34 grams of tailpipe $CO_2$. This $CO_2$ is subtracted from the diesel engine emissions as part of the biological recycle of carbon. No credit is taken for the 13% of the carbon that ends up in various byproducts and waste streams [55].

Table 4.10: Biomass Carbon Balance for Biodiesel Life Cycle (g/bhp-h)

| Life Cycle Stage | g carbon per bhp-h | g $CO_2$/bhp-h |
|---|---|---|
| **Soybean Production** | **169.34** | **621.48** |
| Uptake of carbon in triglycerides and fatty acids | 169.34 | 621.48 |
| **Soybean Crushing** | **160.81** | **590.16** |
| Release of carbon via residual oil in meal | (7.73) | (28.36) |
| Release of carbon via waste | (0.81) | (2.97) |
| **Biodiesel Production** | **148.39** | **544.60** |
| Release of carbon via glycerine | (8.26) | (30.32) |
| Release of carbon via wastewater | (2.36) | (8.67) |
| Release of carbon via solid waste | (1.74) | (6.40) |
| Release of carbon in soapstock | (0.05) | (0.17) |
| **Combustion in bus** | | - |
| Release of carbon in biodiesel (total) | (148.39) | (544.60) |
| Release of carbon in $CO_2$ | (148.05) | (543.34) |
| Release of carbon in HC | (0.04) | (0.16) |
| Release of carbon in CO | (0.28) | (1.01) |
| Release of carbon in PM | (0.02) | (0.08) |
| Release of carbon in HC, CO, and PM | (0.34) | (1.26) |

Source: [55]

### 5.1.2. $CO_2$ Emissions: Comparison of Biodiesel and Petroleum Diesel

Table 4.11 and Figure 4.6 shows the summarized result of $CO_2$ flows from the total life cycles of biodiesel and petroleum diesel and the total $CO_2$ released at the tailpipe for each fuel. The dominant source of $CO_2$ for both the petroleum diesel and the biodiesel life cycles is the combustion of fuel in the bus. For petroleum diesel, $CO_2$ emitted from the tailpipe represents 86.54% of the total $CO_2$ emitted across the entire life cycle of the fuel. Most remaining $CO_2$ comes from emissions at the oil refinery, which contribute 9.6% of the total $CO_2$ emissions. For biodiesel, 84.43% of the $CO_2$ emissions occur at the tailpipe. The remaining $CO_2$ comes almost equally from soybean agriculture, soybean crushing, and soy oil conversion to biodiesel.

Table 4.11: Tailpipe Contribution to Total Life Cycle $CO_2$ for Petroleum Diesel and Biodiesel (g $CO_2$/bhp-h)

| Fuel | Total Life Cycle Fossil $CO_2$ | Total Life Cycle Biomass | $CO_2$ Total Life Cycle CO2 | Tailpipe Fossil $CO_2$ | Tailpipe Biomass $CO_2$ | Total Tailpipe $CO_2$ | % of Total $CO_2$ from Tailpipe |
|---|---|---|---|---|---|---|---|
| Petroleum Diesel | 633.28 | 0.00 | 633.28 | 548.02 | 0.00 | 548.02 | 86.54% |
| B100 | 136.45 | 543.34 | 679.78 | 30.62 | 543.34 | 573.96 | 84.43% |

Source: [55]

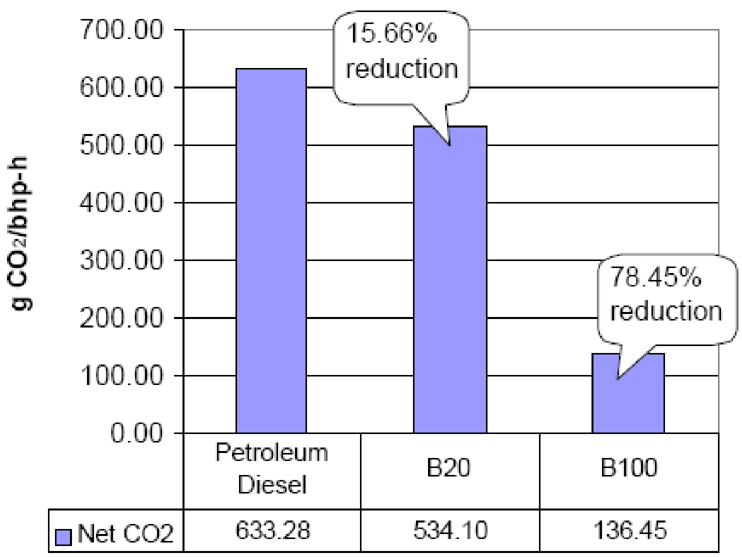


Figure 4.6: Comparison of Net CO2 Life Cycle Emissions for Petroleum Diesel and Biodiesel Blends

Source: [55]

At the tailpipe, biodiesel (most of which is renewable) emits 4.7% more $CO_2$ than petroleum diesel. The nonrenewable portion comes from the methanol. Biodiesel generates 573.96 g/bhp-h compared to 548.02 g/bhp-h for petroleum diesel. The higher $CO_2$ levels result from more complete combustion and the concomitant reductions in other carbon-containing tailpipe emissions. As Figure 4.6 shows, the overall life cycle emissions of $CO_2$ from B100 are 78.45% lower than those of petroleum diesel. The reduction is a direct result of carbon recycling in soybean plants. B20 reduces net $CO_2$ emissions by 15.66%.

## 5.2. Emissions of Regulated air pollutants: CO, $NO_x$, $So_x$, PM10, and NMHC

The emissions of these air pollutants are regulated at the tailpipe for diesel engines. $SO_x$ has no specific tailpipe limits, but it is controlled through the sulfur content of the fuel. Other air emissions included in this study are CH4, benzene, formaldehyde, nitrous oxide ($N_2O$), hydrochloric acid (HCl), hydrofluoric acid (HF), and ammonia. $N_2O$ is associated with agricultural field emissions. HCl and HF are associated with coal combustion in electric power stations. Ammonia is released primarily during fertilizer production.

### 5.2.1. Petroleum Diesel Life Cycle Air Emissions

As data obtained from [55] and tabulated in Appendix – B, Table 7-B, the largest contributor of total hydrocarbon, THC, is the oil refinery, which emits 40.4% of the total life cycle flow. Tailpipe emissions account for 17% of the total in the third place. Transport of foreign crude oil is also a significant contributor, accounting for 10% of the THC released in the life cycle.

Emissions from the end-use of the fuel overwhelm the contributions of CO from any other part of the life cycle. CO from the combustion of diesel in the bus represents 94.5% of the total life cycle emissions.

In the case of the diesel fuel emissions, the TPM includes only PM10, and thus does not reflect emissions of coarser particulates. The engine tailpipe and the oil refinery are the two dominant sources of TPM (37% and 38% of the TPM emissions for the life cycle, respectively).

The largest contribution of SOx emissions comes from the oil refinery, which accounts for 48% of the total. Crude oil production contributes another 23%. Diesel fuel combustion accounts for only 19% of the total $SO_x$ emissions.

As with the CO emissions, $NO_x$ emissions are overwhelmed by the impact of the fuel's end-use. $NO_x$ emissions from the tailpipe of the bus are 96% of the total. Oil refining makes up the bulk of the remaining 4% of $NO_x$ emissions.

### 5.2.2. Biodiesel Life Cycle Air Pollutants Emissions

In this subtopic, the results of B100 is presented considering that blends of biodiesel and petroleum diesel such as B20 and B80 will have emissions that lie between those of diesel and biodiesel, in proportion to the percentage of biodiesel included. According to inventory data obtained from [55], a summary of all of the life cycle air emissions, Appendix – B, Table 8-B, for biodiesel are discussed as under.

As it illustrated in the result table, combustion of biodiesel accounts for only 8% of the THC emissions. The soybean crushing operation contributes 49% of the THC emissions. Soybean agriculture contributes 25% of the total life cycle emissions of THC. The next largest contributor to THC emissions is the soy oil conversion step, representing 17% of the total. Transportation of beans, soy oil and biodiesel contribute very little to the overall life cycle emissions of THC.

As with petroleum diesel, biodiesel life cycle emissions of CO are dominated by end-use combustion of the fuel, which accounts for 77.6% of the total and 73% of the remaining CO is generated in the soybean agriculture step, related to the operation of diesel- and gasoline-powered vehicles.

In case of PM, PM10 from the end-use combustion of biodiesel represent only 18% of the total emissions. Soybean agriculture emissions are split half-and-half between PM10 and unspecified particulates. Half the particulates are from vehicle use and half are associated with the production of fertilizers used on the farm.

Soy oil conversion to biodiesel is responsible for 58% of the emissions. The large contribution of $SO_x$ from this step is related to steam production and indirect emissions associated with methanol production. The soybean crushing step generates $SO_x$ through the consumption of steam, natural gas, and electricity Farming introduces $SO_x$ primarily through consumption of diesel fuel in tractors and consumption of nitrogen fertilizer.

The life cycle $NO_x$ emissions are dominated by emissions from end-use combustion of the fuel. This represents 92% of the total. The remaining emissions track energy consumption for each step, except the agriculture step. Emissions on the farm are disproportionately higher because of the contribution of $NO_x$ from diesel tractor emissions.

### 5.2.3. Comparison of Life Cycle Air Emissions from Biodiesel and Petroleum Diesel

The summary of the overall life cycle air emissions (g/bhp-h) for petroleum diesel, B20, and B100 was given in Table 4.12 below. Therefore, this section provides a discussion of the relative differences in emissions for these three fuels.

Table 4.12: Air Emissions for Petroleum Diesel, B20, and B100 (g/bhp-h)

| **Pollutant** | **Petroleum Diesel** | **B20** | **B100** |
|---|---|---|---|
| $CH_4$ | 0.202839 | 0.201795 | 0.197616 |
| $NO_x$ | 0.006784 | 0.005887 | 0.002297 |
| CO | 1.26981 | 1.18219 | 0.831723 |
| NMHC | 0.131467 | 0.194075 | 0.44451 |
| Hydrocarbons (unspecified) | 0.249053 | 0.229605 | 0.151814 |
| Benzene | 4.24E-05 | 3.43E-05 | 1.84E-06 |
| Formaldehyde | 0.000568 | 0.000459 | 2.48E-05 |
| PM10 | 0.084094 | 0.076589 | 0.046572 |
| Particulates (Unspecified) | 0.130281 | 0.123891 | 0.098329 |
| $SO_x$ | 0.926335 | 0.911458 | 0.851949 |
| $NO_x$ | 5.00856 | 5.1423 | 5.67728 |
| HCl | 0.003164 | 0.00325 | 0.003593 |
| HF | 0.000396 | 0.000383 | 0.000334 |
| $NH_3$ | 3.15E-08 | 0.014694 | 0.073471 |

Source: [55]

As displays in the Table 4.12 above for the three systems, B100 increases THC emissions. The THC includes $CH_4$. As shows in the table, $CH_4$ emissions for B100 and B20 actually drop slightly. The largest contributor to $CH_4$ emissions in the biodiesel life cycle is the production of methanol required in the transesterification. Thus, another opportunity for reducing emissions is to substitute current methanol technology with a renewable process that does not start with natural gas as a feedstock. Likewise, substituting ethanol for methanol would reduce this source of $CH_4$ emissions.

CO emissions for petroleum diesel, B20, and B100 show dramatic differences in life cycle emissions. B100 has lower emissions of CO on a life cycle basis. Because tailpipe emissions dominate both petroleum and biodiesel life cycles, the reductions in CO that occur at the end-use step are key factors in establishing life cycle emissions. TPM drop 32.41% for B100 compared to petroleum diesel. Reductions in PM10 look better.

Even though biodiesel completely eliminates $SO_x$ emissions from the tailpipe, its impact on life cycle emissions is not that great. B100 reduces $SO_x$ emissions compared to petroleum diesel.

As discussed previously, biodiesel increases $NO_x$ emissions in diesel engines unless adjustments are made to the engine, such as retarding of engine timing. The increased level of $NO_x$ emissions for the life cycle versus the tailpipe emissions is caused by diesel fuel use in the agriculture step. Blending biodiesel with petroleum diesel mitigates $NO_x$ emissions. B20 has life cycle emissions of $NO_x$ that are 2.67% higher than petroleum diesel.

# 6. CONCLUSION

Although there is the reality of the problems with the incomplete data availability while studying LCA, it can be possible to conclude the assessment with some points with respect to the possible environmental indicator emissions from the production, processing and utilization of energy. As the study revealed, the overall emission (g/bhp-h) of $CO_2$ to the atmosphere is much more contributed by the life cycle of the petroleum diesel fuel sources of energy, especially through the combustion of the diesel fuel in out bus. On the contrary, the emission (g/bhp-h) of $CO_2$ from the biofuel life cycle is almost insignificant. For instance, the overall life cycle emissions of $CO_2$ from B100 are 78.45% lower than that of petroleum one. In general, biomass-derived fuels reduce the net atmospheric carbon through biological cycling of carbon and displacing fossil fuels, which releases carbon that took millions of years to be removed from the atmosphere. The net effect of shifting from fossil fuels to biomass-derived fuels is thus to reduce the amount of $CO_2$ in the atmosphere.

On the other hand, the assessment line of B100 discovered that there was an increment of the total hydrocarbon emissions when compared with the life cycle of petroleum sources of fuel, diesel fuel. CO emissions, B100 has lower emissions when balanced with B20 and petroleum diesel. Besides, total particulates matter, TPM, and $SO_x$ emissions drop for B100 compared to petroleum diesel. But the production, processing and utilization of biodiesel increases $NO_x$ emissions in relative to the B20 and petroleum based fuel systems. Therefore, blending biodiesel with petroleum diesel mitigates $NO_x$ emissions.

# 7. RECOMMENDATIONS

- Discussions of biomass are often clouded by problems of definition. Several labels are used to refer to the same concept, or tightly overlapping ones: biomass fuels (or biofuels), non-commercial energy, traditional fuels, etc. Thus, there must be an international consensus on common understanding on the naming;
- There is a need of further research so as to avoid the biased previous researchers views on the potential and usage of biomass energy;
- National biomass energy statistics are inadequate both in quantity and quality. Therefore, there is a need of further expansion of the study on the area.
- Some studies have shown that increasing biomass production will force the world to the monoculture agricultural activities that bring negative impact on the biodiversity. But on the contrary, there are also observations that even show increasing production of bioenergy will promote the biodiversity gains resulting from avoided climate change and nitrogen emissions. Therefore, there must be further study that can indicate the correct impact of biomass energy production with respect to biodiversity.
- LCA as it stands has its limitations such as the difficulties in data acquisition and validation, and the misleading results due to the choice of methodology especially on allocation issues. Therefore, there will have to be further studies so as to boost the availability as well as the quality of the data at local, regional, national and international level.

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## ABBREVIATIONS AND NOMENCLATURE

| | |
|---|---|
| **B100** | 100% Biodiesel |
| **B20** | 20% Biodiesel Blend |
| **bhp-h** | brake-horsepower hour |
| **Btoe** | Billion tonnes of oil equivalent |
| **$CO_2$** | Carbon Dioxide |
| **CO** | Carbon Monoxide |
| **DEWA** | Division of Early Warning and Assessment |
| **EIA** | Energy Information Administration |
| **FU** | functional unit |
| **GHE** | Greenhouse Effect |
| **GHG** | Green-House Gases |
| **GWP** | Global Warming Potential |
| **Hp-hr** | horsepower hour |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **IEA** | International Energy Agency |
| **LCA** | Life Cycle Inventory |
| **LCI** | Life Cycle Inventory |
| **LCIA** | Life Cycle Impact Assessment |
| **LPG** | Liquefied Petroleum Gas |
| **MSW** | Municipal Solid Waste |
| **NMHC** | Non-methane Hydrocarbon |
| **$NO_x$** | Nitrogen Oxides |
| **OECD** | Organisation for Economic Co-operation and Development |
| **PM10** | particulate matter of 10 microns or less |
| **$SO_x$** | Sulfur Oxides |
| **StT** | Source-to-Tank |
| **StW** | Source-to-Wheel |
| **THC** | Total Hydrocarbon |
| **TPM** | Total Particulate Matter |
| **TtW** | Tank-to-Wheel |
| **UNEP** | United Nations Environment Programme |
| **UNDP** | United Nations Development Program |
| **VOC** | Volatile Organic Compound |

**APPENDIX -A**

Table 1-A: Biomass Technology Chart

| Technology | Conversion Process Type | Major Biomass Feedstock | Energy or Fuel Produced |
|---|---|---|---|
| Direct Combustion | Thermochemical | wood<br>agricultural waste municipal solid waste residential fuels | heat<br>steam<br>electricity |
| Gasification | Thermochemical | wood<br>agricultural waste municipal solid waste | low or medium-Btu producer gas |
| Pyrolysis | Thermochemical | wood<br>agricultural waste municipal solid waste | synthetic fuel oil (biocrude)<br>charcoal |
| Anaerobic Digestion | Biochemical (anaerobic) | animal manure agricultural waste<br>landfills<br>wastewater | medium Btu gas (methane) |
| Ethanol Production | Biochemical (aerobic) | sugar or starch crops<br>wood waste<br>pulp sludge<br>grass straw | ethanol |
| Biodiesel Production | Chemical | rapeseed<br>soy beans<br>waste vegetable oil<br>animal fats | biodiesel |
| Methanol Production | Thermochemical | wood<br>agricultural waste municipal solid waste | methanol |

Source: Biomass Energy Home Page. Biomass Energy.
http://www.oregon.gov/ENERGY/RENEW/Biomass/BiomassHome.shtml#chart

Table 2-A: Commonly Used Life Cycle Impact Categories

| Impact Category | Scale | Examples of LCI Data (i.e. classification) | Common Possible Characterization Factor | Description of Characterization Factor |
|---|---|---|---|---|
| Global Warming | Global | Carbon Dioxide ($CO_2$)<br>Nitrogen Dioxide ($NO_2$)<br>Methane ($CH_4$)<br>Chlorofluorocarbons (CFCs)<br>Hydrochlorofluorocarbons (HCFCs)<br>Methyl Bromide ($CH_3Br$) | Global Warming Potential | Converts LCI data to carbon dioxide ($CO_2$) equivalents Note: global warming potentials can be 50, 100, or 500 year potentials. |
| Stratospheric Ozone Depletion | Global | Chlorofluorocarbons (CFCs)<br>Hydrochlorofluorocarbons (HCFCs)<br>Halons<br>Methyl Bromide ($CH_3Br$) | Ozone Depleting Potential | Converts LCI data to trichlorofluoromethane (CFC-11) equivalents. |
| Acidification | Regional<br>Local | Sulfur Oxides (SOx)<br>Nitrogen Oxides (NOx)<br>Hydrochloric Acid (HCL)<br>Hydroflouric Acid (HF)<br>Ammonia ($NH_4$) | Acidification Potential | Converts LCI data to hydrogen ($H^+$) ion equivalents. |
| Eutrophication | Local | Phosphate ($PO_4$)<br>Nitrogen Oxide (NO)<br>Nitrogen Dioxide ($NO_2$)<br>Nitrates<br>Ammonia ($NH_4$) | Eutrophication Potential | Converts LCI data to phosphate ($PO_4$) equivalents. |
| Photochemical Smog | Local | Non-methane hydrocarbon (NMHC) | Photochemical Oxident Creation Potential | Converts LCI data to ethane ($C_2H_6$) equivalents. |
| Terrestrial Toxicity | Local | Toxic chemicals with a reported lethal concentration to rodents | LC50 | Converts LC50 data to equivalents; uses multi-media modeling, exposure pathways. |
| Aquatic Toxicity | Local | Toxic chemicals with a reported lethal concentration to fish | LC50 | Converts LC50 data to equivalents; uses multi-media modeling, exposure pathways. |
| Human Health | Global<br>Regional<br>Local | Total releases to air, water, and soil. | LC50 | Converts LC50 data to equivalents; uses multi-media modeling, exposure pathways. |

| | | | | |
|---|---|---|---|---|
| Resource Depletion | Global Regional Local | Quantity of minerals used Quantity of fossil fuels used | Resource Depletion Potential | Converts LCI data to a ratio of quantity of resource used versus quantity of resource left in reserve. |
| Land Use | Global Regional Local | Quantity disposed of in a landfill or other land modifications | Land Availabilit y | Converts mass of solid waste into volume using an estimated density. |
| Water Use | Regional Local | Water used or consumed | Water Shortage Potential | Converts LCI data to a ratio of quantity of water used versus quantity of resource left in reserve. |

Source: [52]

## APPENDIX –B

Table 1-B: LCI Results for Soybean Transport (for 1 kg of soybeans)

| | Units | Transport of Soybeans to Crusher | Truck Loading | Truck Transport |
|---|---|---|---|---|
| Raw Materials | | | | |
| Coal (in ground) | kg | 0.0001062 | 2.07E-07 | 0.000106 |
| Oil (in ground) | kg | 0.0033994 | 7.11E-09 | 0.0033994 |
| Natural Gas (in ground) | kg | 0.0002919 | 2.27E-08 | 0.0002919 |
| Uranium (U, ore) | kg | 2.53E-09 | 4.95E-12 | 2.53E-09 |
| Phosphate Rock (in ground) | kg | 0 | 0 | 0 |
| Potash ($K_2O$, in ground) | kg | 0 | 0 | 0 |
| Perlite ($SiO_2$, ore) | kg | 7.73E-07 | 0 | 7.73E-07 |
| Limestone ($CaCO_3$, in ground) | kg | 2.02E-05 | 3.94E-08 | 2.01E-05 |
| Sodium Chloride (NaCl) | kg | 0 | 0 | 0 |
| Water Used (total) | liter | 0.0004731 | 6.34E-09 | 0.0004731 |
| Air Emissions | | | | |
| Carbon Dioxide ($CO_2$, fossil) | g | 11.3255 | 0.000640 | 11.3249 |
| Carbon Dioxide ($CO_2$, biomass) | g | 0 | 0 | 0 |
| Methane ($CH_4$) | g | 0.0040585 | 1.54E-06 | 0.0040569 |
| Nitrous Oxide ($N_2O$) | g | 0.0011253 | 1.18E-08 | 0.0011253 |
| Carbon Monoxide (CO) | g | 0.0384142 | 1.42E-07 | 0.0384141 |
| Hydrocarbons (except methane) | g | 0.0082712 | 5.19E-09 | 0.0082712 |
| Hydrocarbons (unspecified) | g | 0.00448 | 1.69E-08 | 0.00448 |
| Benzene | g | 7.63E-07 | 0 | 7.63E-07 |
| Formaldehyde | g | 1.02E-05 | 3.33E-17 | 1.02E-05 |
| Particulates (PM10) | g | 0.0128418 | 0 | 0.0128418 |
| Particulates (unspecified) | g | 0.00242 | 2.91E-06 | 0.0024171 |
| Sulfur Oxides ($SO_x$ as $SO_2$) | g | 0.0166862 | 3.65E-06 | 0.0166825 |
| Nitrogen Oxides ($NO_x$ as $NO_2$) | g | 0.106559 | 1.99E-06 | 0.106557 |
| Hydrogen Chloride (HCl) | g | 5.70E-05 | 1.11E-07 | 5.69E-05 |
| Hydrogen Fluoride (HF) | g | 7.13E-06 | 1.39E-08 | 7.12E-06 |
| Ammonia ($NH_3$) | g | 1.45E-08 | 7.60E-13 | 1.45E-08 |
| Water Emissions | | | | |
| Agrochemicals (unspecified) | g | 0 | 0 | 0 |
| BOD5 (Biochemical Oxygen Demand) | g | 0.0022801 | 2.67E-09 | 0.0022801 |
| COD (Chemical Oxygen Demand) | g | 0.0192927 | 2.26E-08 | 0.0192927 |
| Metals (unspecified) | g | 9.43E-05 | 1.69E-10 | 9.43E-05 |
| Ammonia ($NH_4$+, $NH_3$, as N) | g | 0.0003334 | 6.60E-10 | 0.0003334 |
| Nitrates ($NO_3$-) | g | 9.03E-08 | 1.77E-10 | 9.02E-08 |
| Solid Waste (hazardous) | kg | 7.42E-06 | 8.69E-12 | 7.42E-06 |
| Solid Waste (non-hazardous) | kg | 5.09E-05 | 7.56E-08 | 5.08E-05 |
| Total Primary Energy | MJ | 0.162186 | 1.02E-05 | 0.162175 |
| Fossil Energy | MJ | 0.162023 | 9.83E-06 | 0.162014 |

Table 2-B: LCI Results for Soybean Crushing (for 1 kg of soybean oil)

| | Units | Total Soybean Crushing | Natural Gas Use | Steam Production | Electricity Production | Hexane Production | Direct from Crushing |
|---|---|---|---|---|---|---|---|
| Raw Materials | | | | | | | |
| Coal (in ground) | kg | 0.018566 | 4.19E-08 | 4.33E-08 | 0.0185663 | 1.82E-09 | 0 |
| Oil (in ground) | kg | 0.002991 | 5.47E-08 | 5.65E-08 | 0.0006388 | 0.0023523 | 0 |
| Natural Gas (in ground) | kg | 0.050306 | 0.02374 | 0.0245249 | 0.0020365 | 1.50E-08 | 0 |
| Uranium (U, ore) | kg | 4.45E-07 | 1.00E-12 | 1.04E-12 | 4.45E-07 | 0 | 0 |
| Phosphate Rock (in ground) | kg | 0 | 0 | 0 | 0 | 0 | 0 |
| Potash ($K_2O$, in ground) | kg | 0 | 0 | 0 | 0 | 0 | 0 |
| Perlite ($SiO_2$, ore) | kg | 0 | 0 | 0 | 0 | 0 | 0 |
| Limestone ($CaCO_3$, in ground) | kg | 0.00354 | 7.95E-09 | 8.21E-09 | 0.0035403 | 0 | 0 |
| Sodium Chloride (NaCl) | kg | 0 | 0 | 0 | 0 | 0 | 0 |
| Water Used (total) | liter | 0.004097 | 6.74E-09 | 6.96E-09 | 0.0005701 | 0 | 0.00353 |
| Air Emissions | | | | | | | |
| Carbon Dioxide ($CO_2$, fossil) | g | 200.328 | 69.9311 | 72.2291 | 57.519 | 0.649155 | 0 |
| Carbon Dioxide ($CO_2$, biomass) | g | na | na | na | na | na | na |
| Methane ($CH_4$) | g | 0.37326 | 0.1154 | 0.119192 | 0.138668 | 9.77E-08 | 0 |
| Nitrous Oxide ($N_2O$) | g | 0.001814 | 0.00032 | 0.0003303 | 0.0010621 | 0.0001015 | 0 |
| Carbon Monoxide (CO) | g | 0.060743 | 0.02334 | 0.0241107 | 0.0127441 | 0.0005446 | 0 |
| Hydrocarbons (except methane) | g | 1.86624 | 0.0008 | 0.0008255 | 0.0004664 | 0.0147412 | 1.84941 |
| Hydrocarbons (unspecified) | g | 0.001518 | 4.77E-07 | 4.93E-07 | 0.0015171 | 0 | 0 |
| Benzene | g | 0 | 0 | 0 | 0 | 0 | 0 |
| Formaldehyde | g | 3.00E-12 | 6.66E-17 | 6.88E-17 | 3.00E-12 | 0 | 0 |
| Particulates (PM10) | g | 0.003411 | 0.00168 | 0.001733 | 0 | 0 | 0 |
| Particulates (unspecified) | g | 0.261845 | 4.26E-05 | 4.40E-05 | 0.261279 | 0.00048 | 0 |
| Sulfur Oxides ($SO_x$ as $SO_2$) | g | 1.43078 | 0.53839 | 0.556078 | 0.327924 | 0.0083909 | 0 |
| Nitrogen Oxides ($NO_x$ as $NO_2$) | g | 0.375724 | 0.09502 | 0.0981413 | 0.178429 | 0.0041355 | 0 |
| Hydrogen Chloride (HCl) | g | 0.010019 | 2.26E-08 | 2.34E-08 | 0.0100188 | 0 | 0 |
| Hydrogen Fluoride (HF) | g | 0.001252 | 2.83E-09 | 2.92E-09 | 0.0012524 | 0 | 0 |
| Ammonia ($NH_3$) | g | 4.62E-05 | 1.30E-11 | 1.35E-11 | 6.83E-08 | 4.62E-05 | 0 |
| Water Emissions | | | | | | | |
| Agrochemicals (unspecified) | g | 0 | 0 | 0 | 0 | 0 | 0 |
| BOD5 (Biochemical Oxygen Demand) | g | 0.000253 | 2.83E-08 | 2.92E-08 | 0.0002399 | 1.30E-05 | 0 |
| COD (Chemical Oxygen Demand) | g | 0.002069 | 2.39E-07 | 2.47E-07 | 0.0020298 | 3.91E-05 | 0 |
| Metals (unspecified) | g | 1.52E-05 | 1.39E-09 | 1.43E-09 | 1.52E-05 | 0 | 0 |
| Ammonia ($NH_4$+, $NH_3$, as N) | g | 5.93E-05 | 4.19E-09 | 4.33E-09 | 5.93E-05 | 0 | 0 |
| Nitrates ($NO_3$-) | g | 1.59E-05 | 3.58E-11 | 3.70E-11 | 1.59E-05 | 0 | 0 |
| Solid Waste (hazardous) | kg | 7.81E-07 | 9.20E-11 | 9.51E-11 | 7.81E-07 | 0 | 0 |
| Solid Waste (nonhazardous) | kg | 0.015261 | 9.71E-08 | 1.00E-07 | 0.0067949 | 3.41E-06 | 0.00846 |
| Total Primary Energy | MJ | 3.47122 | 1.23473 | 1.2753 | 0.912304 | 0.048883 | 0 |
| Fossil Energy | MJ | 3.44276 | 1.23473 | 1.2753 | 0.883847 | 0.048883 | 0 |

Table 3-B: LCI Results for Soybean Oil Transport (for kg soybean oil)

| | Units | Soy Oil Transport (Total) | Railcar Loading | Rail Transportation |
|---|---|---|---|---|
| Raw Materials | | | | |
| Coal (in ground) | kg | 0.000203966 | 4.13E-07 | 0.000203553 |
| Oil (in ground) | kg | 0.00652741 | 1.42E-08 | 0.0065274 |
| Natural Gas (in ground) | kg | 0.000560541 | 4.53E-08 | 0.000560496 |
| Uranium (U, ore) | kg | 4.86E-09 | 9.90E-12 | 4.85E-09 |
| Phosphate Rock (in ground) | kg | 0 | 0 | 0 |
| Potash ($K_2O$, in ground) | kg | 0 | 0 | 0 |
| Perlite ($SiO_2$, ore) | kg | 1.48E-06 | 0 | 1.48E-06 |
| Limestone ($CaCO_3$, in ground) | kg | 3.87E-05 | 7.88E-08 | 3.86E-05 |
| Sodium Chloride (NaCl) | kg | 0 | 0 | 0 |
| Water Used (total) | liter | 0.000908433 | 1.27E-08 | 0.00090842 |
| Air Emissions | | | | |
| Carbon Dioxide ($CO_2$, fossil) | g | 21.9774 | 0.00127989 | 21.9761 |
| Carbon Dioxide ($CO_2$, biomass) | g | 0 | 0 | 0 |
| Methane ($CH_4$) | g | 0.00790308 | 3.09E-06 | 0.0079 |
| Nitrous Oxide ($N_2O$) | g | 0.000234333 | 2.36E-08 | 0.000234309 |
| Carbon Monoxide (CO) | g | 0.0733493 | 2.84E-07 | 0.073349 |
| Hydrocarbons (except methane) | g | 0.00109545 | 1.04E-08 | 0.00109544 |
| Hydrocarbons (unspecified) | g | 0.0254744 | 3.38E-08 | 0.0254744 |
| Benzene | g | 1.46E-06 | 0 | 1.46E-06 |
| Formaldehyde | g | 1.96E-05 | 6.67E-17 | 1.96E-05 |
| Particulates (PM10) | g | 0.00888317 | 0 | 0.00888317 |
| Particulates (unspecified) | g | 0.00464701 | 5.81E-06 | 0.00464119 |
| Sulfur Oxides ($SO_x$ as $SO_2$) | g | 0.0319926 | 7.30E-06 | 0.0319853 |
| Nitrogen Oxides ($NO_x$ as $NO_2$) | g | 0.362504 | 3.97E-06 | 0.3625 |
| Hydrogen Chloride (HCl) | g | 0.000109523 | 2.23E-07 | 0.000109301 |
| Hydrogen Fluoride (HF) | g | 1.37E-05 | 2.79E-08 | 1.37E-05 |
| Ammonia ($NH_3$) | g | 2.79E-08 | 1.52E-12 | 2.79E-08 |
| Water Emissions | | | | |
| Agrochemicals (unspecified) | g | 0 | 0 | 0 |
| BOD5 (Biochemical Oxygen Demand) | g | 0.00437806 | 5.34E-09 | 0.00437805 |
| COD (Chemical Oxygen Demand) | g | 0.0370451 | 4.52E-08 | 0.037045 |
| Metals (unspecified) | g | 0.000181066 | 3.37E-10 | 0.000181066 |
| Ammonia ($NH_4$+, $NH_3$, as N) | g | 0.000640132 | 1.32E-09 | 0.000640131 |
| Nitrates ($NO_3$-) | g | 1.73E-07 | 3.53E-10 | 1.73E-07 |
| Solid Waste (hazardous) | kg | 1.42E-05 | 1.74E-11 | 1.42E-05 |
| Solid Waste (nonhazardous) | kg | 9.77E-05 | 1.51E-07 | 9.76E-05 |
| Total Primary Energy | MJ | 0.311422 | 2.03E-05 | 0.311402 |
| Fossil Energy | MJ | 0.311111 | 1.97E-05 | 0.311091 |

Table 4-B: LCI Results for Biodiesel Transportation (for kg of biodiesel)

| | Units | Biodiesel Transportation | Truck Loading | Truck Transport |
|---|---|---|---|---|
| Raw Materials | | | | |
| Coal (in ground) | kg | 0.000106422 | 6.20E-07 | 0.000105802 |
| Oil (in ground) | kg | 0.00339281 | 2.13E-08 | 0.00339279 |
| Natural Gas (in ground) | kg | 0.0002914 | 6.80E-08 | 0.000291332 |
| Uranium (U, ore) | kg | 2.54E-09 | 1.49E-11 | 2.52E-09 |
| Phosphate Rock (in ground) | kg | 0 | 0 | 0 |
| Potash ($K_2O$, in ground) | kg | 0 | 0 | 0 |
| Perlite ($SiO_2$, ore) | kg | 7.71E-07 | 0 | 7.71E-07 |
| Limestone ($CaCO_3$, in ground) | kg | 2.02E-05 | 1.18E-07 | 2.01E-05 |
| Sodium Chloride (NaCl) | kg | 0 | 0 | 0 |
| Water Used (total) | liter | 0.000472194 | 1.90E-08 | 0.000472175 |
| Air Emissions | | | | |
| Carbon Dioxide ($CO_2$, fossil) | g | 11.3047 | 0.00191984 | 11.3028 |
| Carbon Dioxide ($CO_2$, biomass) | g | 0 | 0 | 0 |
| Methane ($CH_4$) | g | 0.00405364 | 4.63E-06 | 0.00404901 |
| Nitrous Oxide ($N_2O$) | g | 0.00112314 | 3.54E-08 | 0.0011231 |
| Carbon Monoxide (CO) | g | 0.0383396 | 4.25E-07 | 0.0383392 |
| Hydrocarbons (except methane) | g | 0.00825505 | 1.56E-08 | 0.00825503 |
| Hydrocarbons (unspecified) | g | 0.00447132 | 5.18E-08 | 0.00447127 |
| Benzene | g | 7.61E-07 | 0 | 7.61E-07 |
| Formaldehyde | g | 1.02E-05 | 1.00E-16 | 1.02E-05 |
| Particulates (PM10) | g | 0.0128168 | 0 | 0.0128168 |
| Particulates (unspecified) | g | 0.0024211 | 8.72E-06 | 0.00241238 |
| Sulfur Oxides ($SO_x$ as $SO_2$) | g | 0.0166609 | 1.09E-05 | 0.01665 |
| Nitrogen Oxides ($NO_x$ as $NO_2$) | g | 0.106355 | 5.96E-06 | 0.106349 |
| Hydrogen Chloride (HCl) | g | 5.71E-05 | 3.34E-07 | 5.68E-05 |
| Hydrogen Fluoride (HF) | g | 7.14E-06 | 4.18E-08 | 7.10E-06 |
| Ammonia ($NH_3$) | g | 1.45E-08 | 2.28E-12 | 1.45E-08 |
| Water Emissions | | | | |
| Agrochemicals (unspecified) | g | 0 | 0 | 0 |
| BOD5 (Biochemical Oxygen Demand) | g | 0.00227562 | 8.01E-09 | 0.00227561 |
| COD (Chemical Oxygen Demand) | g | 0.0192552 | 6.77E-08 | 0.0192551 |
| Metals (unspecified) | g | 9.41E-05 | 5.06E-10 | 9.41E-05 |
| Ammonia ($NH_4$+, $NH_3$, as N) | g | 0.000332726 | 1.98E-09 | 0.000332725 |
| Nitrates ($NO_3$-) | g | 9.05E-08 | 5.30E-10 | 9.00E-08 |
| Solid Waste (hazardous) | kg | 7.41E-06 | 2.61E-11 | 7.41E-06 |
| Solid Waste (nonhazardous) | kg | 5.09E-05 | 2.27E-07 | 5.07E-05 |
| Total Primary Energy | MJ | 0.16189 | 3.05E-05 | 0.161859 |
| Fossil Energy | MJ | 0.161727 | 2.95E-05 | 0.161698 |

Table 5-B: LCI Results for Domestic Crude Oil Extraction (for 1 kg of crude oil)

| | Units | Domestic Crude Oil Production | Onshore Conventional Extraction | Conventional Offshore Extraction | Onshore Advanced Extraction |
|---|---|---|---|---|---|
| Raw Materials | | | | | |
| Coal (in ground) | kg | 0.01306 | 0.00968 | 0.00000 | 0.00338 |
| Oil (in ground) | kg | 1.02145 | 0.69551 | 0.21500 | 0.11094 |
| Natural Gas (in ground) | kg | 0.06525 | 0.00436 | 0.00307 | 0.05782 |
| Uranium (U, ore) | kg | 0.00000 | 0.00000 | 0.00000 | 0.00000 |
| Phosphate Rock (in ground) | kg | 0.00000 | 0.00000 | 0.00000 | 0.00000 |
| Potash ($K_2O$, in ground) | kg | 0.00000 | 0.00000 | 0.00000 | 0.00000 |
| Perlite ($SiO_2$, ore) | kg | 0.00000 | 0.00000 | 0.00000 | 0.00000 |
| Limestone ($CaCO_3$, in ground) | kg | 0.00249 | 0.00184 | 0.00000 | 0.00065 |
| Sodium Chloride (NaCl) | kg | 0.00000 | 0.00000 | 0.00000 | 0.00000 |
| Water Used (total) | liter | 0.22170 | 0.00030 | 0.00000 | 0.22140 |
| Air Emissions | | | | | |
| Carbon Dioxide ($CO_2$, fossil) | g | 46.63270 | 38.93490 | 8.98844 | -1.29060 |
| Carbon Dioxide ($CO_2$, biomass) | g | 0.00000 | 0.00000 | 0.00000 | 0.00000 |
| Methane ($CH_4$) | g | 0.49569 | 0.20565 | 0.01859 | 0.27145 |
| Nitrous Oxide ($N_2O$) | g | 0.04432 | 0.00056 | 0.00022 | 0.04354 |
| Carbon Monoxide (CO) | g | 0.06668 | 0.02833 | 0.00883 | 0.02953 |
| Hydrocarbons (except methane) | g | 0.14941 | 0.11073 | 0.01510 | 0.02357 |
| Hydrocarbons (unspecified) | g | 0.00107 | 0.00079 | 0.00000 | 0.00028 |
| Benzene | g | 0.00023 | 0.00017 | 0.00003 | 0.00004 |
| Formaldehyde | g | 0.00303 | 0.00000 | 0.00303 | 0.00000 |
| Particulates (PM10) | g | 0.00212 | 0.00003 | 0.00017 | 0.00192 |
| Particulates (unspecified) | g | 0.18387 | 0.13616 | 0.00000 | 0.04771 |
| Sulfur Oxides ($SO_x$ as $SO_2$) | g | 1.40728 | 0.26233 | 0.00093 | 1.14402 |
| Nitrogen Oxides ($NO_x$ as $NO_2$) | g | 0.26273 | 0.09849 | 0.00977 | 0.15447 |
| Hydrogen Chloride (HCl) | g | 0.00705 | 0.00522 | 0.00000 | 0.00183 |
| Hydrogen Fluoride (HF) | g | 0.00088 | 0.00065 | 0.00000 | 0.00023 |
| Ammonia ($NH_3$) | g | 0.00000 | 0.00000 | 0.00000 | 0.00000 |
| Agrochemicals (unspecified) | g | 0.00000 | 0.00000 | 0.00000 | 0.00000 |
| BOD5 (Biochemical Oxygen Demand) | g | 0.00017 | 0.00013 | 0.00000 | 0.00004 |
| COD (Chemical Oxygen Demand) | g | 0.00143 | 0.00106 | 0.00000 | 0.00037 |
| Metals (unspecified) | g | 0.01953 | 0.00348 | 0.01605 | 0.00000 |
| Ammonia ($NH_4$+ $NH_3$ as N) | g | 0.00004 | 0.00003 | 0.00000 | 0.00001 |
| Nitrates ($NO_3$-) | g | 0.00001 | 0.00001 | 0.00000 | 0.00000 |
| Solid Waste (hazardous) | kg | 0.00000 | 0.00000 | 0.00000 | 0.00000 |
| Solid Waste (non-hazardous) | kg | 0.00479 | 0.00355 | 0.00000 | 0.00124 |
| Total Primary Energy | MJ | 47.04950 | 30.00660 | 9.17476 | 7.86822 |
| Fossil Energy | MJ | 47.02950 | 29.99170 | 9.17476 | 7.86304 |
| Fuel Energy | MJ | 2.96633 | 0.65396 | 0.66676 | 1.64561 |

Table 6-B: LCI Results for Diesel Fuel Transportation (for 1 kg of diesel fuel)

| | Units | Diesel Fuel Transport (Total) | Truck Loading | Truck Transport | Pipeline Transport |
|---|---|---|---|---|---|
| Raw Materials | | | | | |
| Coal (in ground) | kg | 0.00235 | 6.20E-07 | 0.00011 | 0.00224 |
| Oil (in ground) | kg | 0.00347 | 2.13E-08 | 0.00339 | 7.72E-05 |
| Natural Gas (in ground) | kg | 0.00054 | 6.80E-08 | 0.00029 | 0.00025 |
| Uranium (U, ore) | kg | 5.63E-08 | 1.49E-11 | 2.52E-09 | 5.38E-08 |
| Phosphate Rock (in ground) | kg | 0 | 0 | 0 | 0 |
| Potash ($K_2O$, in ground) | kg | 0 | 0 | 0 | 0 |
| Perlite ($SiO_2$, ore) | kg | 7.71E-07 | 0 | 7.71E-07 | 0 |
| Limestone ($CaCO_3$, in ground) | kg | 0.000448 | 1.18E-07 | 2.01E-05 | 0.000428 |
| Sodium Chloride (NaCl) | kg | 0 | 0 | 0 | 0 |
| Water Used (total) | liter | 0.000541 | 1.90E-08 | 0.000472 | 6.89E-05 |
| Air Emissions | | | | | |
| Carbon Dioxide ($CO_2$, fossil) | g | 18.259 | 0.001920 | 11.3028 | 6.95429 |
| Carbon Dioxide ($CO_2$, biomass) | g | 0 | 0 | 0 | 0 |
| Methane ($CH_4$) | g | 0.020819 | 4.63E-06 | 0.00405 | 0.01677 |
| Nitrous Oxide ($N_2O$) | g | 0.001252 | 3.54E-08 | 0.00112 | 0.00013 |
| Carbon Monoxide (CO) | g | 0.039881 | 4.25E-07 | 0.03834 | 0.00154 |
| Hydrocarbons (except methane) | g | 0.008311 | 1.56E-08 | 0.00826 | 5.64E-05 |
| Hydrocarbons (unspecified) | g | 0.006885 | 0.002223 | 0.00448 | 0.0001834 |
| Benzene | g | 7.61E-07 | 0 | 7.61E-07 | 0 |
| Formaldehyde | g | 1.02E-05 | 1.00E-16 | 1.02E-05 | 3.62E-13 |
| Particulates (PM10) | g | 0.012817 | 0 | 0.012817 | 0 |
| Particulates (unspecified) | g | 0.034011 | 8.72E-06 | 0.002412 | 0.0315897 |
| Sulfur Oxides ($SO_x$ as $SO_2$) | g | 0.056308 | 1.09E-05 | 0.01665 | 0.0396474 |
| Nitrogen Oxides ($NO_x$ as $NO_2$) | g | 0.127928 | 5.96E-06 | 0.106349 | 0.0215728 |
| Hydrogen Chloride (HCl) | g | 0.001268 | 3.34E-07 | 5.68E-05 | 0.0012113 |
| Hydrogen Fluoride (HF) | g | 0.000159 | 4.18E-08 | 7.10E-06 | 0.0001514 |
| Ammonia ($NH_3$) | g | 2.27E-08 | 2.28E-12 | 1.45E-08 | 8.26E-09 |
| Water Emissions | | | | | |
| Agrochemicals (unspecified) | g | 0 | 0 | 0 | 0 |
| BOD5 (Biochemical Oxygen Demand) | g | 0.002305 | 8.01E-09 | 0.002276 | 2.90E-05 |
| COD (Chemical Oxygen Demand) | g | 0.019501 | 6.77E-08 | 0.019255 | 0.0002454 |
| Metals (unspecified) | g | 9.59E-05 | 5.06E-10 | 9.41E-05 | 1.83E-06 |
| Ammonia ($NH_4$+, $NH_3$, as N) | g | 0.000340 | 1.98E-09 | 0.00033272 | 7.17E-06 |
| Nitrates ($NO_3$-) | g | 2.01E-06 | 5.30E-10 | 9.00E-08 | 1.92E-06 |
| Solid Waste (hazardous) | kg | 7.50E-06 | 2.61E-11 | 7.41E-06 | 9.44E-08 |
| Solid Waste (non-hazardous) | kg | 0.00087 | 2.27E-07 | 5.07E-05 | 0.0008215 |
| Total Primary Energy | MJ | 0.27219 | 3.05E-05 | 0.161859 | 0.110301 |
| Fossil Energy | MJ | 0.26859 | 2.95E-05 | 0.161698 | 0.106861 |
| Fuel Energy per kg of Diesel | MJ | 42.5 | - | - | - |

Table 7-B: LCI of Air Emissions for Petroleum Diesel (g/bhp-h)

| Air Pollutant | Domestic Crude Oil Production | Foreign Crude Oil Production | Domestic Crude Transport | Foreign Crude Transport | Crude Oil Refining | Diesel Fuel Transport | Diesel Use | Total |
|---|---|---|---|---|---|---|---|---|
| $NH_3$ | 4.39E-09 | 3.84E-09 | 1.85E-09 | 6.69E-09 | 1.08E-08 | 3.92E-09 | 0.00E+00 | 3.15E-08 |
| Benzene | 2.14E-05 | 2.03E-05 | 4.15E-08 | 4.00E-07 | 1.45E-07 | 1.31E-07 | 0.00E+00 | 4.24E-05 |
| CO | 0.006091 | 0.011088 | 0.001064 | 0.001546 | 0.043144 | 0.006875 | 1.200000 | 1.269810 |
| Formaldehyde | 0.000277 | 0.000281 | 0.000001 | 0.000005 | 0.000002 | 0.000002 | 0.000000 | 0.000568 |
| NMHC | 0.013648 | 0.015506 | 0.000103 | 0.000306 | 0.000470 | 0.001433 | 0.100000 | 0.131467 |
| Hydrocarbons (unspecified) [109] | 9.76E-05 | 8.54E-05 | 1.02E-02 | 5.53E-02 | 1.82E-01 | 1.19E-03 | 0.00E+00 | 2.49E-01 |
| Hydrogen Chloride | 0.000644 | 0.000564 | 0.000180 | 0.000201 | 0.001357 | 0.000219 | 0.000000 | 0.003164 |
| Hydrogen Fluoride (HF) | 8.05E-05 | 7.05E-05 | 2.25E-05 | 2.51E-05 | 1.70E-04 | 2.73E-05 | 0.00E+00 | 3.96E-04 |
| $CH_4$ | 0.045281 | 0.093621 | 0.002656 | 0.004278 | 0.053414 | 0.003589 | 0.000000 | 0.202839 |
| $NO_x$ | 0.024000 | 0.015720 | 0.006651 | 0.010242 | 0.129891 | 0.022055 | 4.800000 | 5.008558 |
| $N_2O$ | 0.004049 | 0.001149 | 0.000034 | 0.000082 | 0.001255 | 0.000216 | 0.000000 | 0.006784 |
| PM10 | 0.000194 | 0.000066 | 0.000159 | 0.000006 | 0.001459 | 0.002210 | 0.080000 | 0.084094 |
| Particulates (unspecified) | 0.016796 | 0.014704 | 0.004956 | 0.008848 | 0.079114 | 0.005864 | 0.000000 | 0.130281 |
| $SO_x$ | 0.128553 | 0.083197 | 0.011121 | 0.080880 | 0.440475 | 0.009708 | 0.172402 | 0.926335 |

Table 8-B: LCI Air Emissions for Biodiesel (g/bhp-h)

| Air Pollutant | Soybean Agriculture | Soybean Transport | Soybean Crushing | Soybean Oil Transport | Soybean Oil Conversion | Biodiesel Transport | Biodiesel Use | Total |
|---|---|---|---|---|---|---|---|---|
| $NH_3$ | 0.0734632 | 2.2735E-09 | 8.02E-06 | 4.83E-09 | 5.4472E-09 | 2.94E-09 | 0 | 0.073471 |
| Benzene | 1.313E-06 | 1.195E-07 | 0 | 2.54E-07 | 0 | 1.54E-07 | 0 | 1.84E-06 |
| CO | 0.136856 | 0.00602014 | 0.01054 | 0.012727 | 0.0125584 | 0.007782 | 0.64524 | 0.831723 |
| Formaldehyde | 1.78E-05 | 1.60E-06 | 5.20E-13 | 3.40E-06 | 2.38E-13 | 2.07E-06 | 0 | 2.48E-05 |
| NMHC) | 0.0539448 | 0.00129623 | 0.323816 | 0.00019 | 0.00031698 | 0.001676 | 0.06327 | 0.44451 |
| Hydrocarbons (unspecified) 111 | 0.11591 | 0.00070209 | 0.000263 | 0.00442 | 0.0296103 | 0.000908 | 0 | 0.151813 |
| HCl | 0.000282 | 8.9382E-06 | 0.001738 | 1.9E-05 | 0.00153278 | 1.16E-05 | 0 | 0.003593 |
| HF | 1.23E-05 | 1.12E-06 | 2.17E-04 | 2.38E-06 | 9.97E-05 | 1.45E-06 | 0 | 0.000334 |
| $CH_4$ | 0.0283374 | 0.00063603 | 0.064765 | 0.001371 | 0.101683 | 0.000823 | 0 | 0.197616 |
| $NO_x$ | 0.201205 | 0.0166995 | 0.065193 | 0.062899 | 0.0829794 | 0.021588 | 5.22672 | 5.677283 |
| $N_2O$ | 0.0013084 | 0.00017635 | 0.000315 | 4.07E-05 | 0.00022874 | 0.000228 | 0 | 0.002297 |
| PM10 | 0.0137127 | 0.00201252 | 0.000592 | 0.001541 | 0.00056848 | 0.002602 | 0.025544 | 0.046572 |
| Particulates (unspecified) | 0.0154781 | 0.00037925 | 0.045433 | 0.000806 | 0.0357402 | 0.000491 | 0 | 0.098329 |
| $SO_x$ | 0.0939614 | 0.00261499 | 0.248258 | 0.005551 | 0.498182 | 0.003382 | 0 | 0.851949 |