COMPARATIVE LIFE CYCLE ASSESSMENT OF BIOLUBRICANTS AND MINERAL BASED LUBRICANTS

by

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Biolubricants are employed to various degrees with the hope of minimizing the life cycle environmental impacts compared to mineral based lubricants. Approximately 50 percent of all traditional lubricants are released into the environment during use, spills, and disposal causing impacts that could be reduced with the use of biolubricants. Traditional lubricants, mostly mineral based, are not completely biodegradable and have high toxic content compared to biobased options produced from plant oils, such as: sunflower, soybean, rapeseed, algae, palm, and coconut. Therefore, new and used lubricants can cause significant damage to the environment, especially to water sources. Research on biobased lubricants has generated varying conclusions regarding the environmental effects of these products.

A comparative life cycle assessment of rapeseed, soybean, and mineral based lubricants was performed in this study to determine the environmental impacts caused by these products. The assessment included an evaluation of the impacts to air and water created during extraction and production of these materials. A detailed analysis of the eutrophication potential impact category was completed to address missing inventory data. Additives, lubricant use, and lubricant disposal were not included in the assessment. The assessment resulted in rapeseed lubricants with the largest contribution in several impact categories including: acidification potential, photochemical smog, and eutrophication potential. Mineral lubricants dominated the global warming potential and ozone depletion potential categories.

The effects of an increase in the use of biobased lubricants in the U.S. are discussed in addition to the environmental effects caused by the use of different lubricants. A comparison of the acidification potential and ozone depletion potential emissions from each of the lubricants for different use scenarios was also calculated. In addition, the direct land use impacts from producing 2 billion gallons of lubricants from biobased sources instead of mineral based sources were determined. Finally, a decision matrix framework is developed to include life cycle assessment results and other lubricant properties.

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PREFACE

This thesis reports the results of a comparative life cycle assessment of biobased and mineral lubricants. The objective of this study is to compare the environmental impacts of rapeseed, soybean, and mineral based lubricants, develop the framework for a decision matrix, and integrate the life cycle assessment results into the decision matrix. Life cycle results are also compared to other life cycle studies. The environmental and direct land use impacts from an increase in U.S. biolubricant production and use are discussed.

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ACRONYMS

AP – Acidification potential

CAP – Criteria air pollutant

CED – Cumulative energy demand

CF – Characterization factor

CH – Switzerland

DE – Germany

DM – Decision matrix

EF – Emission factor

EOL – End of life

EP – Eutrophication potential

EPA – Environmental Protection Agency

FU – Functional unit

GHG – Greenhouse gases

GW – Groundwater

GWP – Global Warming Potential

ISO – International Organization for Standardization

LCA – Life Cycle Assessment

LCC – Life Cycle Costing

LCI – Life Cycle Inventory Analysis

LCIA – Life Cycle Impact Assessment

LU – Land use

Min – Mineral

MSDS – Material Safety Data Sheet

N – Nitrogen

OD – Ozone depletion

P – Phosphorus

PennDOT – Pennsylvania Department of Transportation

PM – Particulate matter

PS – Photochemical smog

RE – Respiratory effects

RER – Europe

RNA – North America

RS - Rapeseed

RSO – Rapeseed oil

SB – Soybean

SP - SimaPro

SRO – Surface runoff

UCTE – Union for the Co-ordination of Transmission of Electricity

USDA – United States Department of Agriculture

1.0 INTRODUCTION

Lubricants are utilized everyday for automotive, farming, industrial, aviation, and marine applications. Approximately 50 percent of all lubricants, mostly mineral based, are released into the environment during use, spills, and disposal (Schneider 2006). This is a concern since traditional lubricants are not completely biodegradable and have high toxic content (Schneider 2006). Therefore, new and used lubricants can cause significant damage to the environment, especially to water sources (Schneider 2006). Additionally, burning lubricants for disposal produces airborne pollutants and waste containing heavy metals (Gulyurtlu et al. 1996). Although used lubricant can be recycled, users are skeptical that the lubricant maintains its quality.

Biolubricants are being manufactured and employed with the hope of minimizing the life cycle environmental impacts that are caused by the use of mineral based lubricants. These biolubricants are being produced from oil-based agricultural feedstocks such as: sunflower, soybean, rapeseed, palm, and coconut oils (IENICA 2004; Miller et al. 2007). The oil extracted from these oilseed crops is utilized as base oil for lubricant production (Adamczewska and Wilson 2006; Frier and Roth 2006). In contrast with traditional lubricants, biolubricants can be biodegradable and may have a low toxicity as long as the additives utilized also possess these characteristics (IENICA 2004). In addition to reducing environmental impacts, biolubricants can result in a cleaner work environment, less skin problems, better safety due to flashpoint properties, constant viscosity, less oil mist and vapor emissions, and a competitive tool life (IENICA 2004). Although biolubricants have numerous benefits, several disadvantages have been observed, particularly during the use phase. Some disadvantages include: temperature limitations, bad odor, metal discoloration, viscosity limitations, and poor thermal and oxidative stability (Boyde 2002; IENICA 2004).

Presidential Executive Order #13423 and several other government policies, laws, and initiatives have been created to boost the purchase and use of biobased products throughout government agencies. The executive order establishes that agencies are required to acquire sustainable products and services that are biobased, environmentally preferable, energy-efficient, water-efficient, and have recycled-content, reduce the use of toxic and hazardous materials, and reduce petroleum consumption in vehicle fleets, among other requirements. As for lubricants, the United States Department of Agriculture (USDA) manages the BioPreferred Biobased Products Catalog that includes more than 200 lubricants in the following categories: 2 cycle engine oils, chain and cable lubricants, firearm lubricants, forming lubricants, gear lubricants, greases, hydraulic fluids, penetrating lubricants, and metalworking fluids. However, the BioPreferred program, which will be discussed further in Chapter 4.0, states that each agency shall consider life cycle costs and performance prior to investing in biobased products. Also, re-refined products have a priority over biobased products (Bremmer and Plonsker 2008). Therefore, biobased content is not necessarily the sole criteria for selecting lubricants; an organization may justify the purchase of non-biobased lubricants.

The increase in biobased products in the US, Europe, and other countries has led to many studies on the life cycle impacts of these products particularly during the agricultural phase and up to the production of oil. This oil can then be utilized for cooking, fuel, and lubricant production among other applications. However, not many studies have been conducted on production of lubricants made from different bio sources. Minimal research on biobased lubricants has generated varying conclusions regarding the environmental effects of these products. Most of the studies conclude that the agricultural phase has the highest environmental impact, contributing to the acidification, eutrophication, and smog impact categories (Vag et al. 2002; McManus et al. 2004; Miller et al. 2007). Alternatively, these studies indicate lower impacts to the global warming potential (GWP) and climate change categories from the biobased options than the mineral based products.

1.1 GOALS AND OBJECTIVES

The goal of this research is to complete a comparative life cycle assessment (LCA) and incorporate the LCA results in a decision making tool for biobased products. The decision making tool will be utilized to evaluate mineral based lubricants and biobased lubricants derived from plant based oils including rapeseed, which is the major vegetable oil utilized for industrial purposes in Europe, and soybean, which is widely used in the U.S. (Bremmer and Plonsker 2008). No studies investigating the use of rapeseed in the U.S. for industrial purposes were found. In addition, the major sources of environmental impacts (i.e. hot spots) will be identified, and recommendations will be provided for improvement of the detrimental life cycle stages. This study presents a comparison of the emissions from each of the lubricants, the contribution to global warming, acidification, eutrophication, and other impact categories, and an evaluation of lubricant performance during use. The environmental effects and land use effects due to an increase in the use of biobased lubricants at state level will be discussed.

Originally, the results of this work were intended to inform the ‘Biolubricant Study for District 2’ for the Pennsylvania Department of Transportation (PennDOT). Specific data related to the PennDOT District 2 case study will no longer be included due to the termination of the study, which aimed to provide recommendations on best practices for the use and implementation of biolubricants for its vehicle fleet. However, this thesis establishes a framework for selecting appropriate lubricants as well as assessing the environmental impacts and costs of lubricants for such an application.

The specific objectives of this research are:

Objective 1 – Perform a comprehensive, comparative life cycle assessment of mineral, soybean, and rapeseed based lubricants

Objective 2 – Develop a decision matrix to screen and evaluate potential lubricants

Objective 3 – Integrate the results of the LCA and decision matrix to evaluate the use of selected lubricants

The objectives are further developed and discussed in specific chapters. The respective chapter numbers for each objective are presented below in Table 1.1.

Table 1.1. Objective and associated chapter

Objective No.	Chapter No.
1	3.0
2	4.0
3	4.0

1.2 LIFE CYCLE ASSESSMENT

A life cycle assessment (LCA) is a tool utilized to determine the environmental impacts caused by a product or process throughout its life. The stages considered in the life of the product or process, shown in Figure 1.1 are: raw material extraction, transportation, manufacturing, use and disposal. Recycling or reuse of materials can also be included. An LCA can compare one or more products or processes to determine which one causes less impacts to the environment. It can also be utilized to identify hot spots throughout the life cycle of a single product or process. LCA quantifies the energy inputs; raw materials inputs; emissions to air, soil, and water; and waste generated to be examined at every stage of the life of the product or process (McManus et al. 2004).

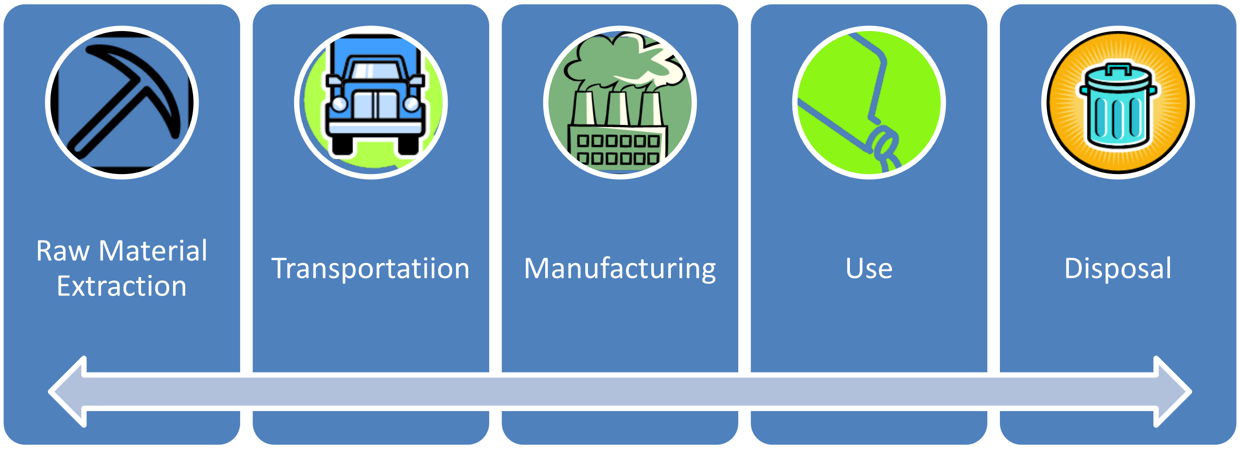


Figure 1.1. Life cycle stages

The LCA method is standardized by the International Organization for Standardization (ISO) under the 14040 series (ISO 2006). Other organizations, such as the U.S. Environmental Protection Agency (EPA) and the Society of Environmental Toxicology and Chemistry (SETAC), have also developed criteria to standardize the LCA procedure. This method, as shown in Figure 1.2, consists of the following four mutually dependent phases (Baumann and Tillman 2004):

1. Goal and Scope Definition – defines the extent of analysis and the system boundaries
2. Life Cycle Inventory Analysis (LCI) – documents material and energy flows that occur within the system boundaries
3. Life Cycle Impact Assessment (LCIA) – characterizes and assesses the environmental effects using the data obtained from the LCI
4. Improvement Analysis – identifies areas where the environmental burden can be reduced in the life of the product

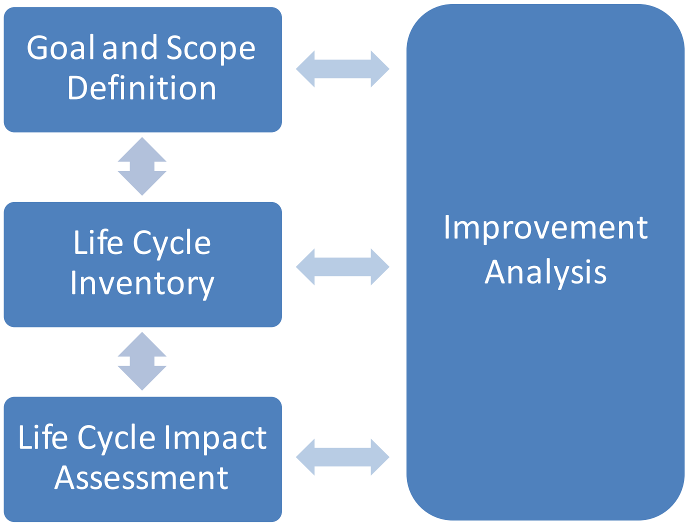


Figure 1.2. LCA phases

It should be noted that due to the complex nature of this method life cycle assessments may not include all of the life cycle stages or all of the LCA phases stated above. Many life cycle assessments model the system from cradle to grave, i.e. from raw material extraction to disposal or end-of-life (EOL) (Baumann and Tillman 2004). However, a system can also be modeled from cradle to gate, where the use and disposal stages are not included in the analysis, and there is a focus on the manufacturing or production stage of the system's life cycle (Baumann and Tillman 2004). Another type of LCA is cradle to cradle. In cradle to cradle assessments, products are reused or recycled instead of being disposed of in landfills, making the system basically waste free (McDonough and Braungart 2002). Also carbon footprinting can be utilized to calculate the GHG emissions caused by an individual, organization, product or system (Wiedmann and Minx 2007).

The first phase of the LCA consists of defining the goal, scope, and other basic characteristics to ensure the objectives are clear, specific, and achievable, since an LCA can be very time consuming. The purpose of the study is defined as well as the application of the product or products to be evaluated, and the parties interested in the results. Additionally, modeling specifications are selected, which include: functional unit, system boundaries, environmental impacts to be considered, and level of detail of the data (Baumann and Tillman 2004). The functional unit allows the results of the LCA to be expressed quantitatively, and ensures a reasonable comparison based on the function of the products. The system boundaries establish which processes are included in the LCA. For example, a study may include one, two, or all of the life cycle stages of a product or process. Natural, geographical, time, and technical boundaries should be defined (Baumann and Tillman 2004). The geographical boundary is relevant to LCA since the life cycle phases do not always occur in the same place, i.e., state or country, these places do not provide the same infrastructure such as electricity production and transportation, and have different sensitivity to pollutants (Baumann and Tillman 2004). Environmental impacts are evaluated based on impact categories that affect human health, ecosystem health, resource depletion, and social welfare. The LCA practitioners and commissioners may select various categories that align with the established goal and purpose of the LCA study. These may include global warming, acidification, eutrophication, and land use categories. The level of detail established determines whether site specific or average values will be utilized in the LCA (Baumann and Tillman 2004).

The LCI is the modeling phase of the LCA. The first step of the LCI is developing a flowchart consistent with the goal and scope. Although a preliminary flowchart can be created in the first phase of the LCA process, the LCI flowchart is more elaborate and contains more details of the system to be analyzed. The flowchart is continuously updated throughout the process as new information is gathered. The second LCI step is data collection; both quantitative and qualitative data are required. Data can be obtained from numerous sources, such as: published articles, reports, government, research facilities, software packages, manufacturers, and suppliers. Many LCI databases exist for the purpose of conducting an LCA. Some LCI databases are: US LCI, GREET, ecoinvent and BUWAL (Wang 1999; Norris 2003; Spriensma 2004; Frischknecht and Jungbluth 2007). This research employs GREET, US LCI, and other LCI databases that provide US data or specific rapeseed, soybean or lubricant data as discussed further in Chapter 3. Validation of the data collected is required per ISO 14041 (ISO 2006). Data should be validated; this can be done by comparison to other data, verifying against system boundaries, and performing mass and energy balances. Finally, calculation of inputs and outputs of the product system with respect to the functional unit is completed. Inputs and outputs include resource use, energy use, and emissions to air and water, which are converted, and expressed in terms of the functional unit. For example, most emissions are expressed as kg emission/functional unit. Another factor that needs to be considered in this phase is allocation. When a process produces two or more products, the inputs and outputs related to that process need to be divided among those products. Recycling also involves allocation considerations, and affects the flowchart design (ISO 2006).

The third LCA phase is the LCIA. The impact assessment determines how the LCI results impact the environment and other categories. The first step of the impact assessment is selecting the applicable impact categories that match the goals established at the beginning of the study. Next, the LCI results are assigned to the respective impact categories, also known as classification (Baumann and Tillman 2004). In some cases, LCI results can be assigned to several impact categories. Common impact categories are global warming potential (GWP), acidification potential, eutrophication potential, ecotoxicity, ozone depletion potential, photochemical smog, energy use, and land use. The following step is characterization (Baumann and Tillman 2004), which consists of calculating the impacts caused by the LCI results. In this step, the impacts are expressed in common units to allow for comparisons. Finally, normalization, weighting or valuation is performed, where a weight or value is assigned to each impact based on relative importance. However, this step is seldom performed, since it is not required by ISO, and determining the importance has high uncertainty.

There are a host of LCIA tools available including: TRACI, Eco-indicator 99, and EDIP/UMIP (Wenzel et al. 1997; Goedkoop and Spriensma 2001; Bare et al. 2003). These tools match the LCI to the impact categories, and calculate the impacts caused by the system being evaluated. Within this research, TRACI will be utilized as the LCIA method, since this tool provides impact categories that represent potential effects in the United States as discussed further in Chapter 3.

The improvement analysis is the final phase of the LCA, although it can be performed throughout the LCA at each phase as depicted in Figure 1.2. The purpose of this phase is to improve the LCA by identifying flaws, conducting a sensitivity and uncertainty analysis, and performing data quality assessments to ensure that the goal and scope is met and provide conclusions and recommendations (Baumann and Tillman 2004). LCA results often present unexpected findings that are not aligned with the goal and scope of the study (Baumann and Tillman 2004). However, these results should also be presented to ensure the LCA is complete.

In addition to LCI and LCIA tools, several programs are available that integrate both of these tools in one LCA program. These programs can be used to obtain a LCI, perform a LCIA, or complete a full LCA among other functions. Some of these programs include: SimaPro, GaBi, and TEAM (Ecobilan 2008; PRéConsultants 2008; PE-International 2009). SimaPro was developed by PRé Consultants and released in 1990 as a tool for assessing products, processes and services (PRéConsultants 2008). PE International developed GaBi, a tool that also assesses the sustainability of products and processes (PE-International 2009). Another LCA software is Ecobilan’s Tools for Environmental Analysis and Management, also known as TEAM (Ecobilan 2008).

1.3 DECISION MAKING METHODS

As previously mentioned, LCA is a very complex method, and making decisions throughout the LCA is a difficult task. According to Clemen (1996), there are four basic sources of difficulty in every decision. These are: complexity, uncertainty, multiple conflicting objectives, and different perspectives that lead to different conclusions (Clemen 1996). However, Clemen (1996) states that decision analysis provides effective methods for organizing a complex problem into a structure that can be analyzed, and that decision analysis can provide insight about the situation , uncertainty, objectives and trade-offs, and possibly yield a recommended course of action (Clemen 1996). Due to this, many research studies have concluded that decision analysis can improve LCA not only in the interpretation of results but also when defining the goal and scope, and during other LCA phases as well. Table 1.2 summarizes several studies that analyzed or utilized decision making methods to complete an LCA.

From another perspective, LCA results can also be utilized to inform a decision making process as will be done in this study. For example, Kijak and Moy (2004) developed a framework to assess municipal solid waste management within a local government area by utilizing several environmental, social, and economic tools including LCA (Kijak and Moy 2004). Multiattribute utility theory was used to integrate qualitative and quantitative data (Kijak and Moy 2004). Cunningham et al. (2004) developed a decision matrix to analyze hydraulic fluids using environmental, social, and economic factors (Cunningham et al. 2004).

Table 1.2. Studies with decision analysis within LCA

Author(s)	**LCA phase**	**Case study**
(Miettinen and Hämäläinen 1997)	Goal and scope definition LCIA	Beverage packaging
(Boufateh et al. 2009)	Goal and scope definition LCI, LCIA, & Interpretation	Textile industry
(Werner and Scholz 2002)	LCI	None
(Hertwich and Hammitt 2001)	LCIA	None
(Seppälä et al. 2001)	LCIA	None
(Geldermann and Rentz 2005)	Interpretation	Industrial coatings

1.4 LUBRICANTS

A lubricant is a substance used to improve the ease of movement between surfaces (Lansdown 2004). Lubricants are used to reduce friction, reduce wear, and prevent overheating and corrosion (Lansdown 2004). They are complex products that consist of 70-99% base oils mixed with additives that modify the natural properties of the fluid to meet its intended requirements (Mang and Dresel 2001; IENICA 2004). There are four classes of lubricants: oils, greases, dry lubricants, and gases (Lansdown 2004), which can be produced from mineral oil, plant oil, synthetic oil, or re-refined oil (IENICA 2004). However, mineral oil is the most common lubricating oil utilized due to its availability, cost, and compatibility with many systems (Lansdown 2004).

Lubricants have many properties that are evaluated prior to selection to ensure that it is compatible with the system where it is to be used, and that it continues to provide adequate lubrication under different conditions. The main property of a lubricant is its viscosity, since this is what prevents contact between the bearing surfaces (Lansdown 2004). Other important factors used to select a lubricant are temperature stability, chemical stability, compatibility, corrosiveness, flammability, toxicity, environmental effects, availability, and price (Lansdown 2004).

1.4.1 Uses and Applications

Lubricants are designed for specific uses and applications to ensure they meet system specifications and operating conditions. The following major types of components have lubricant requirements: plain bearings, rolling contact bearings, enclosed gears, steam turbines, open gears, ropes and chains, clock and instrument pivots, and hinges, locks, and latches (Lansdown 2004). Each component demands the use of a particular lubricant. For example, enclosed gears usually utilize oil for lubrication, while rolling contact bearings typically use grease, which prevents lubricant loss and lubricant contamination (Lansdown 2004). However, as mentioned previously, many others factors influence lubricant selection.

North America is the second major consumer of lubricants, which are mostly manufactured for use in automotive, industrial, marine, and aviation applications (IENICA 2004), as depicted in Figure 1.3. Specific lubricants are created for each of these applications and its components, such as: lubricants for internal combustion engines, gear lubrication oils, hydraulic oils, chainsaw oils, compressor oils, greases, metalworking fluids, turbine oils, forming lubricants, drilling oils, solid lubricants, and lubricants for textile and food applications (Mang and Dresel 2001; IENICA 2004). For example, a system such as a pick-up truck requires a variety of lubricants as shown in Figure 1.4. Lubricants are also designed and produced for systems prone to leakage and total loss applications, which end up almost completely in the environment (IENICA 2004). Most of the lubricants used in the United States are mineral based, mainly due to the inherent tendency to design components for use with mineral based lubricants (Lansdown 2004).

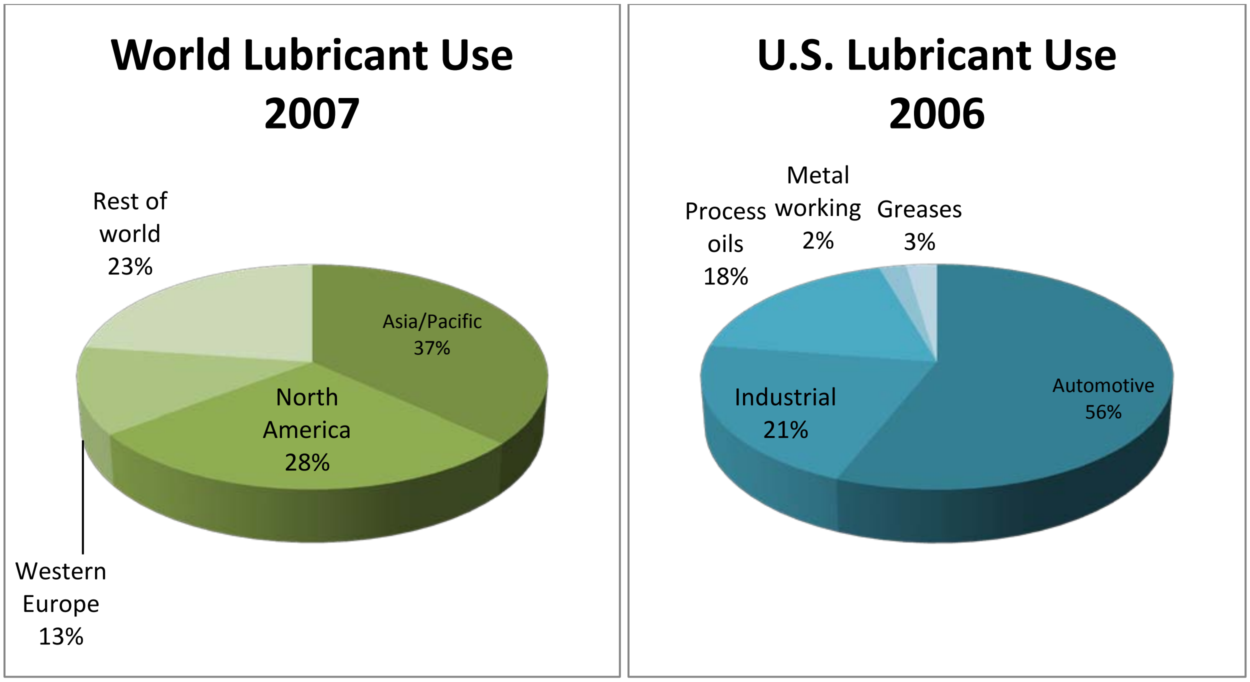


Figure 1.3. Lubricant usage

(Bremmer and Plonsker 2008)

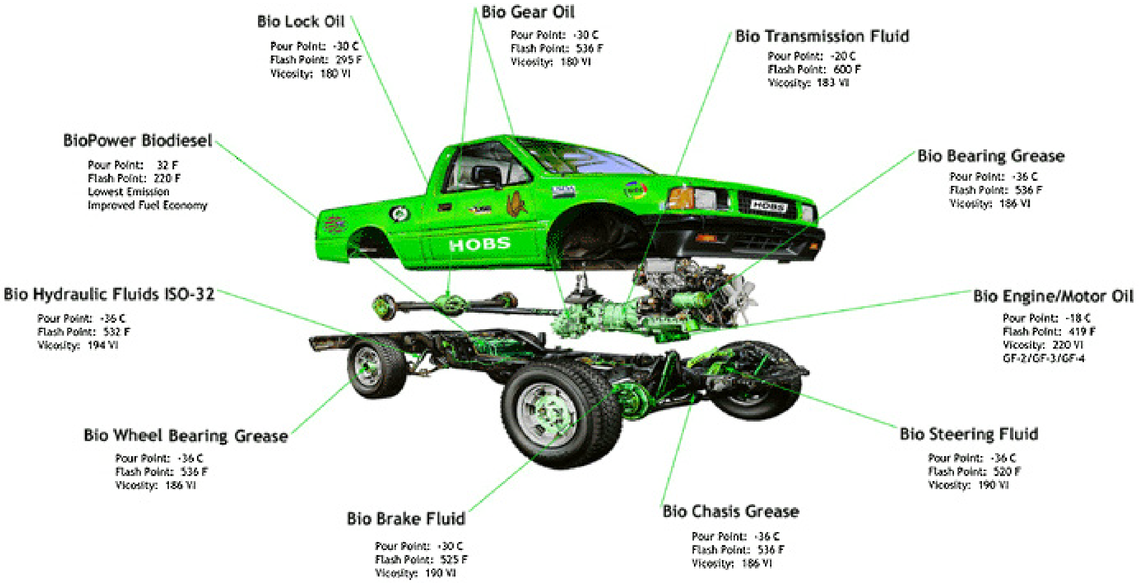


Figure 1.4. Lubrication requirements for a pick-up truck

(Taken from www.biolubricants.com)

1.4.2 Additives

Base oils alone are sometimes unable to meet the lubrication requirements of a component. Therefore, additives are utilized to improve lubrication by modifying the properties of the base oil or modifying the properties of the metal surfaces where it is used (Mang and Dresel 2001). Typically, additives represent approximately 7% of a lubricant (Mang and Dresel 2001). Additives can provide different characteristics to base oils, such as: antioxidant, corrosion inhibitor, rust inhibitor, anti-wear, anti-foam, extreme pressure, friction modifiers, and viscosity index improver (Lansdown 2004). Table 1.3 provides a list of several types of additives and their function. However, not all lubricant characteristics can be modified by additives (Mang and Dresel 2001). Although additives can improve lubricant performance, high performance is only achieved with the use of high quality base oils (Mang and Dresel 2001).

Table 1.3. Types of additives

(Mang and Dresel 2001; Rudnick 2003; Lansdown 2004)

Additive	**Function**	**Example**
Antioxidant	Improve oxidation resistance	Diphenylamine
Corrosion inhibitor	Protect against chemical attack	Sulphurized terpenes
Rust inhibitor	Prevent corrosion of ferrous materials	Amine phosphates
Antiwear	Reduce wear	Ethyl stearate
Antifoam	Prevent foaming	Polydimethylsiloxanes
Extreme pressure	Prevent welding	Cetyl chloride
Friction modifier	Prevent oscillations and noise	Ethers
Viscosity index improver	Improve viscosity-temp. relation	Polyisobutylene
Emulsifier	Disperse water in base oil	Naphthenic acids
Thickener	Converts oil into solid or semisolid lube	Calcium soap
Detergents	Disperse particulate matter	Phenates
Pour point depressant	Affect fluidity by controlling crystal formation	Polyalkyl methylacrylates

1.4.3 Biolubricants

Typically, biolubricants are made from plant oils such as: soybean, rapeseed, sunflower, palm and coconut (IENICA 2004; Miller et al. 2007). However, there is no clear and consistent definition of a biolubricant. Often, biolubricants are generally considered to be lubricants that have high biodegradability and low human and environmental toxicity (IENICA 2004; Lansdown 2004). Biolubricants can also be made from synthetic esters or petroleum oils that meet established biodegradability and toxicity criteria (IENICA 2004; Bremmer and Plonsker 2008). For example, some countries only require 50% of the oil to be renewable, or that biolubricants be utilized when near non-navigable waters (IENICA 2004; Bremmer and Plonsker 2008).

According to Pal and Singhal (2000) , the best opportunity for biolubricant usage is in situations where the lubricant can be unintentionally exposed to humans, food or the environment, since the use of high toxicity products in these scenarios has the potential to cause severe damage (Pal and Singhal 2000). Therefore, further considerations should be made for lubricants that will be used in total loss applications, food industry, or systems with leakage. However, as mentioned earlier, additives must also have biodegradable and low toxicity characteristics for the biolubricants to be used in these applications (IENICA 2004).

Recently, U.S. regulations have favored the use of biolubricants to meet the government’s goal of reducing dependence on petroleum products (Bremmer and Plonsker 2008). Unfortunately, some biolubricants have higher costs and sometimes are considered to have inferior performance than traditional mineral based products, which limits their development and competitiveness (IENICA 2004; Bremmer and Plonsker 2008).

In Europe, rapeseed and sunflower oils are the major vegetable oils used for industrial purposes, including lubricant production, while soybean and corn are mostly utilized in the United States (Mang and Dresel 2001; Bremmer and Plonsker 2008). Europe utilizes rapeseed and sunflower oils due to their availability, thermal oxidation stability, and superior flowing properties compared to other vegetable oils (Mang and Dresel 2001). However, the oxidation, hydrolytic and thermal stability of these vegetable oils is not sufficient for use in a circulating system (Mang and Dresel 2001). Rapeseed has approximately 40-42% oil, while soybean contains 18-20% oil (Frier and Roth 2006). Although rapeseed has a higher oil yield, in the U.S. only 847,000 acres were planted in 2009 compared with 77.5 million acres of soybeans planted in 2009 (USDA 2009). After the oil seeds have been processed, these vegetable oils are then utilized for food, fuel, lubricants and other oil products.

1.4.4 Existing products

Biolubricants in today's market are typically made from rapeseed, soybean, corn, and sunflower or a mix of these vegetable oils. Biobased lubricants can be utilized in many applications and are classified in several categories or uses including: hydraulic fluids, greases, motor oils, transmission and gear oils, chain and cable lubricants, metalworking fluids, degreaser, corrosion inhibitor, food grade oils, 2-cycle engine oils, penetrating oils, and compressor oils. Numerous biolubricant manufacturers/distributors are listed in Table 1.4. A complete list of biolubricants, their manufacturer/distributor, application, and website is included in Appendix A.

Table 1.4. Biolubricant manufacturers/distributors

Lubricant Manufacturers/Distributors
Renewable Lubricants Inc.
BioBlend
Green Earth Solutions LLC
Bio-Gem Services Inc.
DSI Ventures Inc.
Creative Composites, LTD.
Plews/Edelmann
Cortec Corporation
Environmental Lubricants Manufacturing, Inc.
SoyClean
RyDol Products, inc.
LPS Laboratories
Eco Fluid Center, Inc.
McNovick, Inc.
Houghton International, Inc.
Desilube Technology, Inc.
The Dow Chemical Company
American Chemical Technologies
Hill and Griffith Company
Bunge Oils
Hydro Safe Oil Division, Inc.
Cargill Industrial Oils and Lubricants
Panolin America, Inc.
Fuchs Lubricants Co.
Cognis Corporation
G-C Lubricants
GEMTEK Products
Starbrite Distributing
Milacron LLC
UNIST, Inc.
Sunnen Products Company
RS Farm and Harvest Supply, Inc.
NATOIL AG
Terresolve Technologies
BioPlastic Polymers and Composites, LLC
Nutek, LLC
Bi-O-Kleen Industries, Inc
Acuity Specialty Products, Inc.

2.0 LITERATURE REVIEW

The objective of this literature review is to discuss some of the research and experimental work that relates to the production, use, and disposal of lubricants mostly made from rapeseed, soybean, and mineral oils. A summary of the conclusions made in these studies will be provided to allow for comparison of the different products evaluated. In particular, this literature review will focus on the tools utilized to complete the LCA, LCA model characteristics, product performance, and environmental impacts.

2.1 LUBRICANTS

A life cycle assessment was performed by McManus et al. (2004) on the use of mineral and rapeseed oil in mobile hydraulic systems to support a study for the Engineering Design Centre for Fluid Power Systems at Bath in the United Kingdom. This study utilized SimaPro and Eco-indicator 95 to assess the impacts of 1 kg of oil used in a forestry harvester and a road sweeper. Due to conflicting opinions on oil performance, a sensitivity analysis was completed assuming mineral oil could be 1.5, 2 and 3 times better than rapeseed oil (McManus et al. 2004). Under all circumstances the mineral oil had the most impact on greenhouse gas emissions. However, it was concluded that the rapeseed oil had greater environmental impacts due to its performance characteristics, and its effects on the hydraulic components (McManus et al. 2004).

Finally, this study recommended the improvement of rapeseed oil production, and improvement in the design of the components within the hydraulic systems to reduce the overall life cycle impacts of the rapeseed oil (McManus et al. 2004). Continuous consumption of mineral oil was not recommended, since it is derived from nonrenewable resources.

Similar to the McManus study, Vag et al. (2002) concluded that the production of rapeseed oil has the lowest global warming potential, and acidification potential compared to lubricants made from mineral oil and synthetic ester, with values of approximately 1250 kg of CO_2/m^3 of oil and 11 kg of SO_2 equivalent/m^3 of oil, respectively (Vag et al. 2002). Rapeseed oil also had the lowest energy consumption among the three base oils studied with 12,000 MJ/m^3 of oil (Vag et al. 2002). However, no other impact categories were evaluated in this study, which utilized LCA inventory Tool 3.0 (LCAiT) to complete the assessment. The impact of the oils was also evaluated in the use of a forestry harvester utilized in Sweden. The analysis ignored the pesticides used in rapeseed production, did not consider the influence of additives, and assumed the lubricants were used in total loss applications (Vag et al. 2002).

Another comparative life cycle assessment was performed between petroleum and soybean based lubricants by Miller et al. (2007). Although the study focused on soybean oil use at an aluminum rolling plant, it utilized the GREET Model as intended for this study. Carbon sequestration and end-of-life impacts were considered. The assessment concluded that soybean oil lubricants had a considerably reduced impact on climate change and fossil fuel use, but a significant impact on eutrophication when compared to petroleum based lubricants (Miller et al. 2007). Other impact categories - acidification, human health, and smog - presented varying results due to the analysis of soybean oil by mass and by performance.

Herrmann et al. (2007) also evaluated mineral and biobased lubricants. The article compared mineral, plant, animal fat, and used cooking oil for use as lubricants in cooling applications by evaluating the technical, ecological and economical aspects involved in production of these materials. As found in the previous articles, mineral oil has the highest impact on global warming potential. It has the potential to cause the largest harm to the environment, and can be sold the cheapest (Herrmann et al. 2007). However, rapeseed contributes the most to acidification and nutrification potential (Herrmann et al. 2007). Overall, it concluded that used cooking oil and animal fats have the lowest environmental impacts, but are not yet in the market (Herrmann et al. 2007).

Wightman et al. (1999) and Reinhardt et al. (2002) also performed a life cycle assessment of rapeseed and mineral oil lubricants. Wightman et al. (1999) completed two articles that studied the use of the lubricants in a forestry harvester, and included a cost benefit analysis. Mineral oil continued to have the largest impact on global warming potential, while rapeseed oil had the largest contribution to nutrient enrichment potential (Wightman et al. 1999; Wightman et al. 1999). Reinhardt et al. (2002) concluded that acidification, eutrophication, and ozone depletion were affected more by rapeseed oil lubricant than conventional lubricant (Reinhardt et al. 2002). However, energy demand and greenhouse effect were affected more by conventional lubricant as found in all the previous studies.

Detailed flowcharts for production of mineral, soybean, and rapeseed oil lubricants were presented in several articles, and utilized as a guide for this research. Some of these figures are shown in Figure 2.1, Figure 2.2, Figure 2.3, and Figure 2.4.

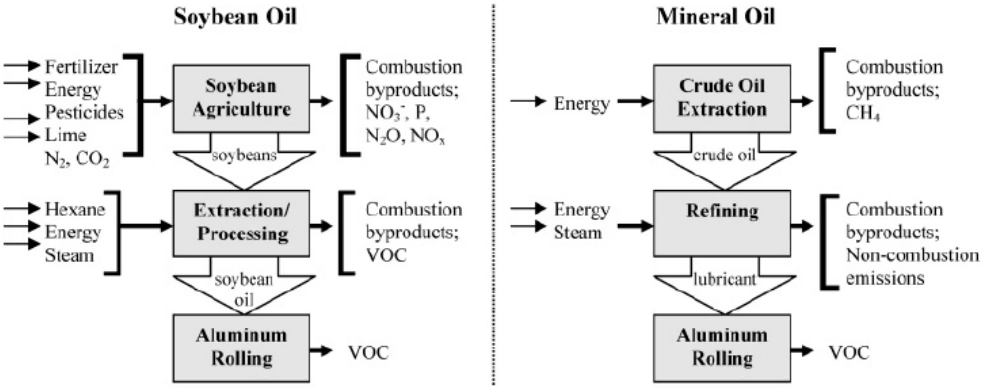


Figure 2.1 Soybean and mineral oil flowcharts

Taken from Miller et al. (2007).

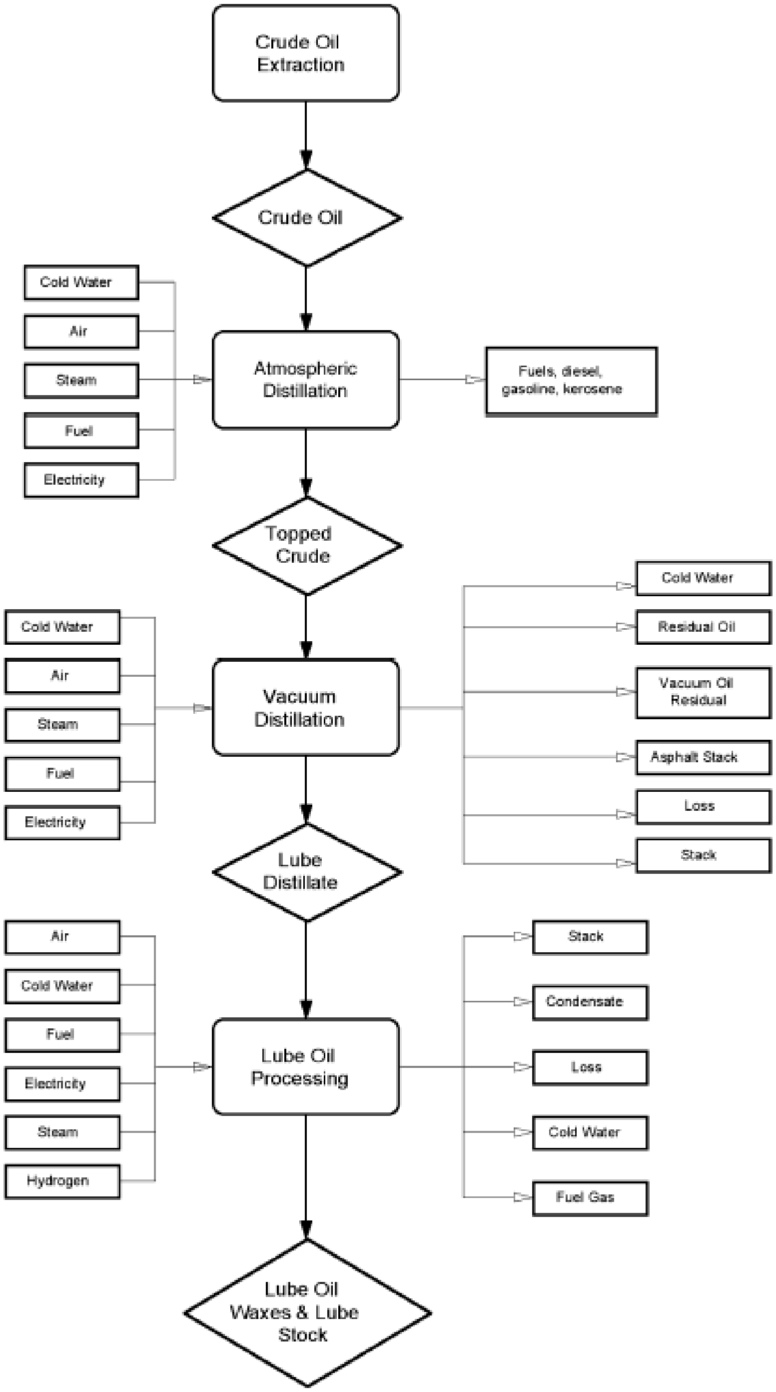


Figure 2.2. Stages in the production of mineral oil

Taken from McManus et al. (2004)

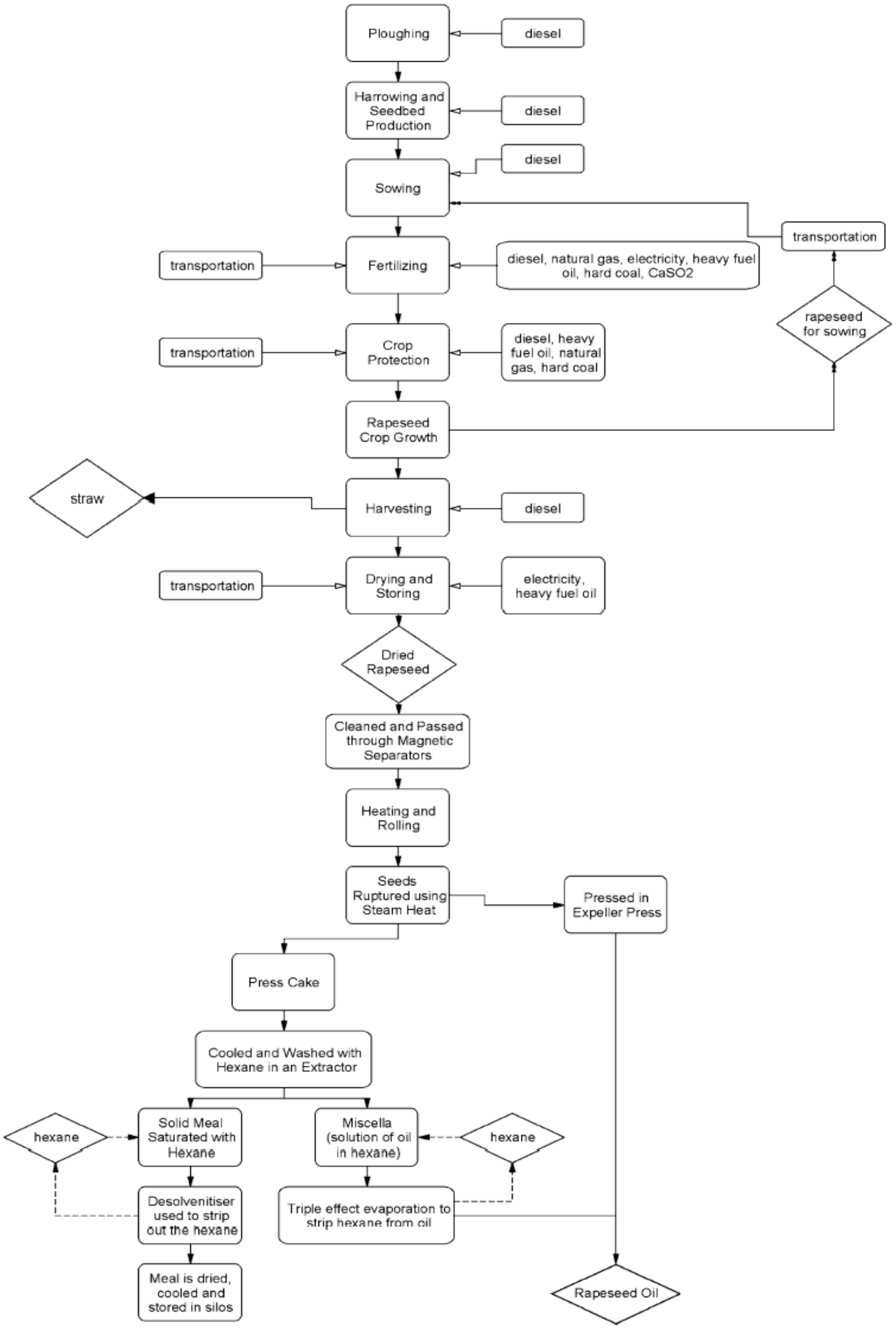


Figure 2.3. Stages in the production of rapeseed oil

Taken from McManus et al. (2004).

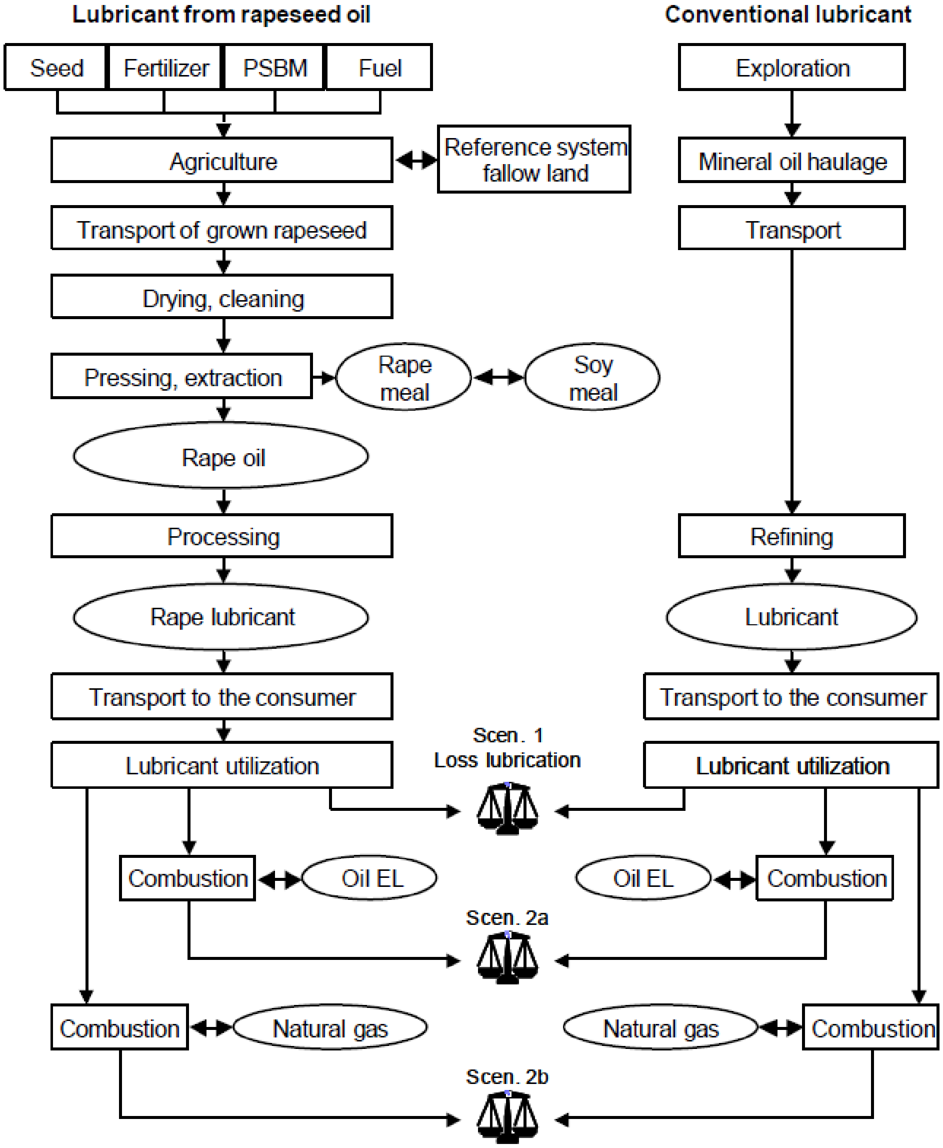


Figure 2.4. Life cycles of rapeseed and mineral based lubricants

Taken from Reinhardt et al. (2002).

2.2 BIOBASED PRODUCTS

Other rapeseed and soybean products have been developed with the intention to reduce environmental impacts, in particular greenhouse gases (GHG) due to dependence on fossil fuels. Halleux et al. (2008) evaluated the use of rapeseed and sugar beet for production of biofuels. The study determined the impacts caused by a middle-size car over 100 km to several impact categories, including global warming, respiratory effects, acidification-eutrophication, fossil fuels, and others. A qualitative analysis of land use consumption was also performed, where the crop by-products provided a credit and reduced the final impact on land use. The mineral based products had the largest impact on global warming and fossil fuels, while the bio products had a significant contribution to the ecotoxicity, acidification-eutrophication, and inorganic respiratory effects categories (Halleux et al. 2008). Unlike many studies, Halleux et al. (2008) established weighting factors for human health, ecosystem quality, and resources based on a hierarchist perspective (Halleux et al. 2008).

Similar to Halleux et al. (2008), Panichelli et al. (2008) also completed a LCA of biofuels, specifically for soybean-based biodiesel produced in Argentina, and transported to Switzerland using the ecoinvent 2.01 database and CML 2001 (Panichelli et al. 2008). The analysis was completed using a functional unit of '1 km driven with diesel by a 28t truck', and included the following stages: cultivation, oil extraction, transesterification, distribution, and use (Panichelli et al. 2008). The results were compared to palm oil and rapeseed based biodiesel, and to fossil low-sulphur diesel. The impact categories addressed were: GWP, cumulative energy demand (CED), eutrophication, acidification, terrestrial, human, and aquatic toxicity, and land use consumption. Unlike other studies, fossil diesel was not the major GWP contributor. The only impact category where fossil diesel was the largest contributor was CED.

Kim and Dale (2004) evaluated the cumulative energy and global warming impacts associated with producing corn, soybeans, alfalfa, and switchgrass and transporting these crops to a processing facility (Kim and Dale 2004). A detailed analysis of the agricultural processes and transportation is described. No other life cycle stage is included in the analysis. For soybeans, the major contributor of greenhouse gases is the diesel use followed by gasoline use. The total global warming impact amounts to 159 to 163 g CO_2 equivalent/kg of soybean (Kim and Dale 2004). The cumulative energy required is 1.98 to 2.04 MJ/kg of soybean, which is mostly from the diesel and gasoline used in the production and transportation of this crop (Kim and Dale 2004).

Pelletier et al. (2008) utilized LCA to study the effects on cumulative energy demand, global warming, acidification, and ozone-depletion of changing from conventional to organic production of several field crops in Canada (Pelletier et al. 2008). The crops evaluated were canola, soy, corn, and wheat, using a functional unit of 1 kilogram of crop. Farm machinery emissions, seeds, fertilizer production and pesticide production were included in the analysis. Calculations were performed by using SimaPro 7.0 with the CML 2 Baseline 2000 method and ecoinvent database. It was determined that fertilizer production was the major contributor to cumulative energy demand, and ozone-depletion, while the field-level emissions associated with fertilizer use was the major contributor in the global warming and acidification categories (Pelletier et al. 2008). All the organic crops had smaller contributions in all impact categories. Similar to the Kim and Dale (2004) study, only the agricultural phase was assessed.

An LCA of soybean meal was completed by Dalgaard et al. (2008) to determine the global warming, ozone depletion, acidification, eutrophication, and photochemical smog impacts from this product. SimaPro 6.0 with the EDIP97 method was utilized. An increase in soybean meal affects the demand for other vegetable oils, including palm and rapeseed oil, which were also included in this study (Dalgaard et al. 2008). Therefore, an LCA of soybean meal that displaces palm oil was completed, and another for the scenario where rapeseed is displaced. Cultivation, transport, and milling information for soybean, palm, rapeseed, and spring barley were included in this LCA. A functional unit of 'one kilogram of soybean meal produced in Argentina and delivered to Rotterdam Harbor in the Netherlands' was used (Dalgaard et al. 2008). The soybean meal/rapeseed loop had the lower environmental impact in all categories evaluated except photochemical smog. Among the crops studied, rapeseed had the highest contribution in all the impact categories. A small land use evaluation was also completed. Pesticide use was not included in the study.

The findings in the Daalgard et al. (2008) study were part of the doctoral dissertation of Schmidt (2007). Schmidt (2007, 2010) presented a comprehensive study of the agricultural, transport, milling, and refining stages for several products, but with a focus on rapeseed and palm oil. Although, the objective of the thesis was to present detailed LCI data, LCIA results were provided with no discussion or interpretation (Schmidt 2007; Schmidt 2010). A comprehensive sensitivity analysis was completed on more than 20 parameters, including: LCIA methods, energy, land use, and several cultivation and milling factors. In addition to the thesis, Schmidt also completed studies on land use effects from biodiesel production (Schmidt et al. 2009).

Another study that utilized GREET like Miller et al. (2007) was performed by Huo et al. (2009). This study performed an analysis of soybean derived fuels utilizing several allocation methods and concluded that soybean fuels had a smaller impact on greenhouse gas emissions when compared to petroleum gasoline and diesel (Huo et al. 2009).

2.3 COMPARISON OF RESULTS

The articles in this literature review were collected through a comprehensive search of several databases. The findings were recorded in Table 2.1, however only relevant articles were utilized in this research. Table 2.2 provides basic information regarding the articles discussed in this literature review. The table includes the products studied, the functional unit, the tool utilized to perform the assessment, the application of the products, the country of the data utilized, and the impact categories evaluated in the study. The results of the literature review are further discussed and compared below.

McManus et al. (2004), Vag et al. (2002), Miller et al. (2007), Herrmann et al. (2007), Wightman et al. (1999) and Reinhardt et al. (2002) all performed an analysis of biolubricants compared to traditional mineral based lubricants. The remaining assessments included in the literature review analyzed specific crops or the products obtained from those crops. For example, Halleux et al. (2008) and Panichelli et al. (2008) performed an LCA on the production of biofuels. The differences in products evaluated did not allow simple comparison of LCA results.

Another factor that impeded an easy comparison between the studies was the significant variety of functional units utilized in the assessments. Although, several of the studies have common products and applications, the functional unit was not similar. Some studies utilized the amount of product (i.e. kg of oil), while other studies used the amount of product used to complete a process (i.e. 1 km driven with diesel by a 28 ton truck). These differences, however, do not mean that the functional unit chosen was incorrect. The functional unit selected depends on the goals and scope set at the beginning of the LCA. Therefore, the products and applications affect the choice of functional unit. For example, Wightman et al. (1999) studied chainsaw oil, and used ‘volume of oil used to cut 1000 m^3 of wood’ (Wightman et al. 1999; Wightman et al.

1999). On the other hand, Halleux et al. (2008) used ‘road transport over 100 km’ to compare sugar beet ethanol and rapeseed methyl ester utilized for biofuels production (Halleux et al. 2008).

The goal and scope also defines the system boundaries for the LCA. Is the data available? Are certain flow or life cycle stages disregarded? Is allocation performed? These are some questions that are addressed when defining the goal and scope. For instance, Vag et al. (2002) did not address additives, probably since they represent a small percentage of the total lubricant. Vag et al. (2002) did not include the use of pesticides in their assessments. This could be a mistake when analyzing acidification and eutrophication potential, since fertilizers and pesticides tend to have significant effects on these categories. Daalgard et al. (2008) decided to perform consequential allocation, which consisted in expanding the system and avoiding co-product allocation (Dalgaard et al. 2008).

Data sources also cause significant differences among the results. As shown in Table 2.2, the data utilized in each study comes from different tools, which are many times associated with one or more countries. For example, SimaPro has available multiple databases that contain data from the U.S, Europe, or other countries. The use of tools like SimaPro, GREET, and LCAiT may depend on the location of interest, or the type of results desired. It should be noted that the use of different tools can provide very different results as demonstrated by Miller and Theis (2006) and Dreyer et al. (2003). The Miller and Theis (2006) study consisted in evaluating U.S. soybean agriculture and processing utilizing GREET, economic input-output (EIO) LCA, and SimaPro with the Franklin database (Miller and Theis 2006). Dreyer et al. (2003) compared inventories from the EDIP97, CML2001, and Eco-indicator 99 databases using a water-based UV-lacquer as the case study (Dreyer et al. 2003). In both studies each tool produced a unique inventory, each with advantages and disadvantages. Therefore, the tool to be utilized in any LCA should be selected carefully to ensure that the best results are obtained. If necessary, various tools can be utilized as done in this research.

Although many impact categories were evaluated, the most common impact categories among the studies were global warming potential, ozone depleting potential, cumulative energy demand, acidification potential, and eutrophication potential. Other categories evaluated were related to toxicity, human health, smog, particulate matter, and land use. Some of the studies provided LCIA results without presenting detailed information on the inputs or methods utilized during the LCI phase, such as: Herrmann et al. (2007) and Reinhardt et al. (2002). However, where agricultural and production data were provided it was incorporated into the LCI of this research.

The reviewed articles that performed analyses of biobased products and compared them to mineral based products obtained similar results when analyzing the global warming potential, mineral based oil produces the highest impact. All of the studies reached this conclusion with one exception. Panichelli et al. (2008) determined that biodiesel production in Argentina and Brazil had a larger GWP than fossil diesel, with the agricultural phase having the largest contribution. Herrmann et al. (2007) concluded that rapeseed contributes the most N_2O to the GWP due fertilizer production and use (Herrmann et al. 2007). In another case, although mineral oil had the most impact on greenhouse gas emissions in the McManus et al. (2004) study, it was concluded that rapeseed oil had greater environmental impacts overall due to agricultural and performance factors. These results stress the importance of performing a sensitivity analysis and how results are not always as expected.

Most of the articles evaluated the energy used at the different life cycle stages. The largest contributor was mineral oil due to its high embodied energy (Miller et al. 2007). This was the case in the following studies: Vag et al. (2002), Miller et al. (2007), Herrmann et al. (2007), Reinhardt et al. (2002) and Panichelli et al. (2008). McManus et al. (2004) had a different conclusion, stating that the rapeseed oil had a higher energy contribution due to the energy required in the crushing stage in rapeseed oil production (McManus et al. 2004).

The studies that evaluated eutrophication concluded that the plant based oil, rapeseed or soybean, had a more significant impact on this category than mineral based oil. Miller et al. (2007) concluded that soybean oil lubricants when compared to mineral based lubricants had a reduced impact on climate change and fossil fuel use, but a significant impact on eutrophication similar to the results obtained in the McManus et al. (2004) study. Herrmann et al. (2007) also determined that rapeseed greatly affected the eutrophication and acidification potential (Herrmann et al. 2007). Similarly, Reinhardt et al. (2002) concluded that acidification, eutrophication, and ozone depletion potential were affected more by rapeseed oil lubricant than conventional mineral lubricant.

Schmidt (2007, 2010), Dalgaard et al. (2008), Kim and Dale (2004) and Pelletier et al. (2008) performed assessments of several agricultural products. Although these studies focused on the impacts from agricultural crops, useful cultivation and milling data for rapeseed and soybean was provided and utilized in this research. Other data provided was the type and amount of fertilizers used for each crop, and fuel use during the agricultural stage. No comparisons to mineral products were possible.

Overall the papers reviewed had common results when analyzing the GWP, mineral based oil and products have the highest contribution. Alternately, the studies that evaluated acidification and eutrophication potential concluded that the plant based oil (rapeseed and soybean) had a more significant impact than mineral based products on the acidification and eutrophication categories. The functional unit in the different studies varied considerably impeding simple comparison of results between existing and new studies. Other limitations in the articles found was the use of European data, the use of tools like SimaPro and LCAiT, and the disregard of certain flow or life cycle stages. Performing an LCA is an elaborate process where data is often unavailable, or data varies significantly due to location, approach, and tools utilized. Additionally, allocation is a further obstacle in obtaining accurate results. Therefore, thorough review of data, calculations, and methods was required to ensure a comprehensive and accurate LCA was completed for this study.

Table 2.1. Search term database

Search term	Science Direct	Scopus	InterScience[1]	Springerlink[2]
Biolubricants	2	26	9	10
Biolubricant/life cycle	0	1	2	1
Lubricant/life cycle	0	40	28	1506
Lubricant/LCA	0	6	1	93
Lubricant/env. impact	1	183	32	1,373
Rapeseed	320	3,828	1,408	3,847
Rapeseed/life cycle	3	22	43	1,161
Rapeseed/lubricant	0	54	42	191
Rapeseed/biofuel	6	89	46	170
Rapeseed/env. impact	1	52	38	969
Canola	245	1,873	797	3,329
Canola/life cycle	0	4	20	1,068
Canola/lubricant	0	14	8	115
Canola/biofuel	0	17	6	93
Canola/env. impact	0	14	36	1,127
Soybean	2,685	34,157	7,739	27,406
Soybean/life cycle	4	60	226	9,056
Soybean/lubricant	7	44	28	353
Soybean/biofuel	4	105	53	350
Soybean/env. impact	2	157	245	5,933
Land use/life cycle	14	172	618	26,765
Land use/lubricant	0	0	5	652
Land use/ env. Impact	20	2,109	3,148	46,300
Decision/life cycle	0	1,787	1,568	47,251
Decision matrix/life cycle	0	0	114	10,399
MCDM/life cycle	2	5	0	119
MCDA/life cycle	0	10	7	85
Decision tree/life cycle	0	22	63	10,346
Agent based modeling/LC	0	21	726	54,846

[1] InterScience includes: Journal of Industrial Ecology, Journal of Synthetic Lubrication, Biotechnology and Bioengineering, Lubrication Science, and other journals.

[2] Springerlink includes International Journal of LCA.

Updated on October 26, 2009.

Table 2.2. LCA characteristics of articles

Article	Product	Functional Unit	Application	Tool	Country	Impact Categories[1]
McManus et al. 2004	Mineral oil Rapeseed oil	1 kg of oil Production of machines	Hydraulic fluid	SimaPro Eco-indicator 95	UK	GHG, OD, AP, EP, HM, CE, WS, SS, SW, energy use, pesticides
Vag et al. 2002	Mineral oil Synthetic ester Rapeseed oil	1 m^3 of hydraulic fluid	Hydraulic fluid	LCA inventory Tool (LCAiT) 3.0	Sweden	GWP, AP, CED
Miller et al. 2007	Mineral oil Soybean oil	Area of aluminum rolled	Metalworking	GREET 1.6 TRACI	USA	AP, EP, PS, HH, climate change, and fossil energy
Herrmann et al. 2007	Mineral oil Rapeseed oil Palm oil Animal fat Used cooking oil	1000 work pieces produced	Coolant	ISO 14040	Germany	GWP, AP, NP, CED, PS, PM, RD, CE
Wightman et al. 1999	Mineral oil Rapeseed oil	Volume of oil used to cut 1000 m^3 of wood	Chainsaw oil	SETAC guidelines	UK Europe	GWP, NP
Reinhardt et al. 2002	Mineral oil Rapeseed oil	1 ton of lubricant	Lubricant	ISO 14040	Unknown	GWP, AP, EP, CED
Halleux et al. 2008	Sugar beet ethanol Rapeseed methyl ester	Road transport over 100 km	Biofuels	SimaPro 7.1 Eco-indicator 99	Europe	GWP, CE, RE (organic and inorganic) , ET, AP/EP, FF
Panichelli et al. 2008	Soybean, Palm, and Rapeseed biodiesel Fossil diesel	1 km driven with diesel by a 28 ton truck	Biodiesel	ecoinvent 2.01 CML 2001	Argentina Switzerland Europe	GWP, CED, EP, AP, ET (water and soil), HT, LU
Kim and Dale 2004	Corn Soybeans Alfalfa Switchgrass	1 kg of crop	Biomass	GREET 1.5a Egrid	USA	CED, GWP
Pelletier et al. 2008	Canola Corn Soy Wheat	1 kg of crop produced, at the farm gate	Conventional and organic crop production	SimaPro 7.0 CML2-Baseline 2000 ecoinvent	Canada	CED, GWP, OD, AP
Dalgaard et al. 2008	Soybean/meal Palm Rapeseed Spring barley	1 kg of soybean meal	Livestock protein	SimaPro 6.0 EDIP 97	Argentina Netherlands Europe	GWP, OD, AP, EP, PS
Schmidt 2007, 2010	Palm oil Rapeseed oil	1 tonne vegetable oil	Vegetable oils	SimaPro 7.0 EDIP 97	Denmark Malaysia Indonesia Europe	GWP, OD, AP, EP, LU, PS, biodiversity, ET (water and soil)

[1] GWP -Global warming potential, GHG-Greenhouse gases, OD-ozone depletion, AP-acidification potential, EP-eutrophication potential, HM-heavy metals, CE-carcinogenic effects, WS-winter smog, SS-summer smog, PS-photochemical smog, HH-human health, NP-nutrification potential, SW-solid waste, CED-cumulative energy demand, ET-ecotoxicity, LU-land use, FF-fossil fuels, HT-human toxicity, RE-respiratory effects, PM-particulate matter, RD-resource depletion

3.0 LIFE CYCLE ASESSMENT OF LUBRICANTS

3.1 GOAL AND SCOPE DEFINITION

The goal of this study is to complete a comparative life cycle assessment (LCA) by evaluating the life cycle of biolubricants derived from plant based oils including rapeseed, and soybean. Biolubricants are being utilized as a substitute to mineral based lubricants, since they are more biodegradable and can have lower toxicity. Biolubricants are compared to traditional lubricants made from mineral oil, and results from other comprehensive studies. This study also considered allocation, land use impacts, and further evaluated the lubricants through the development and use of a decision matrix. The results of this study can inform future researchers, the Department of Transportation and other entities that utilize lubricants on a day to day basis for their vehicles, industrial equipment and other applications.

The main life cycle stages of a biolubricant include farming, milling, refining, use and disposal. For traditional lubricants the life cycle stages include crude oil recovery, crude refining, lubricant refining, use and disposal. Figure 3.1 shows simplified flowcharts of the life cycle stages for rapeseed and soybean biolubricants, and for production of mineral based lubricants. The system boundary of this LCA includes the cultivation of rapeseed and soybean up to the production of biolubricant, and for the mineral based lubricant, from crude oil recovery to lubricant production. The use and disposal phases were not included in the LCA. Transportation is also considered, but is not depicted in the flowcharts. These system boundaries are also delineated in the flowcharts.

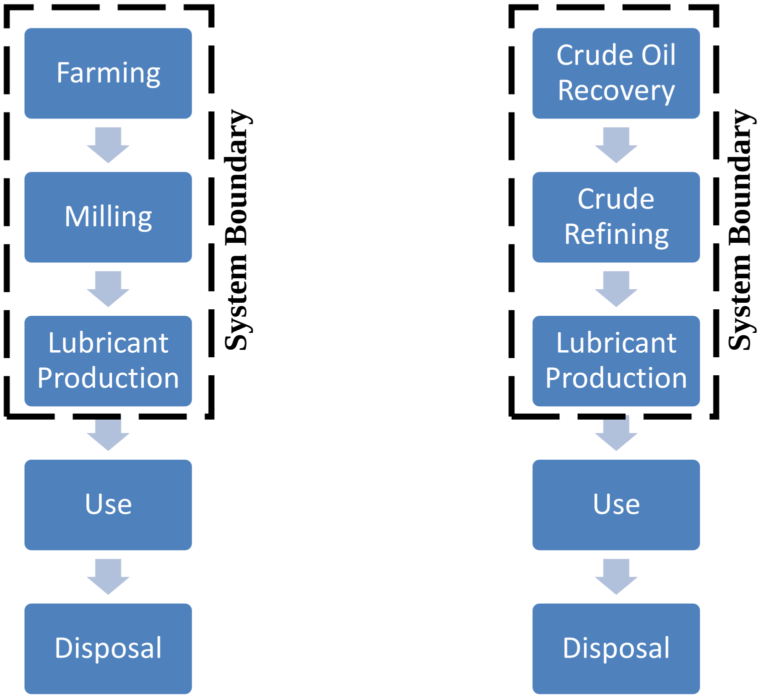


Figure 3.1. Life cycle stages of a biolubricant (left) and a mineral lubricant (right)

In any LCA it is important to select an adequate functional unit. The functional unit allows results from the different stages and from the different feedstocks to be compared. The functional unit selected for this LCA was 1 kg of lubricant. This allowed a fair comparison between the LCI data and the environmental impacts. Rapeseed has a oil content of 40-42% (Frier and Roth 2006) , which was used to convert all data in terms of the functional unit, 1 kg of lubricant. It was assumed that 1 kg of oil is equal to 1 kg of lubricant, since the transformation of oil into a lubricant requires products that are later removed, and the additives only represent a small portion of the lubricant. Table 3.1 outlines the major components of this LCA.

Table 3.1. LCA Goal and Scope

LCA characteristics	Components used in study
Alternatives to be compared:	• Rapeseed lubricant • Soybean lubricant • Mineral lubricant
Functional unit:	• kg of lubricant
Type of LCA:	• Comparative • Retrospective
Geographical system boundaries:	• Input data from US and Europe • Tools: o GREET (Wang 2007) o SimaPro (PRéConsultants 2008) o ecoinvent (Frischknecht and Jungbluth 2007) o U.S. LCI database (Norris 2003) o TRACI (Bare et al. 2003)
Time horizon of study:	• Biolubricants – From cultivation to production of biolubricant • Mineral based lubricant – From crude oil recovery to lubricant production
Environmental impacts considered:	• Global Warming • Acidification • Carcinogenics • Non carcinogenics • Respiratory effects • Eutrophication • Ozone Depletion • Ecotoxicity • Photochemical Smog

3.2 LIFE CYCLE INVENTORY AND IMPACT ASSESSMENT

3.2.1 System Boundaries

The life cycle inventory (LCI) is the modeling phase of the LCA, and consists of several steps. The first step is to develop detailed flowcharts for the products to be analyzed. The detailed life cycle of a biolubricant is shown in Figure 3.2, black borders define the processes included in this study. In addition to the farming, milling, and refining stages, the processes and the inputs and outputs for each stage are also depicted. In the first stage, farming equipment is utilized to prepare the land, plant the seeds, apply fertilizers, herbicides and pesticides, irrigate and harvest the oil seeds (McManus et al. 2004; Miller et al. 2007). Plant residues are assumed to be left on the field. The milling stage consists of drying, heating and rolling the oil seeds to prepare them for the oil extraction process (EPA 1995; WHC Co. 2000; McManus et al. 2004). Hexane is used as a solvent to allow further extraction of the oil, and is then recovered through distillation from the oil produced, and by desolventizing the meal byproduct (EPA 1995; WHC Co. 2000; McManus et al. 2004). The vegetable oil is refined by removing gums with hot water or steam, neutralizing free fatty acids with an alkali solution, removing excess water, adsorbing color producing substances, and removing odors through distillation (EPA 1995; WHC Co. 2000). Finally, additives are blended with the oil to improve lubricant quality (WHC Co. 2000; Mang and Dresel 2001). Additives are not included in this study, since they typically constitute a small percentage of the total lubricant, and there are many types of additives. However, an LCA could be conducted to obtain more information on additive production and use if needed. The use and disposal phases are not included in the LCA.

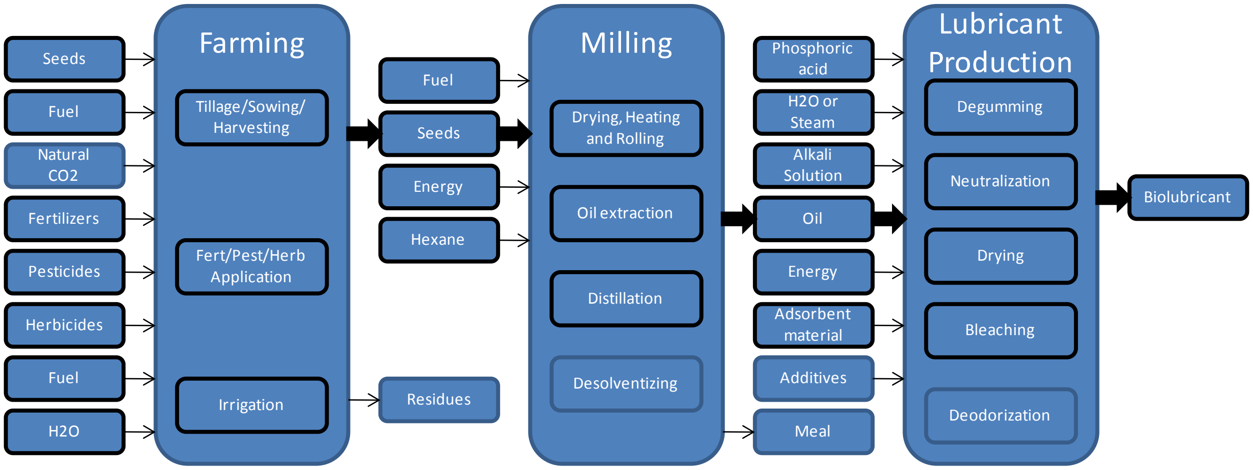


Figure 3.2. Detailed life cycle of a biolubricant

The detailed life cycle of a mineral based lubricant is shown in Figure 3.3, black borders define the processes included in this study. Crude oil can be recovered in three different phases (DOE 2008). In the primary recovery, 10% of the reservoir’s crude oil is obtained by natural pressure, gravity and pumps, 20-40% is obtained in the secondary phase by injecting water or gas to displace the oil, and the remaining 30-60% can be recovered by high cost enhanced oil recovery techniques (DOE 2008). The crude oil is distilled using atmospheric distillation to remove gases, naphthas, kerosene, and gas oils as shown in Figure 3.4 (Sequeira 1994; Mang and Dresel 2001). The atmospheric residue is processed using vacuum distillation and fractional vacuum distillation to obtain products with the required viscosity (Sequeira 1994; Mang and Dresel 2001). The vacuum distillates and residue are further refined into lubricants by removing asphalt and resins using propane in the de-asphalting process, reducing aroma and other components through hydrocracking and distillation, separating paraffinic waxes in the de-waxing process, improving the color, odor, and stability in the finishing process and finally, mixing in additives to obtain the final product (Sequeira 1994; Mang and Dresel 2001). The use and disposal phases are not included in the LCA.

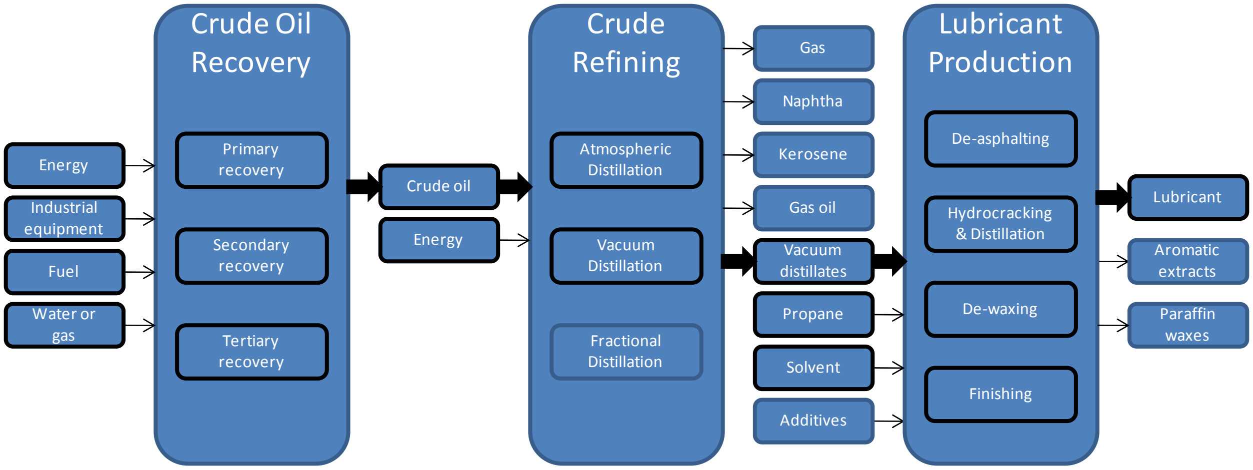


Figure 3.3. Detailed life cycle of a mineral based lubricant

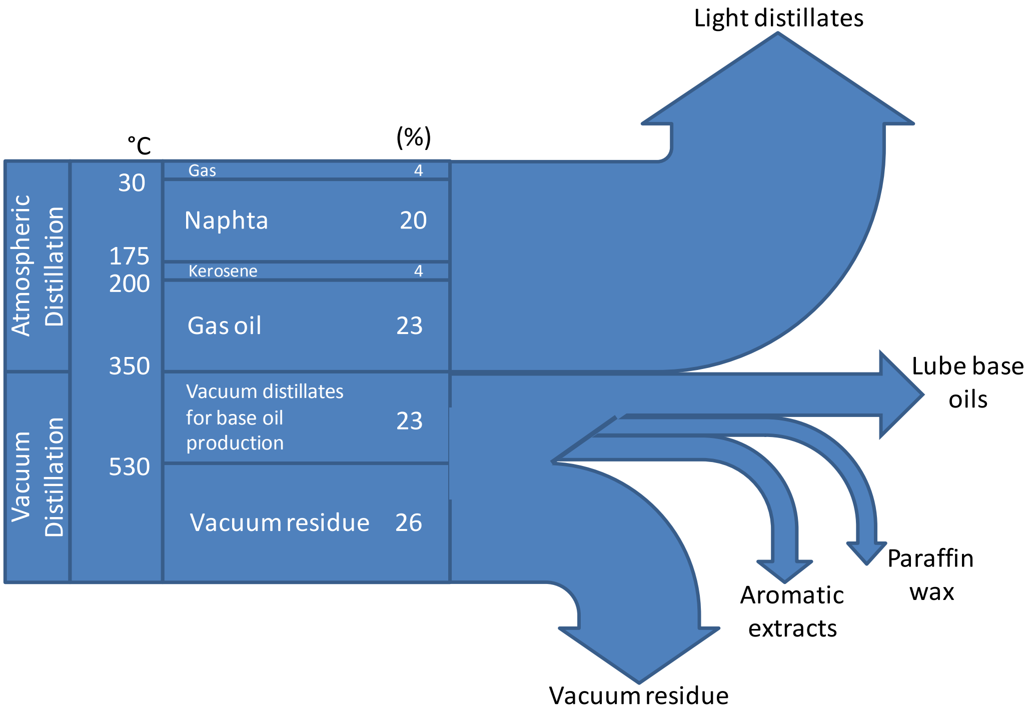


Figure 3.4. Product yields from crude oil refining

(Adapted from Mang and Dresel 2001)

3.2.2 LCI

After the flowcharts were completed, data collection for each of the different stages and processes was performed. Data was collected from scientific journals, reports, life cycle databases, and government resources, and organized in Microsoft Excel. The rapeseed data sources are listed in Table 3.2 and Table 3.3. The LCI was created by utilizing the outputs from the Greenhouse Gases, Regulated Emissions, and Energy use in Transportation (GREET) model and extracting inventory data from SimaPro. Rapeseed lubricant is compared to SimaPro – ecoinvent processes ‘Soybean oil, at oil mill/US U’ and ‘Lubricating oil at plant/RER U’.

Table 3.2. Rapeseed yield and fertilizer data sources

Data sources	Seed yield	Nitrogen fertilizer	Phosphorous fertilizer	Potassium fertilizer
(Vag et al. 2002)	2470 kg/ha	160 kg/ha	14 kg/ha	28 kg/ha
(McManus et al. 2004)	2975-3500 kg/ha	187 kg/ha oil	70 kg/ha oil	130/kg oil
(Frier and Roth 2006)	2000-3500 lbs/acre	20-30 lbs/acre 80-100 lbs/acre	25-50 lbs/acre	25-50 lbs/acre
(Dalgaard et al. 2008)	2830 kg/ha	167 kg/ha	24 kg/ha	77 kg/ha
(Schmidt 2007)	140 kg/ha	-	57 kg/ha	99 kg/ha
(Pelletier et al. 2008)	1288 kg/ha	46.1 g/kg rapeseed	50.4 g/kg rapeseed	12 g/kg rapeseed
(NASS 2009)	1100-1500 lbs/acre	-	-	-
MD Cooperative Extension	-	120-150 lbs/acre	60-80 lbs/acre	-
ND State University Extension	-	20-30 lbs/acre	-	-

Table 3.3. Rapeseed herbicide and pesticide data sources

Data Source	**Herbicide**	**Pesticide**
(Pelletier et al. 2008)	1.4 g/kg rapeseed	-
(McManus et al. 2004)	0.7 kg/ha 0.04 kg/ha	2.2 kg/ha 0.87 kg/ha

The GREET model Version 1.8c was utilized to convert rapeseed data into inventory data. GREET was developed by the Argonne National Laboratory under the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (Wang 2007; ANL 2008). This tool can calculate the consumption of total energy, fossil fuels, petroleum, coal, and natural gas, greenhouse gas emissions, and criteria air pollutant emissions for a vehicle or fuel system (ANL 2008). The GREET model calculates three greenhouse gases (GHG): carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), and five criteria air pollutants (CAPs): volatile organic compounds (VOC), carbon monoxide (CO), nitrogen oxides (NO_X), particulate matter with diameters of 10 micrometers or less (PM_{10} and $PM_{2.5}$), and sulfur oxides (SO_X) (Wang 1999).

The GREET model was selected for this study, since it also models U.S. conditions for production of soybean biodiesel. The soybean biodiesel worksheet in GREET was utilized to develop a worksheet for rapeseed. The rapeseed data obtained, from the sources in Table 3.2 and Table 3.3, were averaged and used as inputs to the GREET tool. If rapeseed data were not available, default GREET Version 1.8c data were used. These default values correspond to soybean life cycle stages, which were assumed to be similar to rapeseed life cycle stages. Table 3.4 presents the rapeseed values used to replace the GREET values for soybean.

Through GREET, allocation can be performed on a mass, market, or energy basis (Wang 1999). The rapeseed and soybean milling process produces oil and meal. These products were evaluated using mass-based allocation. In GREET, soy oil is 18.2% and soy meal is 81.8% by weight (Wang 1999). However, by market value soy oil is 33.6% and soy meal is 66.4% (Wang 1999). On the other hand, rapeseed oil is 40% of total mass while rapeseed meal represents 60% of total mass produced during milling (McManus et al. 2004). Each product, oil and meal, is assigned its corresponding environmental impacts, which is known as allocation (Baumann and Tillman 2004).

Table 3.4. GREET Modifications

Parameter	Unit	Soybean value[1]	Rapeseed value	Rapeseed references and notes
Density	lbs./bushel	60	50	(Buffington 2008)
Use	lbs. oil seed/lb. oil	5.7	2	(McManus et al. 2004)
Meal	lbs per lbs of oil	4.48	1.5	(McManus et al. 2004)
Nitrogen	g/bushel	61.2	1240	Average, see Table 3.2
P2O5	g/bushel	186.1	431	Average, see Table 3.2
K2O	g/bushel	325.5	670	Average, see Table 3.2
Herbicide	g/bushel	43.02	15	Average, see Table 3.3
Pesticide	g/bushel	0.43	8.5	Average, see Table 3.3

[1] All soybean values from GREET – Biodiesel worksheet.

SimaPro was also utilized to obtain inventory data from the ecoinvent v. 2.0 and U.S. LCI databases. SimaPro was developed by PRé Consultants in 1990 (PRéConsultants 2008). SimaPro is a tool that contains the environmental performance of products and services from a number of databases, and can be used to model and analyze complex life cycles following the ISO 14040 series recommendations (PRéConsultants 2008). SimaPro allows you to obtain LCI data, calculate LCIA as well as perform scenario analyses. In addition to greenhouse gases and criteria air pollutants, SimaPro databases, such as ecoinvent and U.S. LCI, provide an extensive inventory of substances to determine the environmental impact of products and services.

SimaPro 7.1 was utilized to obtain additional inventory data to complement or replace the GHG and CAP data from GREET as necessary. The GHG and CAP data from GREET and SimaPro are presented in Table 3.5 (a)-(f), all inputs are expressed in terms of the functional unit, 1 kg of lubricant. The inputs utilized in the final assessment are highlighted with bold font. The final GHG and CAP data sources for the different life cycle stages are stated in Table 3.6. The GHG and CAP inventory graphs for rapeseed and mineral based lubricants are shown in Figure 3.5 and Figure 3.6.

The GHG and CAP inventory for rapeseed lubricants varies significantly from the mineral lubricant inventory (see Figure 3.6). Rapeseed has higher values for all GHG and CAP emissions, especially for NO_x and SO_x with 1.74E-02 and 1.99E-02 kg emission/kg lubricant for rapeseed and 2.91E-03 and 6.64E-03 kg emission/kg lubricant for mineral lubricants, respectively. However, there is a smaller gap between PM_{10} and $PM_{2.5}$ values, where rapeseed contributes 1.52E-03 kg PM_{10}/kg lubricant and 1.86E-03 kg $PM_{2.5}$/kg lubricant, and mineral contributes 1.58E-04 kg PM_{10}/kg lubricant and 3.19E-04 kg $PM_{2.5}$/kg lubricant to the inventory.

Table 3.5. GHG and CAP comparisons for 1 kg of lubricant

(a) Farming	**GREET**	**SimaPro**
VOC (kg)	1.80E-04	**1.49E-03**
CO (kg)	8.57E-04	**3.25E-03**
NO_x (kg)	1.54E-03	**1.09E-02**
PM_{10} (kg)	1.41E-04	**2.32E-04**
$PM_{2.5}$ (kg)	1.06E-04	**9.54E-04**
SO_x (kg)	9.02E-05	**1.30E-03**
CH_4 (kg)	3.37E-04	**1.21E-03**
N_2O (kg)	3.95E-06	**7.68E-03**
CO_2 (Mg)	2.14E-01	**7.39E+00**

(b) Nitrogen	**GREET**	**SimaPro**
VOC (kg)	**7.90E-04**	3.28E-04
CO (kg)	7.44E-04	**7.52E-04**
NO_x (kg)	4.42E-04	**1.59E-03**
PM_{10} (kg)	1.18E-04	**1.85E-04**
$PM_{2.5}$ (kg)	6.13E-05	**2.24E-04**
SO_x (kg)	2.32E-04	**4.45E-03**
CH_4 (kg)	3.76E-04	**3.20E-03**
N_2O (kg)	2.12E-04	**1.71E-03**
CO_2 (Mg)	3.16E-01	**7.12E-01**

(c) P2O5	**GREET**	**SimaPro**
VOC (kg)	1.67E-05	**2.55E-05**
CO (kg)	5.69E-05	**1.33E-04**
NO_x (kg)	**3.24E-04**	2.15E-04
PM_{10} (kg)	**7.74E-05**	7.42E-05
$PM_{2.5}$ (kg)	**4.75E-05**	4.51E-05
SO_x (kg)	**2.88E-03**	1.58E-03
CH_4 (kg)	7.97E-05	**1.09E-04**
N_2O (kg)	8.09E-07	**1.15E-06**
CO_2 (Mg)	4.42E-02	**7.27E-02**

(d) K2O	**GREET**	**SimaPro**
VOC (kg)	8.40E-06	**2.15E-05**
CO (kg)	3.00E-05	**1.10E-04**
NO_x (kg)	**1.28E-04**	1.08E-04
PM_{10} (kg)	**4.39E-05**	1.30E-05
$PM_{2.5}$ (kg)	**1.55E-05**	9.80E-06
SO_x (kg)	**9.35E-05**	5.60E-05
CH_4 (kg)	6.77E-05	**1.23E-04**
N_2O (kg)	6.65E-07	**2.50E-06**
CO_2 (Mg)	**4.57E-02**	3.34E-02

(e) Pesticide	**GREET**	**SimaPro**
VOC (kg)	**5.93E-06**	9.47E-07
CO (kg)	**2.30E-05**	1.04E-06
NO_x (kg)	**6.65E-05**	3.02E-06
PM_{10} (kg)	**2.95E-05**	1.54E-07
$PM_{2.5}$ (kg)	**1.40E-05**	4.69E-07
SO_x (kg)	**3.86E-05**	7.36E-06
CH_4 (kg)	**5.60E-05**	3.74E-06
N_2O (kg)	**4.73E-07**	3.78E-08
CO_2 (Mg)	**3.81E-02**	1.62E-03

(f) Milling	**GREET**	**SimaPro**
VOC (kg)	**1.07E-02**	8.63E-05
CO (kg)	**4.18E-04**	1.27E-04
NO_x (kg)	**1.04E-03**	2.98E-04
PM_{10} (kg)	**3.96E-04**	1.49E-05
$PM_{2.5}$ (kg)	**1.34E-04**	2.39E-05
SO_x (kg)	**7.42E-04**	3.79E-04
CH_4 (kg)	**2.62E-03**	4.51E-04
N_2O (kg)	**1.69E-05**	4.18E-06
CO_2 (Mg)	**9.95E-01**	2.60E-01

Table 3.6. Rapeseed LCI data sources

Inputs	**Data Source**
Farming	SimaPro - ecoinvent: • Rape seed, at farm/US U • Sowing/CH U • Tillage, cultivating, chiselling/CH U • Tillage, harrowing, by spring tine harrow/CH U • Tillage, ploughing/CH U • Application of plant protection products, by field sprayer/CH U • Fertilising, by broadcaster/CH U • Combine harvesting/CH U • Rape seed IP, at regional storehouse/CH U
Fertilizers	GREET SimaPro – ecoinvent: • Ammonia, liquid, at regional storehouse/RER U • Urea, as N, at regional storehouse/RER U • Ammonium nitrate, as N, at regional storehouse/RER U • Diammonium phosphate, as P2O5, at regional storehouse/RER U • Potassium chloride, as K2O, at regional storehouse/RER U SimaPro – U.S. LCI: • Nitrogen fertilizer, production mix, at plant/US
Herbicides	GREET
Pesticides	GREET
Milling	GREET SimaPro - ecoinvent: • Heat, natural gas, at industrial furnace >100kW/RER U • Oil mill/CH/I U • Hexane, at plant/RER U • Electricity, medium voltage, production UCTE, at grid/UCTE U • Grain drying, low temperature/CH U
Transportation	GREET
Refining	SimaPro - ecoinvent: • Heat, natural gas, at industrial furnace >100kW/RER U • Bentonite, at processing/DE U • Phosphoric acid, industrial grade, 85% in H2O, at plant/RER U • Electricity, medium voltage, production UCTE, at grid/UCTE U • Refinery/RER/I U SimaPro – U.S. LCI: • Hydrogen, liquid, chlor-alkali electrolysis, at plant/kg/RNA

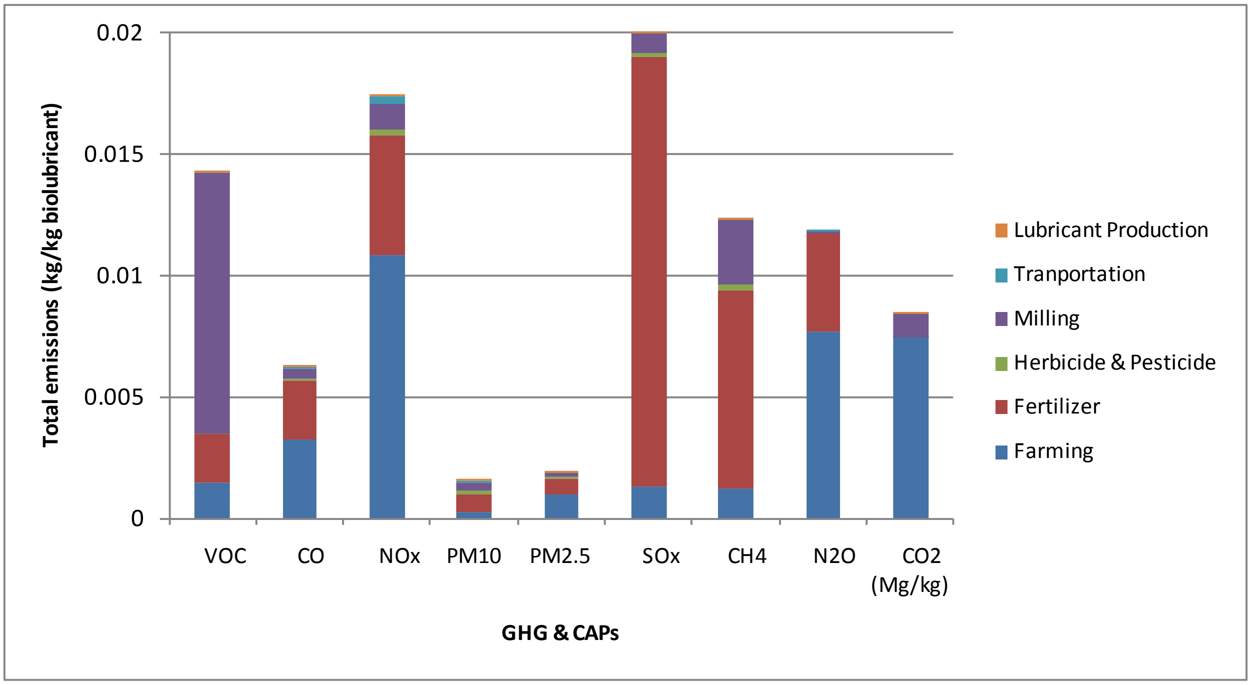


Figure 3.5. GHG & CAP Inventory for Rapeseed Lubricant

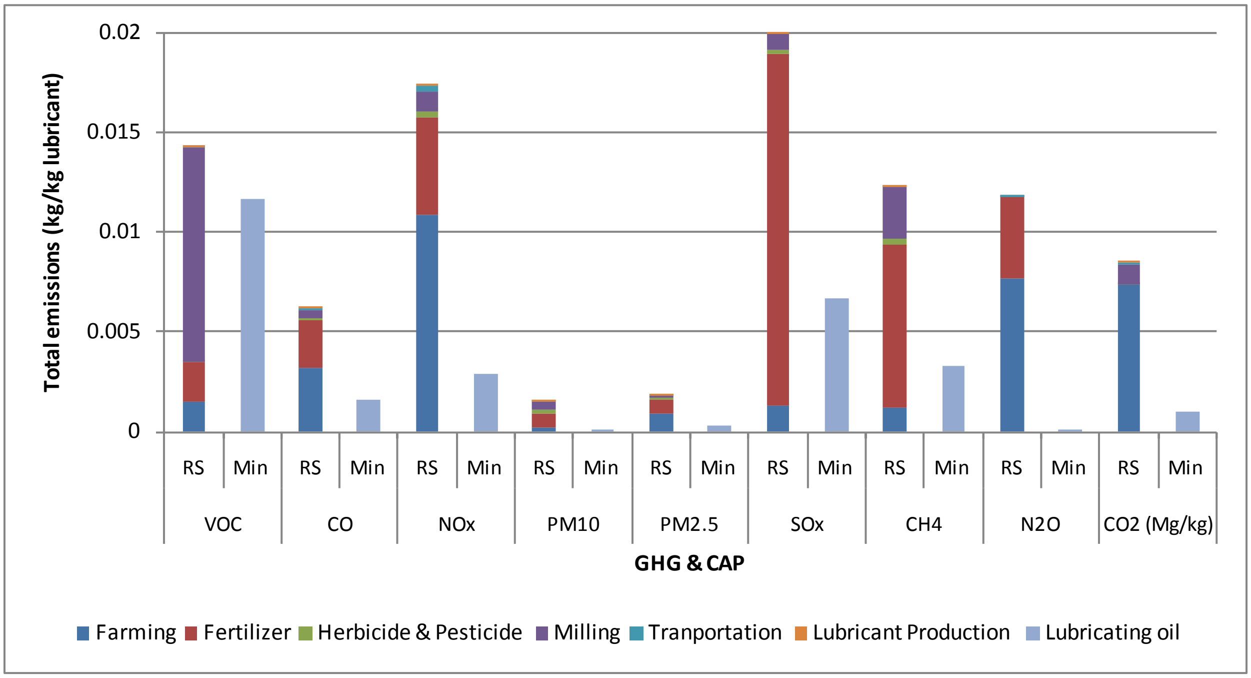


Figure 3.6. GHG & CAP Inventory for Rapeseed and Mineral Lubricants

3.2.3 Eutrophication Potential

Eutrophication occurs in water bodies that have a high concentration of nitrogen (N) and phosphorus (P), which stimulates plant growth and disrupts the balance between the production and metabolism of organic matter (Cloern 2001). The increase in N and P in surface waters and ground waters can be caused by deforestation, navigation channelization, production and application of fertilizers, discharge of human waste, animal production, and fossil fuel combustion (Cloern 2001; Costello et al. 2009). Excessive plant growth produces hypoxia, which is a decrease in dissolved oxygen levels that disrupts the natural functioning of the ecosystem and causes a reduction in fish, crab and shrimp populations (Costello et al. 2009). Eutrophication and hypoxia are evaluated in more detail because they are important environmental impacts for biobased products and are often underestimated in LCA studies (Miller et al. 2006; Powers 2007; Costello et al. 2009).

The eutrophication potential (EP) was modified by evaluating the water emissions from N and P fertilizer impacts, since these emissions are often overlooked and air emissions are typically the primary focus in many LCA studies (Miller et al. 2006). Other limitations include missing air inventory data and missing fertilizers from the farming stage, but these were not addressed in this study. The N and P inputs, shown in Table 3.7, were ammonia, urea, ammonium nitrate, and diammonium phosphate from the SimaPro process ‘Rape seed at farm/US U’. These inputs were utilized to determine the NO_3 river or surface runoff (SRO) and the P groundwater emission, which were missing from the SimaPro output inventory as shown in Table 3.8, using an emission factor approach.

The N and P farming inputs and outputs from two rapeseed studies were utilized to calculate the emission factor (EF), where EF is the ratio between N_{output} to N_{input} or P_{output} to

P_{input}. The N related emission factor was 13.37% from McManus et al. (2004) and 26.25% from the Vag et al. (2003) study as shown in Table 3.9. For P, the emission factors calculated were 0.24% and 2.14% for McManus et al. (2004) and Vag et al. (2003), respectively. Miller et al. (2006) obtained nitrogen EFs for corn and soybean at approximately 38% and 21% respectively (Miller et al. 2006). Based on these results, 25% was assumed for the NO_3 SRO EF and 2% for the P groundwater EF from Vag et al. (2003) were utilized in this study.

The total N and P inputs from 'Rape seed at farm' were multiplied by the EFs (25% and 2%) and the appropriate TRACI CF to obtain the missing LCIA factors. Table 3.10 shows the CFs that correspond to the TRACI LCIA method, discussed further in Section 3.2.4. NO3 SRO and P groundwater emissions resulted in 2.01E-02 kg N eq/kg lubricant and 1.55E-03 kg N eq/kg lubricant, respectively, which were added to the original EP of 5.44E-02 kg N eq/kg lubricant. The final EP utilized in this study was 7.61E-02 kg N eq/kg lubricant. Final EP sources for each compartment (groundwater, surface runoff, and air) are shown in Table 3.11. Figure 3.7 depicts the original EP results and the final EP results that included the missing SRO and GW data.

Table 3.7. SimaPro inputs from 'Rape seed at farm/US U'

Input materials	Input to farm	
Ammonia, liquid, at regional storehouse/RER U	0.052966	kg/kg seed
Urea, as N, at regional storehouse/RER U	0.01832	kg/kg seed
Ammonium nitrate, as N, at regional storehouse/RER U	0.025299	kg/kg seed
Total N input	**0.03426**	**kg N/kg seed**
Diammonium phosphate, as P2O5, at regional storehouse/RER U	0.01902	kg/kg seed
Total P input, (PO_4)	**0.0136886**	**kg PO4/kg seed**
Total P input (P)	**0.0044668**	**kg P/kg seed**

Table 3.8. SimaPro outputs from ‘Rape seed at farm/US U’

Compound	Compartment	Emission from farm	Total emission	% of total emission
Nitrate	Groundwater	0.050138 kg/kg seed	50.485507 g	99.31
Phosphorus	River	0.00066 kg/kg seed	661.08346 mg	99.83
Phosphate	River	0.000892 kg/kg seed	1.9851295 g	44.92
Phosphate	Groundwater	5.92E-05 kg/kg seed	1.9851295 g	2.98

Table 3.9. Nitrogen and phosphorus emission factors

Reference	Input	Output	Emission factor
McManus (2004)	187 kg NO_3/ha	25 kg NO_3/ha	13.37%
McManus (2004)	70 kg PO_4/ha	0.17 kg P/ha	0.24%
Vag (2003)	160 kg N/ha	42 kg N/ha	26.25%
Vag (2003)	14 kg P/ha	0.3 kg P/ha	2.14%

Table 3.10. TRACI CFs from EP category

Compartment	Compound	TRACI CF	
Water	Phosphate	2.38	kg N eq / kg
Water	Phosphorus	7.29	kg N eq / kg
Water	Nitrate	0.2367	kg N eq / kg
Water	Nitrogen	0.9864	kg N eq / kg

Table 3.11. LCIA data sources for EP

LCIA_{EP}	Units	NO_3	P	PO_4
EP_{GW}	kg N eq/kg lubricant	SimaPro 2.83E-02	Cuevas 1.55E-03	SimaPro 3.36E-04
EP_{SRO}	kg N eq/kg lubricant	Cuevas 2.01E-02	SimaPro 1.15E-02	SimaPro 5.05E-03
EP_{Air}	N/A	N/A	N/A	N/A

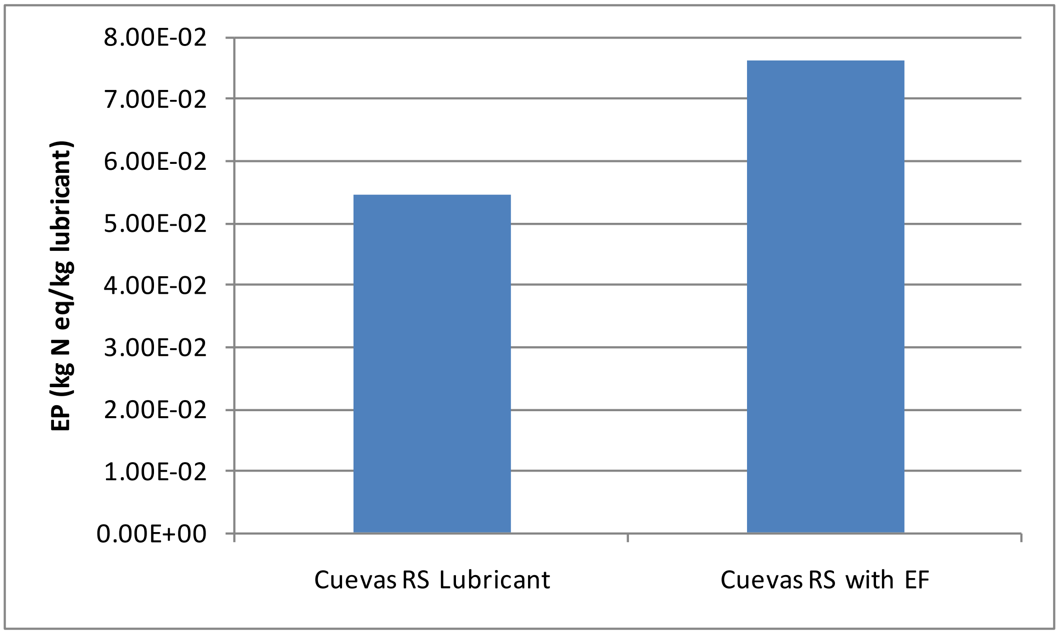


Figure 3.7. Comparison of original and modified EP results

3.2.4 LCIA

SimaPro LCI data were also utilized to complete the life cycle impact assessment (LCIA). The LCIA allows the LCI results to be aggregated based on the contribution of numerous pollutants to a certain impact category. This study utilized the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI 2 V3.01) to perform the LCIA. TRACI was developed by the U.S. Environmental Protection Agency to be used with LCA (Bare et al. 2003). The tool establishes characterization factors that can be utilized to determine the effects of pollutants on 12 categories. These categories are the following: acidification, ecotoxicity, eutrophication, fossil fuel depletion, global warming, human health – cancer, human health – criteria, human health – non-cancer, land use, ozone depletion, photochemical smog, and water use. The LCIA results include all LCI data, GHG and CAP data as well as SimaPro, ecoinvent and U.S. LCI, inventory data for rapeseed, soybean and mineral lubricant. The results are shown in Table 3.12 and Figures 3.8 to Figure 3.17.

In summary, the following steps were performed to obtain the LCI data and complete the LCIA:

1. Gather LCI data:
    a. Find literature data for rapeseed and update GREET.
    b. Extract and evaluate rapeseed and mineral data from SimaPro.
2. LCI data selection:
    a. Compare GHG & CAP data from GREET with SimaPro data.
    b. Select appropriate data and evaluate range of LCI inputs.
3. LCIA results:
    a. Calculate LCIA values for the selected LCI data using TRACI CF.
        i. If the selected LCI data is from GREET, then:

           Final LCIA value = SP LCIA Total - (SP LCI×CF) + (GREET LCI×CF)
        ii. If the selected LCI data is from SimaPro, use LCIA values calculated in 3.a.

The farming and fertilizer stages were the largest contributors to the rapeseed LCIA results. However, milling was also a significant contributor in the GWP and PS categories. Therefore, a reduction in fertilizer usage would significantly reduce the overall environmental impacts caused by rapeseed lubricant. In addition, a reduction in the contributions from the rapeseed farming stage would require a considerable cutback in machinery use.

The rapeseed LCIA results from this study (Cuevas rapeseed) were compared to SimaPro – ecoinvent processes: ‘Rape oil, at oil mill/RER U’, ‘Soybean oil, at oil mill/US U’ and ‘Lubricating oil, at plant/RER U’. ‘Rape oil at mill’ includes transport of rape seeds to the mill, processing the seeds to rape oil and rape meal, and oil extraction using the cold-press extraction technique. The system boundary is at the oil mill. The inventory refers to production of 1 kg of rape oil using European data. The ‘soybean oil at oil mill’ process includes transport of soybeans to the mill, and the processing of soybeans through pre-cracking of soybeans, dehulling, oil extraction, meal processing and oil purification. The inventory refers to the production of 1 kg soybean oil using U.S. data. The ‘lubricating oil’ process includes raw materials and chemicals used for production, transport of materials to manufacturing plant, estimated emissions to air and water from production, and estimation of energy demand and infrastructure of the plant. The inventory refers to 1 kg of liquid lubricating oil based on European data.

The rapeseed, soybean and mineral lubricant comparison was completed by analyzing all of the processes using TRACI. The comparison is depicted in Figure 3.18. The results were normalized to the highest contributor of that impact category. Cuevas rapeseed lubricants dominated the majority of the affected impact categories – acidification potential (AP), carcinogenics, respiratory effects (RE), eutrophication and photochemical smog (PS). For example, rapeseed contributed 5.91E-03 kg benzene eq/kg lubricant in the carcinogenics category, while soybean and mineral lubricants contributed 9.84E-04 kg benzene eq/kg lubricant and 2.54E-03 kg benzene eq/kg lubricant, respectively. ‘Rape oil at oil mill’ had the largest non-carcinogenics and ecotoxicity contributions, while ‘lubricating oil’ governed the GWP and ODP categories. ODP contributions from rapeseed totaled 2.83E-07 kg CFC-11 eq/kg lubricant, contributions from soybean totaled 4.73E-08 kg CFC-11 eq/kg lubricant, while the mineral lubricant totaled 6.48E-07 kg CFC-11 eq/kg lubricant. Based on these results, it is clear that there were significant differences between both of the rapeseed processes. These differences could be due to differences in the system boundary, inventory sources, among others.

In the GWP category, the rapeseed and soybean processes presented negative values due to the assumption that CO_2 is sequestered during the farming stage. Soybean also had a negative contribution in the ecotoxicity category, as shown in Figure 3.15, due to cadmium, chromium, copper, nickel and zinc emissions, which were probably assumed to be absorbed by the soil (Lenntech 2009). The ‘soybean oil at oil mill’ documentation provided no discussion regarding the negative emissions. These results could be misleading when making biofuel/crop decisions, since a user could assume that applying more fertilizers, which is one of the sources of these metals, would produce a negative ecotoxicity impact. Therefore, the ecotoxicity results were recalculated without the negative emissions to soil, and the results are shown in Figure 3.16. For AP, the rapeseed processes had the highest contributions, mainly from the farming and fertilizer stages. Lubricating oil followed in AP contributions; it has no farming or fertilizer stages. EP is also commonly affected by farming and fertilizer practices. The rapeseed and soybean processes had the highest EP values. ‘Lubricating oil’ had the largest ODP contribution, where the main contributor was bromotrifluoromethane - Halon 1301, which is utilized as a fire suppressant in lube oil systems. ‘Cuevas rapeseed’ leads the PS category by 65% or more with the milling stage having the most VOC contributions.

Table 3.12. LCIA results for 1 kg of rapeseed, soybean and mineral lubricant

Impact category	Unit	Rapeseed lubricant	Soybean lubricant	Lubricating oil
Global Warming	kg CO2 eq	-3.62E-01	-1.65E+00	1.07E+00
Acidification Potential	H+ moles eq	2.70E+00	1.97E-01	4.58E-01
Carcinogenics	kg benzen eq	5.91E-03	9.84E-04	2.54E-03
Non carcinogenics	kg toluen eq	3.34E+01	3.29E+00	1.43E+01
Respiratory effects	kg PM2.5 eq	4.91E-03	6.66E-04	2.29E-03
Eutrophication Potential	kg N eq	7.61E-02	2.90E-02	2.31E-03
Ozone Depletion Potential	kg CFC-11 eq	2.83E-07	4.73E-08	6.48E-07
Ecotoxicity	kg 2,4-D eq	1.78E+00	-2.08E+00	1.22E+00
Photochemical Smog	kg NOx eq	2.29E-02	3.86E-03	3.09E-03

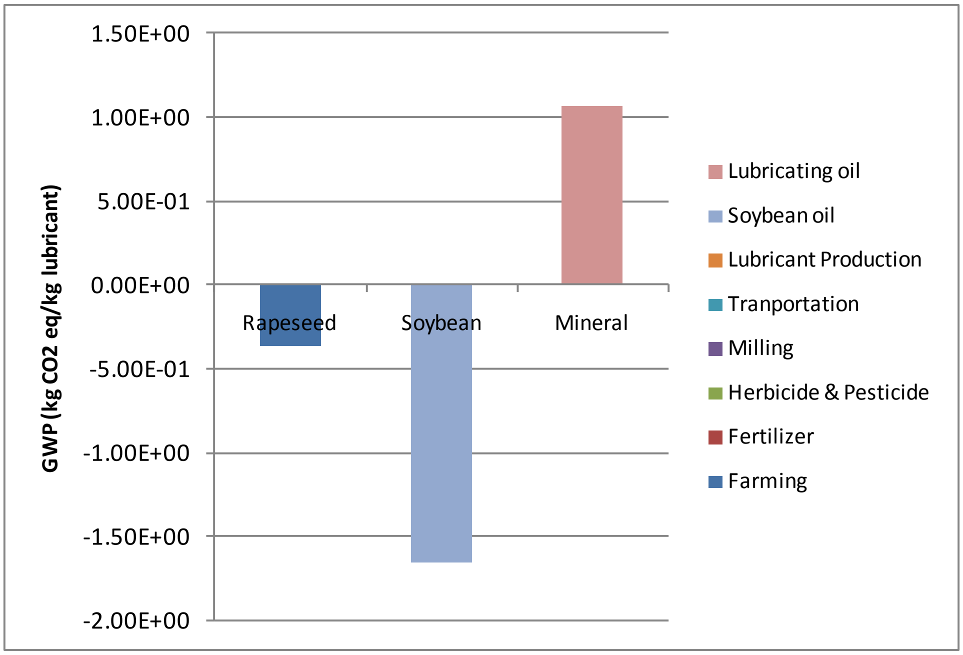


Figure 3.8. LCIA Results: Global Warming Potential

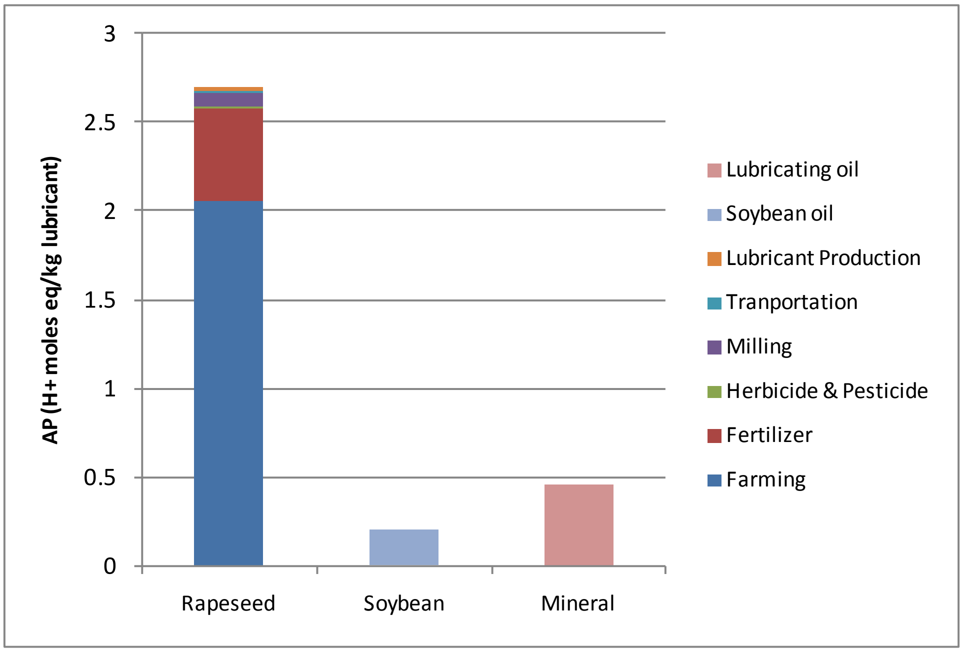


Figure 3.9. LCIA Results: Acidification Potential

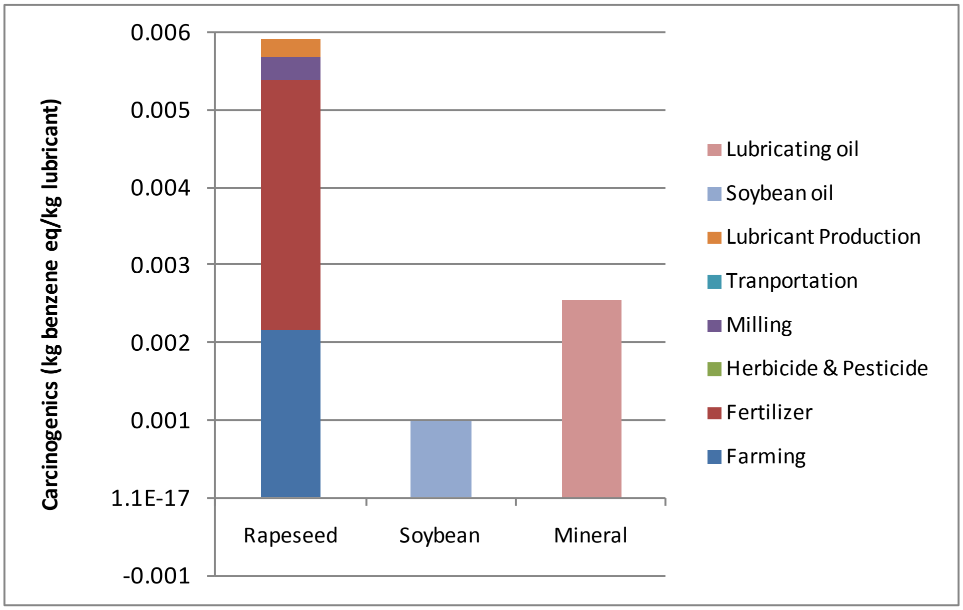


Figure 3.10. LCIA Results: Carcinogenics

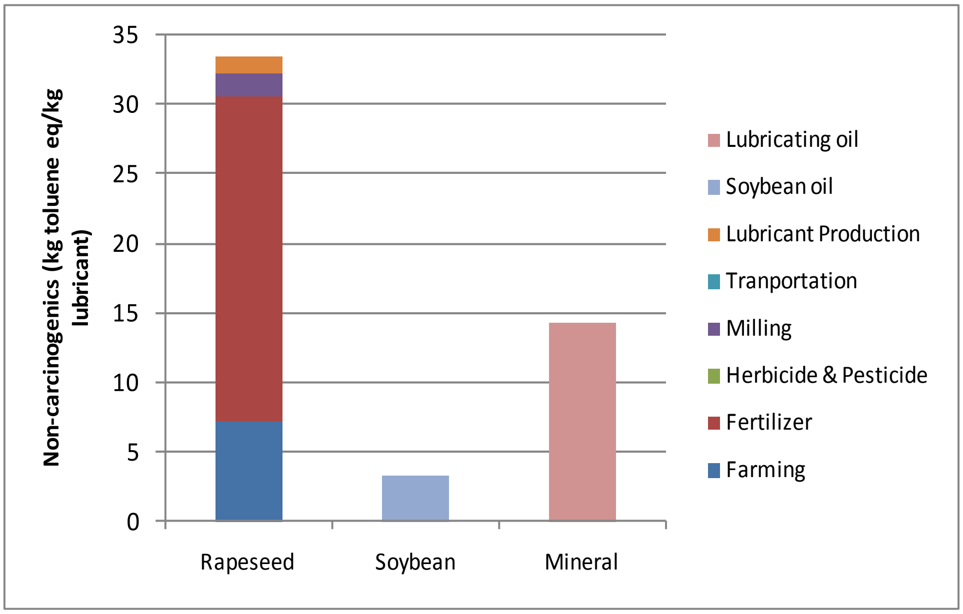


Figure 3.11. LCIA Results: Non-carcinogenics

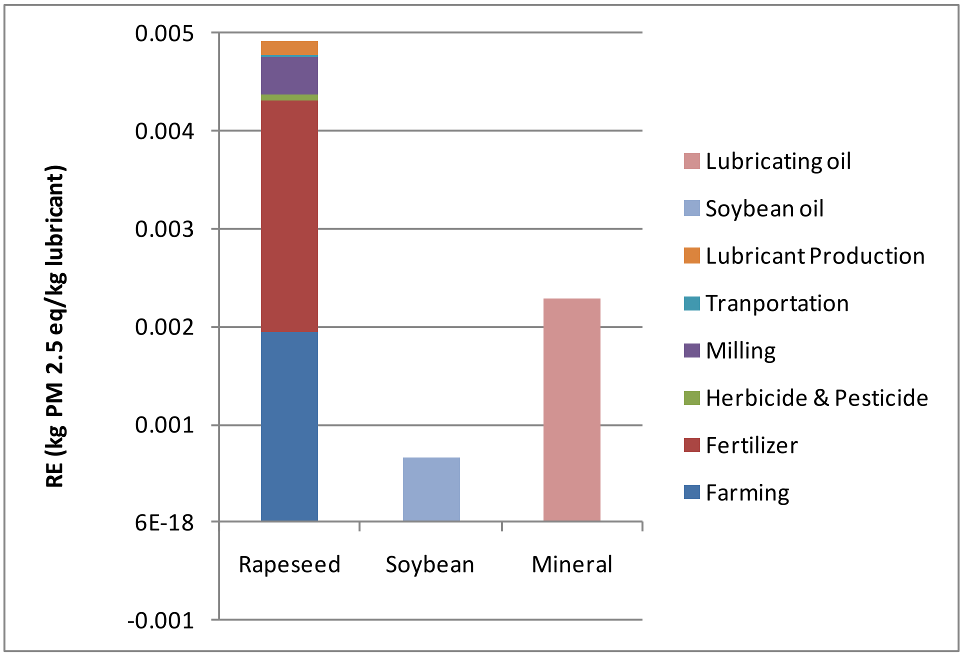


Figure 3.12. LCIA Results: Respiratory Effects

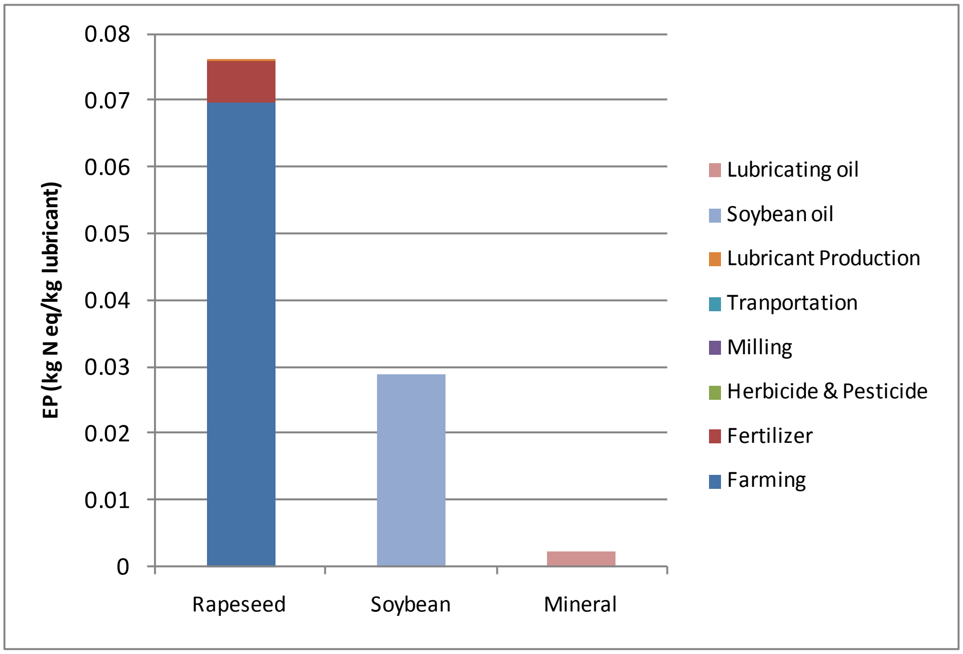


Figure 3.13. LCIA Results: Eutrophication Potential

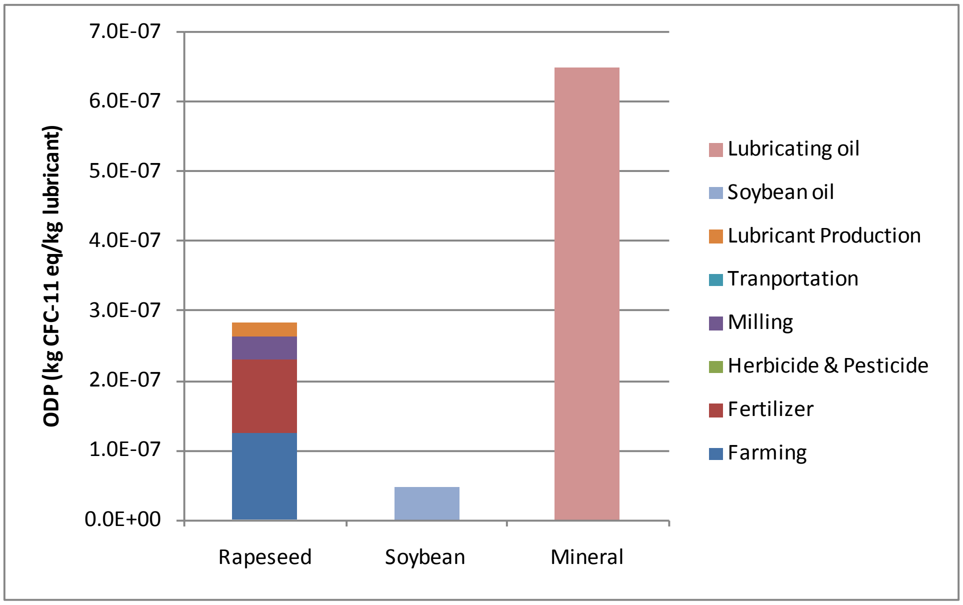


Figure 3.14. LCIA Results: Ozone Depletion Potential

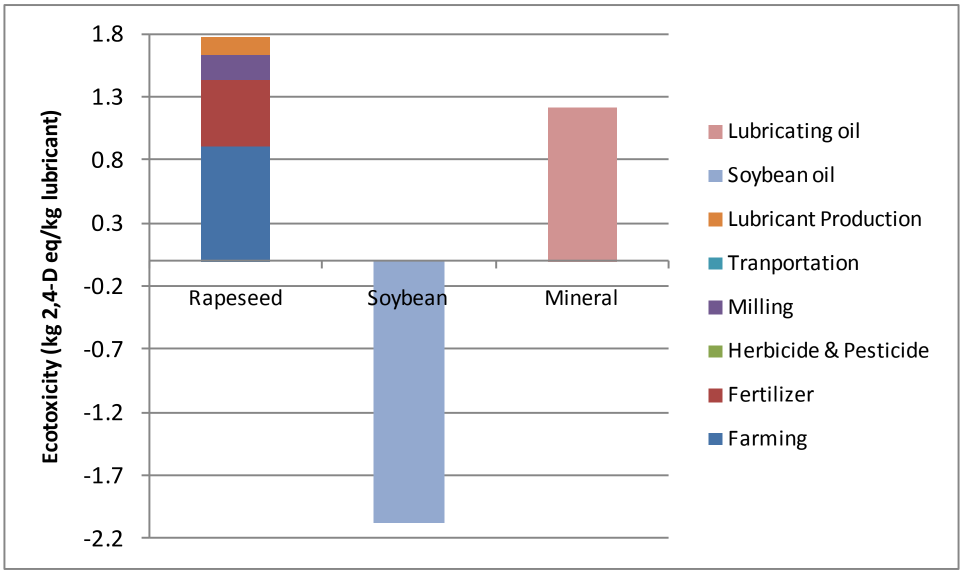


Figure 3.15. LCIA Results: Ecotoxicity

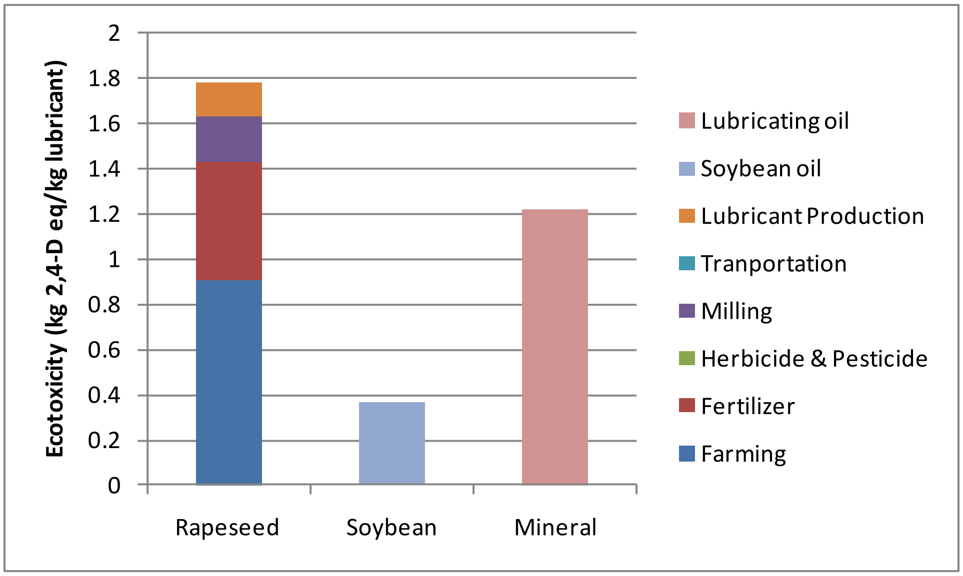


Figure 3.16. LCIA Results: Modified Ecotoxicity

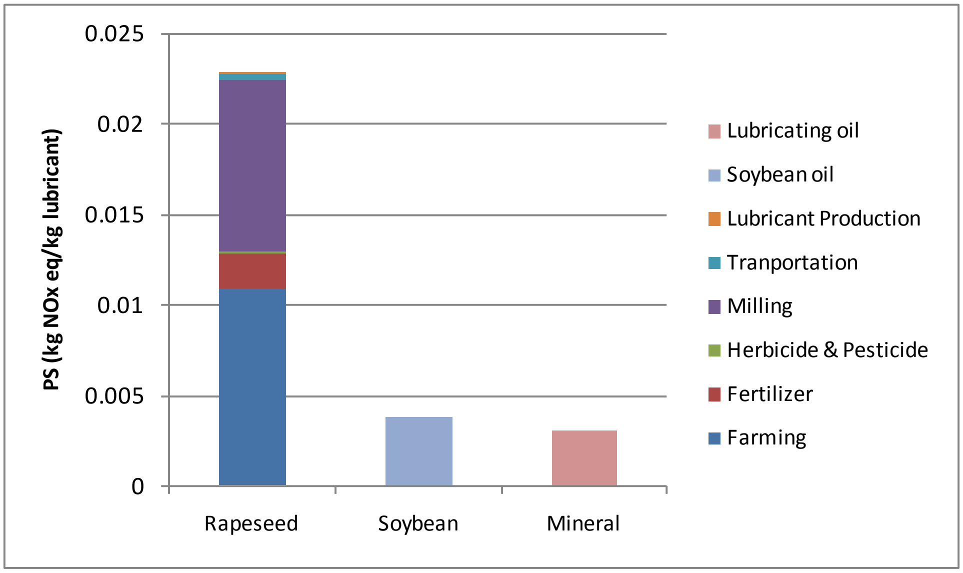


Figure 3.17. LCIA Results: Photochemical Smog

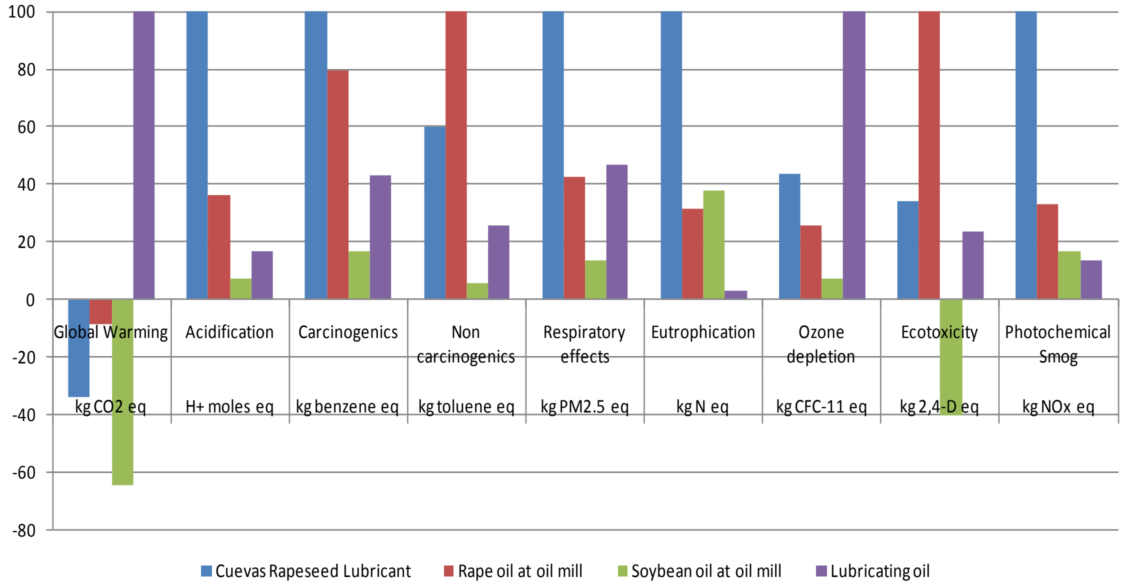


Figure 3.18. Normalized LCIA results

3.2.5 Validation

In order to further validate the approach of this study, the LCIA results were also compared to LCIA results from other rapeseed, soybean and mineral LCA studies. Only GWP, AP, EP and ODP categories were compared due to major differences in functional units and impact category units among the studies. In order to compare the results from this study to other findings, the reference units must be the same. Therefore, Cuevas results for AP and EP were converted to comparable units using CFs from TRACI, while McManus EP was converted to comparable units utilizing CFs from the Eco-indicator 95 LCIA database. The characterization factors utilized to complete the conversions are shown in Table 3.13. The original data and the converted results for all the studies are tabulated in Table 3.14 through Table 3.16. The results of these comparisons are depicted in Figure 3.18 through Figure 3.21.

Each study included in the comparison had its own characteristics. Major differences existed between goal, system boundary, and functional unit as shown previously in Table 2.2. The ‘Cuevas rapeseed’, ‘Rape oil at oil mill’, ‘Soybean oil at oil mill’, Schmidt (2010), and McManus (2006) studies include the stages from farming up to milling. While the following studies only included farming: Kim and Dale (2004), Pelletier (2008), and Dalgaard (2008). ‘Lubricating oil’ includes all stages up to refining, where the lube oil is produced. Finally, Vag et al. (2002) analyzes rapeseed and mineral lubricants from farming or crude oil extraction to lubricant use.

Several studies were not included due to these major differences; however some conversions were utilized to allow data analysis. For example, the results from Kim and Dale (2004), Pelletier et al. (2008), and Dalgaard et al. (2008) had functional units in terms of ‘1 kg of crop/seed’. Therefore, 42% oil content for rapeseed and 20% oil content for soybeans (Frier and Roth 2006) was utilized to convert the results in terms of ‘1 kg of oil’. A rapeseed density of 0.91 g/cm^3 (Gunstone 2004) was also utilized to convert data from the Vag et al. (2002) study.

The normalized results show ‘Vag mineral’ with the highest GWP impacts, followed by ‘Dalgaard rapeseed’ – 96%, ‘McManus mineral’ – 93%, and ‘Dalgaard soybean’ – 83%. ‘Lubricating oil’ did not have similar results as the other mineral studies scoring only 28%. The lowest impact was from ‘Soybean oil at oil mill’ with approximately -43% due to the carbon credit discussed above. The remaining studies ranged from approximately -9% to 58%. As mentioned previously there were significant differences in system boundaries and LCIA methods utilized.

For AP, ‘Cuevas rapeseed’ had the highest contribution followed by ‘Pelletier RS’ – 90%, ‘Pelletier SB’ – 68%, ‘Vag mineral’ – 54%, and ‘Dalgaard RS’- 53%. Mineral lubricant results were inconsistent, and presented no similarities. The lowest AP impacts were from 'McManus RS', 'Soybean oil at mill', 'Dalgaard SB, and 'McManus mineral' with normalized value sthat ranged from 6-7.5%. The remaining studies ranged from approximately 17% to 38%.

EP results were very irregular. 'Dalgaard RS' resulted in the highest EP impact followed by 'Cuevas rapeseed', 'Soybean oil at oil mill', and 'Rape oil at oil mill' with approximately 97%, 37%, and 30%, respectively. The remaining studies all resulted in less than 1.5%.

Finally, 'Lubricating oil' had the largest ODP contribution followed by 'Dalgaard rapeseed' with 85% and 'Dalgaard soybean' with 62%. The impacts from McManus using Eco-indicator 95 resulted in less than 0.1% in both the rapeseed and mineral lubricant cases. Pelletier rapeseed and soybean, which included only the farming stage in its CML 2 analysis, resulted in ODP impacts of 10% and 8%, respectively. Average ODP impacts resulted from 'Cuevas rapeseed' – 44%, 'Rape oil at oil mill' – 26%, and 'Schmidt rapeseed' – 25%.

Throughout all the comparisons, the studies that only included farming, especially Dalgaard et al. (2008), had higher results than some of the studies that included all of the life cycle stages of the lubricant. These results seemed inconsistent, and it was not clear why this major difference occurred. However, several hypotheses were made. For instance, the Dalgaard et al. (2008) study utilized an average from Danish farming practices for the inventory, used EDIP97 as the LCIA method, and performed consequential LCA, which could have affected the results. Pelletier et al. (2008) utilized SimaPro 7.0 with the CML 2 Baseline 2000 LCIA method to study the effects of changing from conventional to organic production of several field crops in Canada. Conventional rapeseed results were consistently higher than the other conventional crop results.

Table 3.13. LCIA conversions for comparative purposes

Category	Desired unit	Cuevas RS unit	TRACI CF[1]	McManus unit	Eco-ind. 95 CF[1]
GWP	kg CO$_2$ eq	kg CO$_2$ eq	no conversion	kg CO$_2$ eq	no conversion
AP	kg SO$_2$ eq	H+ moles eq	50.79 H+ moles eq/kg SO$_2$	kg SO2 eq	no conversion
EP	kg NO$_3$ eq	kg N eq	0.2367 kg N eq/kg NO3	kg PO3-4 eq	0.1 kg PO$_3^{-4}$ eq/kg NO3
ODP	kg CFC-11 eq	kg CFC-11 eq	no conversion	kg CFC-11 eq	no conversion

[1] Conversions completed using the characterization factor (CF) from each study's tool.

Table 3.14. GWP and AP results from other studies

Study	FU	GWP	AP
Cuevas RS	kg lube	-3.62E-01 kg CO2 eq	2.70 H+ moles eq
RSO at oil mill	kg lube	-9.36E-02 kg CO2 eq	9.74E-01 H+ moles eq
McManus RS	kg oil	3.00E-01 kg CO2 eq	3.27E-03 kg SO2-4 eq
Vag RS	m3 lube	1400 kg CO2 eq	11 kg SO2 eq
Pelletier RS	kg crop	696.3 g CO2 eq	2.02E-02 kg SO2 eq
Dalgaard RS	kg RS	1550 g CO2 eq	11.8 g SO2 eq
Schmidt RS	tonne oil	2.22 t CO2 eq	20.2 kg SO2 eq
SBO at oil mill	kg lube	-1.65E+00 kg CO2 eq	1.97E-01 H+ moles eq
Pelletier SB	kg crop	247.6 g CO2 eq	7.2 g SO2 eq
Dalgaard SB	kg RS	642 g CO2 eq	0.8 g SO2 eq
Kim SB	kg crop	163 g CO2 eq	Not included
Lubricating oil	kg oil	1.07 kg CO2 eq	4.85E-01 H+ moles eq
McManus Min	kg oil	3.56 kg CO2 eq	3.83E-03 g SO2-4 eq
Vag Min	m3 lube	3500 kg CO2 eq	26 kg SO2 eq

Table 3.15. EP and ODP results from other studies

Study	FU	EP	ODP
Cuevas RS	kg lube	7.61E-02 kg N eq	2.83E-07 kg CFC-11 eq
RSO at oil mill	kg lube	2.38E-02 kg N eq	1.66E-07 kg CFC-11 eq
McManus RS	kg oil	1.02E-03 kg PO3-4 eq	4.25E-10 kg CFC-11 eq
Vag RS	m3 lube	Not included	Not included
Pelletier RS	kg crop	Not included	27.6 µg CFC-11 eq
Dalgaard RS	kg RS	139 g NO3 eq	0.23 mg CFC-11 eq
Schmidt RS	tonne oil	140 t NO3 eq	163 mg CFC-11 eq
SBO at oil mill	kg lube	2.90E-02 kg N eq	4.73E-08 kg CFC-11 eq
Pelletier SB	kg crop	Not included	10.4 µg CFC-11 eq
Dalgaard SB	kg RS	1 g NO3 eq	0.08 mg CFC-11 eq
Kim SB	kg crop	Not included	Not included
Lubricating oil	kg oil	2.38E-02 kg N eq	1.66E-07 kg CFC-11 eq
McManus Min	kg oil	3.78E-04 kg PO3-4 eq	8.9E-12 kg CFC-11 eq
Vag Min	m3 lube	Not included	Not included

Table 3.16. LCIA results from other studies for 1 kg oil/lube

Study	GWP	AP	EP	ODP
unit	kg CO2 eq	kg SO2 eq	kg NO3 eq	kg CFC-11 eq
Cuevas RS	-3.62E-01	5.32E-02	3.21E-01	2.83E-07
RSO at oil mill	-9.36E-02	1.92E-02	1.01E-01	1.66E-07
McManus RS	3.00E-01	3.27E-03	1.02E-03	4.25E-10
Vag RS	1.54E+00	1.21E-02	Not included	Not included
Pelletier RS	1.66E+00	4.81E-02	Not included	6.57E-08
Dalgaard RS	3.69E+00	2.81E-02	3.31E-01	5.48E-07
Schmidt RS	2.22E+00	2.02E-02	1.40E+02	1.63E-07
SBO at mill	-1.65E+00	3.88E-03	1.22E-01	4.73E-08
Pelletier SB	1.24E+00	3.60E-02	Not included	5.20E-08
Dalgaard SB	3.21E+00	4.00E-03	5.00E-03	4.00E-07
Kim SB	8.15E-01	Not included	Not included	Not included
Lubricating oil	1.07E+00	9.02E-03	2.31E-03	6.48E-07
McManus Min	3.56E+00	3.83E-03	3.78E-03	8.90E-12
Vag Min	3.85E+00	2.86E-02	Not included	Not included

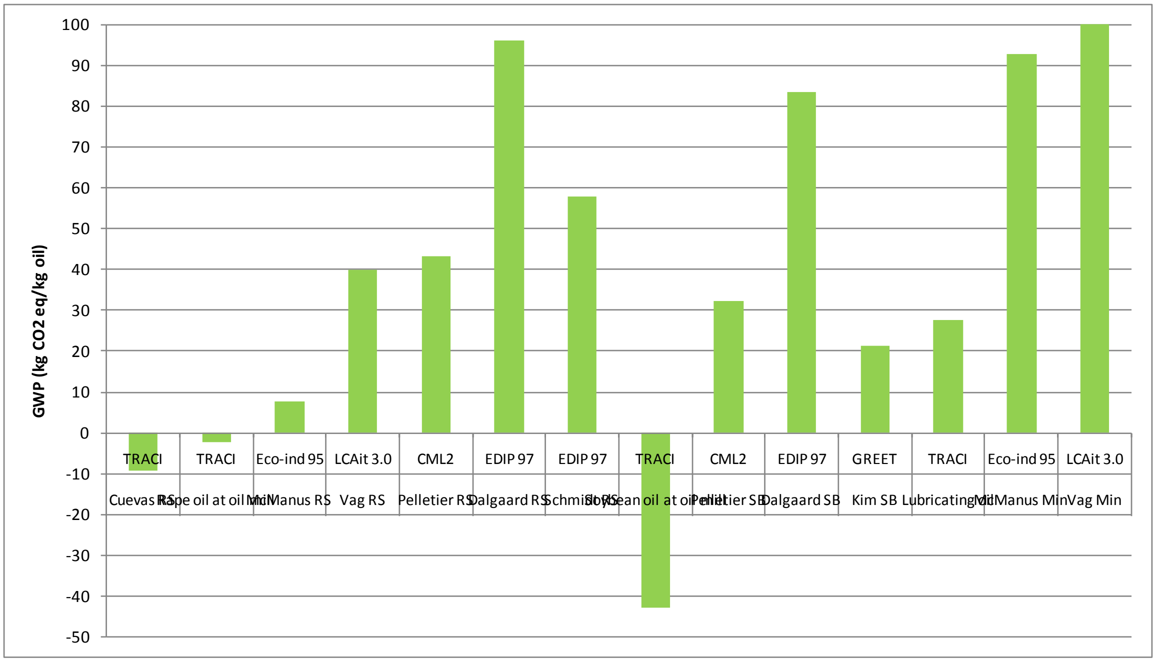


Figure 3.19. Validation: Normalized Global Warming Potential results

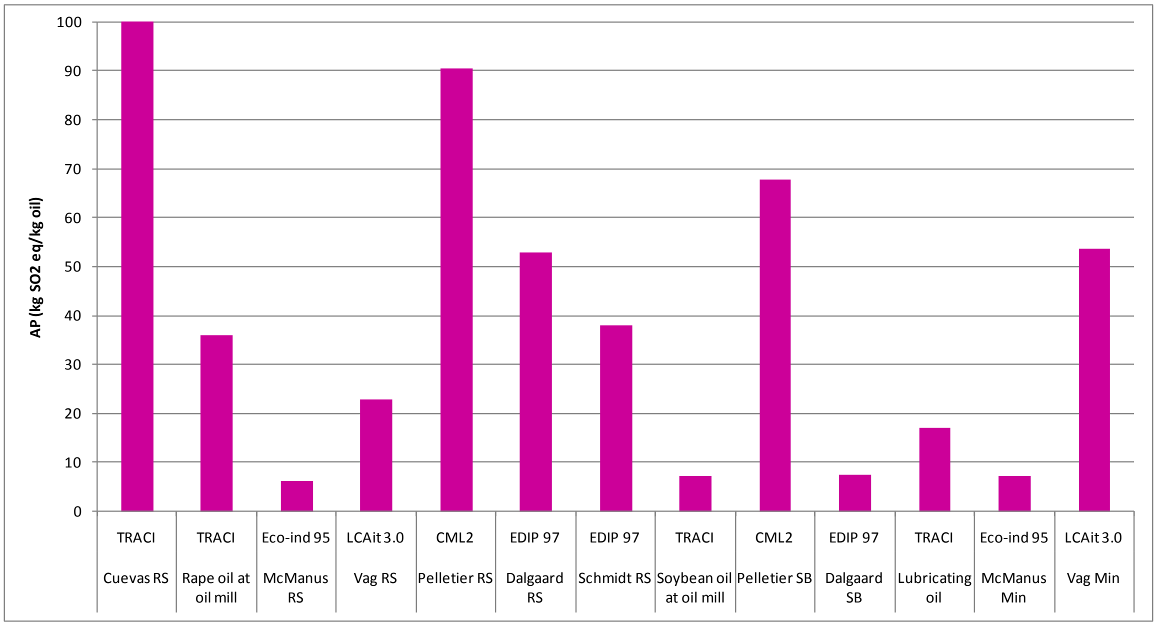


Figure 3.20. Validation: Normalized Acidification Potential results

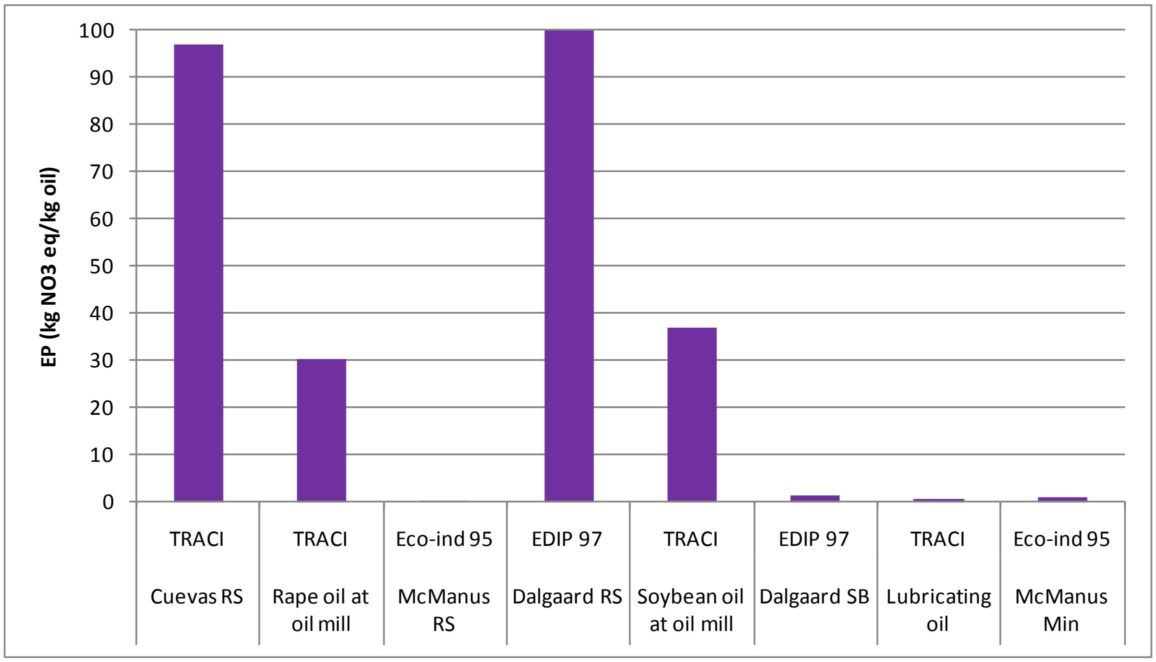


Figure 3.21. Validation: Normalized Eutrophication Potential results

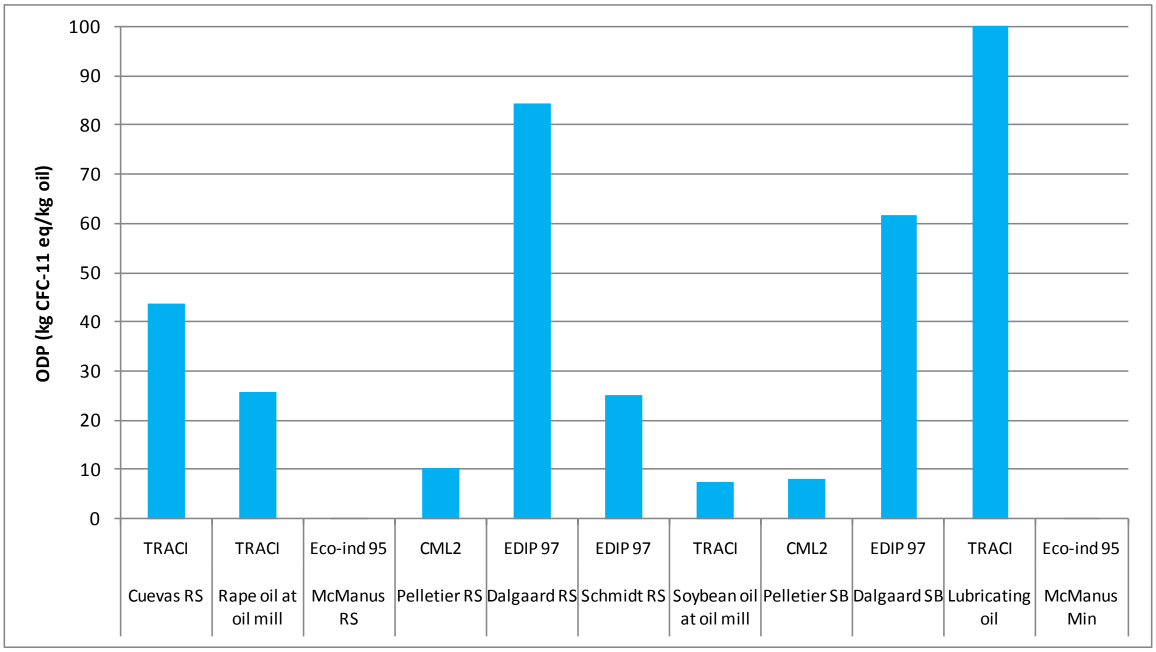


Figure 3.22. Validation: Normalized Ozone Depletion Potential results

‘Cuevas rapeseed’ results were also compared to Schmidt (2010) results. This study modeled different scenarios for rapeseed oil (RSO) from farming to refining using the EDIP 97 LCIA method. Most scenarios address consequential modeling, which considers system expansion in the agricultural stages. An attributional scenario, where allocation is typically done by economic value, by energy content or by mass, and system expansion is not taken into account (Schmidt 2010), was also modeled. The RSO scenarios are described in Table 3.17.

GWP, AP, EP, and ODP impact categories were compared, and the results are shown in Figure 3.22 through Figure 3.25. In all categories RSO3, RSO1a, and RSO1b had the highest impacts, in that order. These scenarios considered increases in RSO production through an increase in agricultural yields, which is achieved by additional fertilizer inputs that create higher impacts (Schmidt 2010). ‘Cuevas rapeseed’ results are comparable to the LCIA results from all other scenarios, except in the EP category where the impact is significantly lower. Detailed comparisons were not possible, since Schmidt (2010) did not provide information regarding fertilizer application rates or related nitrate/phosphate runoff data.

Table 3.17. Schmidt (2010) RSO Scenarios

Scenario	**Description**
RSO1a/b	Consequential modeling in oil mill and agricultural stages. Marginal increases are assumed to be achieved by a combination of increase in agricultural area and yields. (a) Constrained area. (b) Local expansion
RSO2a/b	Consequential modeling in oil mill and agricultural stages. Marginal increases are assumed to be achieved by a combination of increase in agricultural area only. (a) Constrained area. (b) Local expansion
RSO3	Consequential modeling in oil mill and agricultural stages. Marginal increases are assumed to be achieved by a combination of increase in agricultural yields only.
RSO4	Semi-consequential modeling, system expansion in oil mill stage and attributional modeling in agricultural stage.
RSO5	Attributional modeling, i.e. economic allocation and no system expansion.

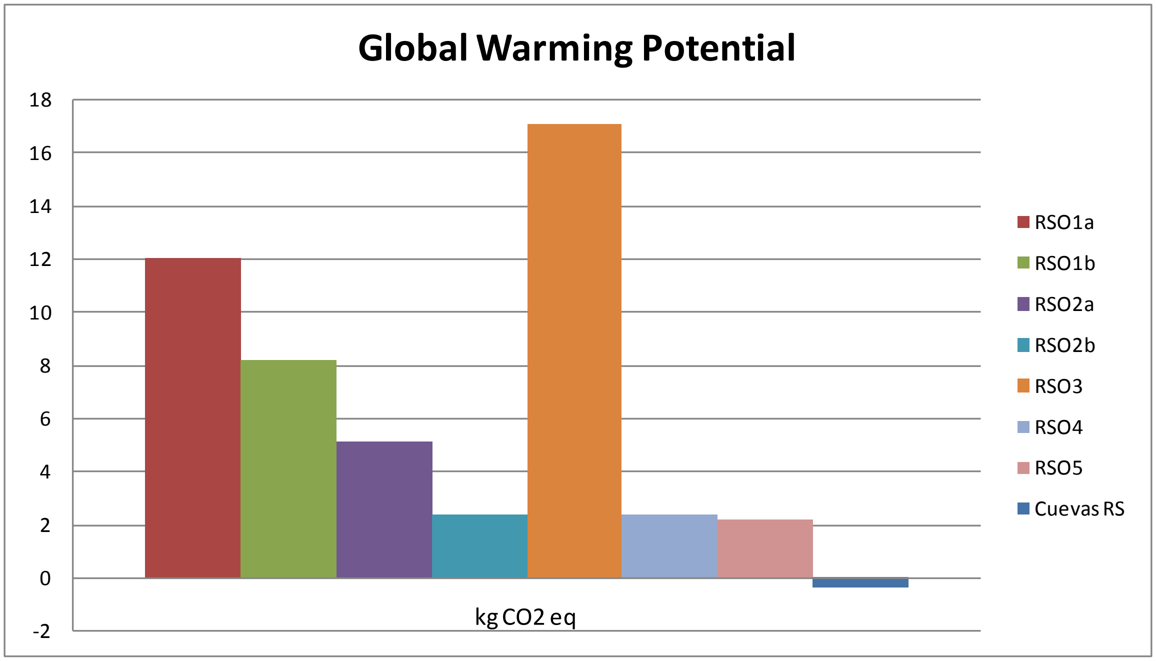


Figure 3.23. Comparison to Schmidt 2010: Global Warming Potential

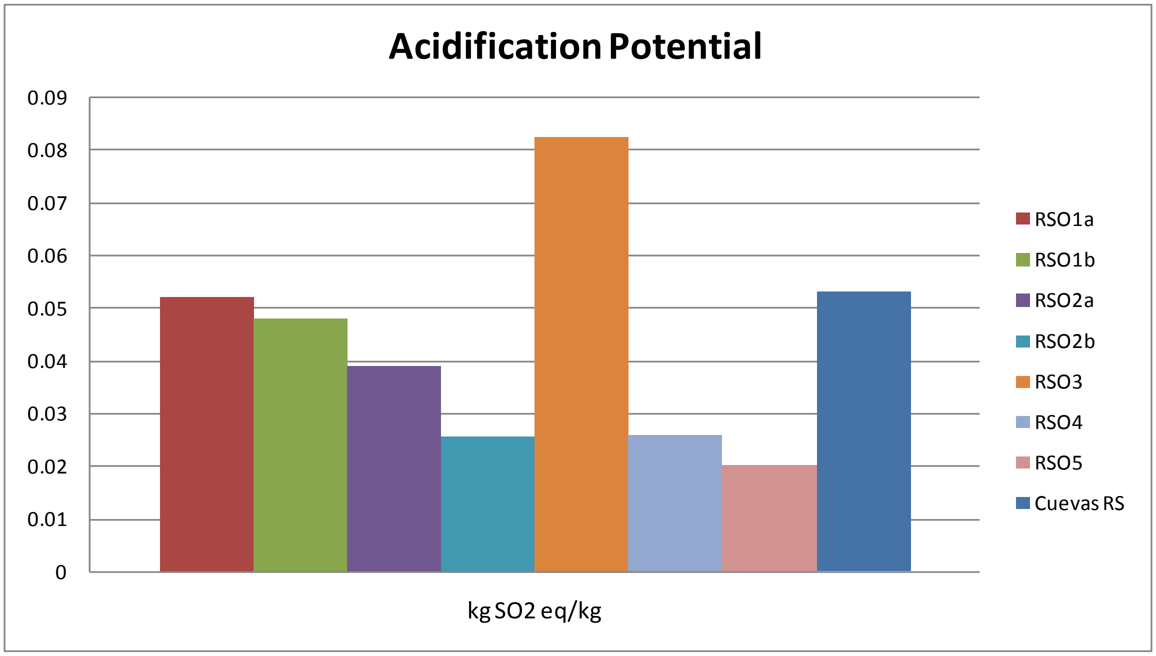


Figure 3.24. Comparison to Schmidt 2010: Acidification Potential

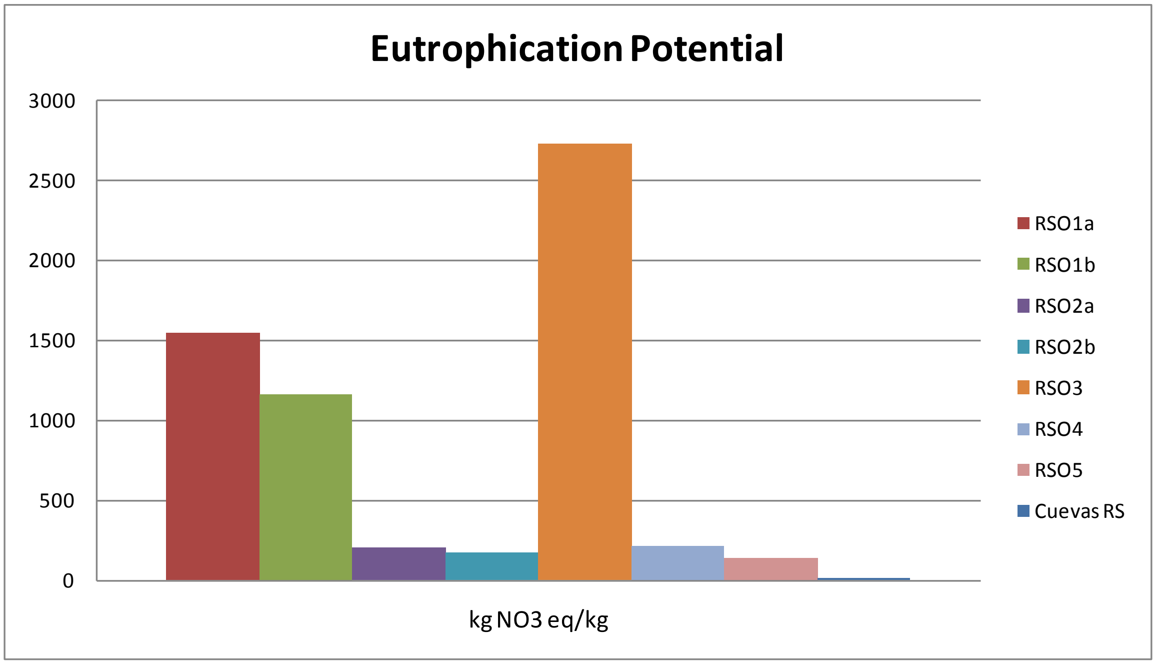


Figure 3.25. Comparison to Schmidt 2010: Eutrophication Potential

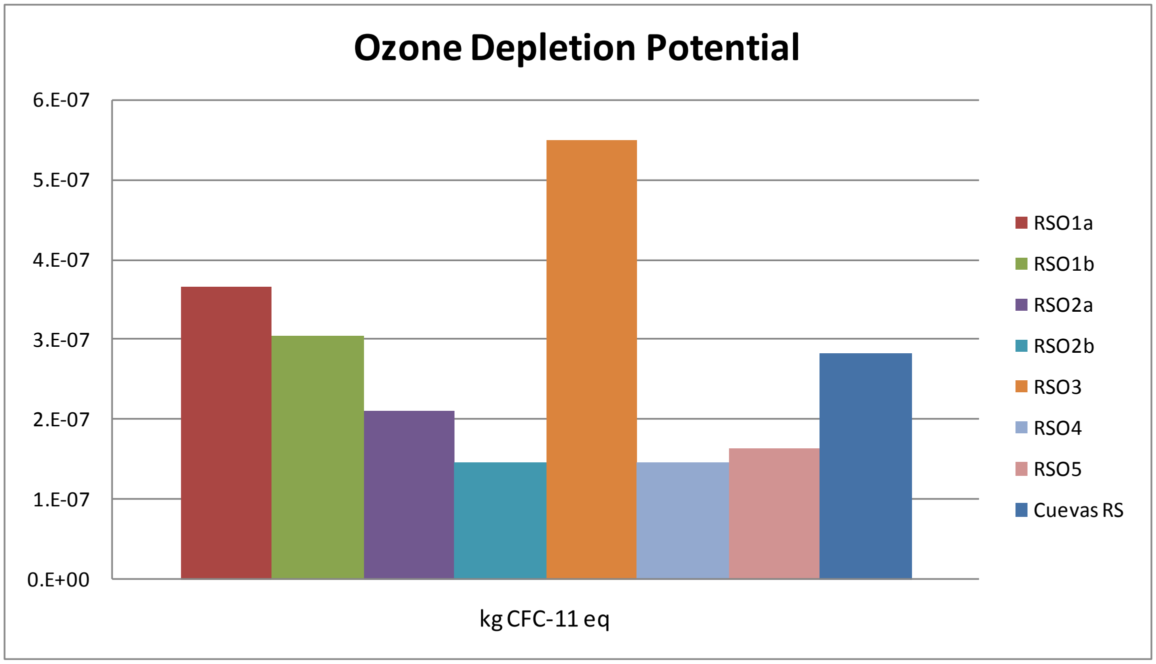
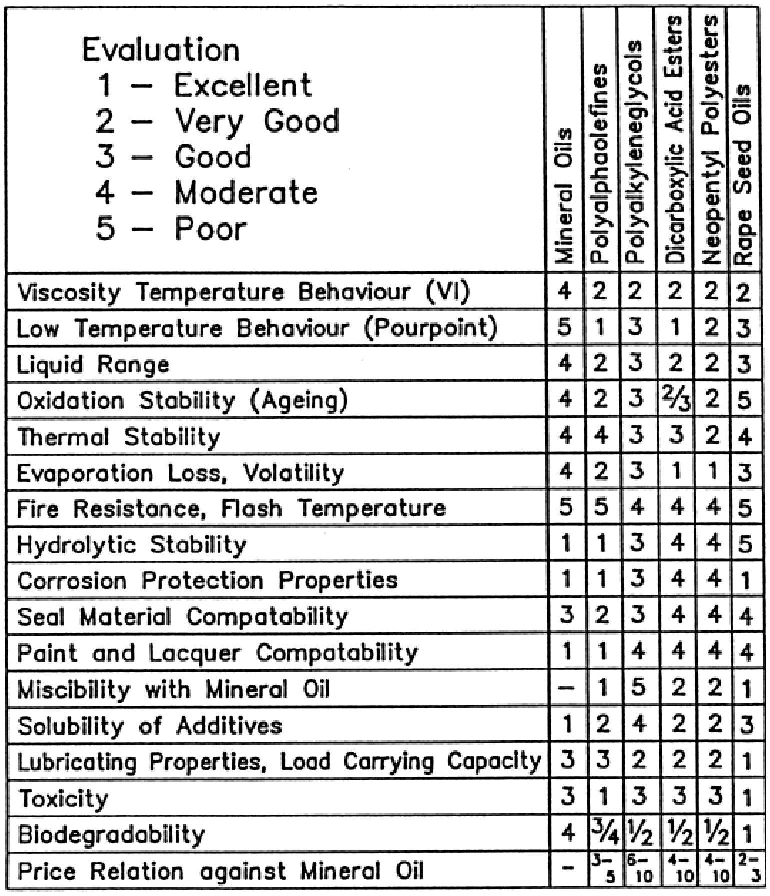


Figure 3.26. Comparison to Schmidt 2010: Ozone Depletion Potential

4.0 LUBRICANT DECISION MATRIX

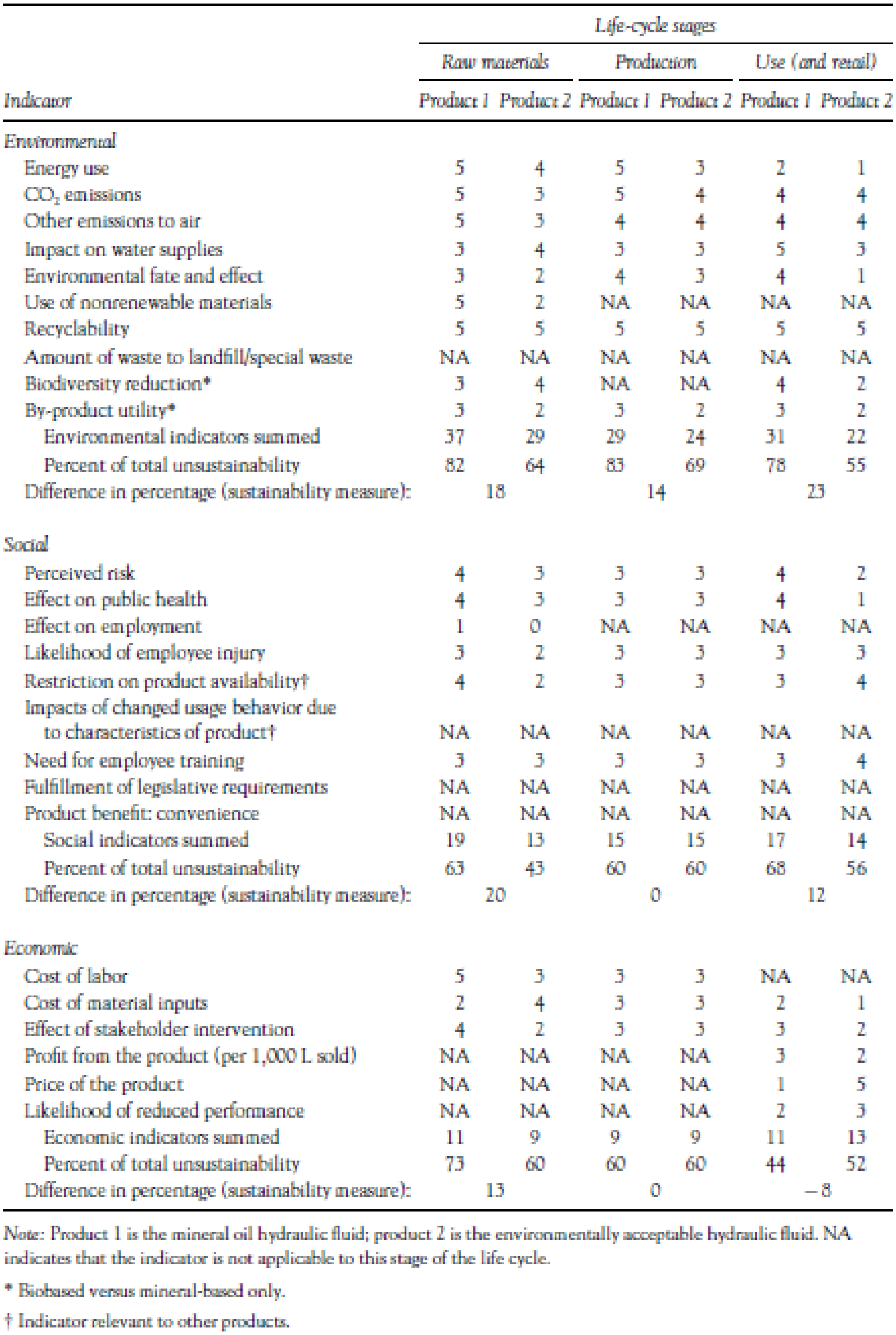
Lubricant selection can be very difficult due to the immense variety of products and manufacturers in today's market. However, a decision matrix can be utilized to facilitate the selection process. The decision matrix (DM) developer establishes the relevant criteria needed to evaluate a certain product, e.g. lubricants. The products are then screened against the criteria and scored using a defined scale, e.g. 1 for excellent and 5 for poor. The criteria can also be weighted to give more importance to one criterion over another. However, weighting can be misleading, since potentially optimal products may not be considered due to a deceptive score (Mullur et al. 2003). All scores are summed to obtain a total score for each product being evaluated that can then be ranked. A decision matrix framework will be developed below.

The most important lubricant property is viscosity, since this is what prevents contact between the bearing surfaces (Lansdown 2004). Other properties that should be considered when selecting a lubricant are: temperature stability, chemical stability, compatibility, corrosiveness, flammability, toxicity, environmental effects, availability, and price (Lansdown 2004). All of these properties were considered by Bartz (1998) in the decision matrix for different base oils shown in Figure 4.1. However, no LCA results were used as criteria. In another study, Cunningham et al. (2004) developed a sustainability matrix to evaluate the environmental, social, and economic impacts of a product using a biolubricant as an example (Cunningham et al. 2004). The purpose of the tool was to quicken and reduce the costs of performing a full LCA by focusing on specific criteria of the life cycle of the product (Cunningham et al. 2004). LCA criteria such as energy use, CO_2 emissions, air emissions, impacts on water supplies, and others are considered in the matrix. Each criterion was assigned a score using the following scale: 0 - Negligible, 1 - Low, 2 - Low/medium, 3 - Medium, 4 - Medium/high, 5 - High, and NA - Not applicable. All scores were summed within each category, i.e. environmental, converted to a percentage of the least sustainable case possible, where all scores were 5 (Cunningham et al. 2004). A sustainability score was obtained by subtracting the 2 total scores. The DM is shown in Figure 4.2.



Evaluation 1 – Excellent 2 – Very Good 3 – Good 4 – Moderate 5 – Poor	Mineral Oils	Polyalphaolefines	Polyalkyleneglycols	Dicarboxylic Acid Esters	Neopentyl Polyesters	Rape Seed Oils
Viscosity Temperature Behaviour (VI)	4	2	2	2	2	2
Low Temperature Behaviour (Pourpoint)	5	1	3	1	2	3
Liquid Range	4	2	3	2	2	3
Oxidation Stability (Ageing)	4	2	3	2/3	2	5
Thermal Stability	4	4	3	3	2	4
Evaporation Loss, Volatility	4	2	3	1	1	3
Fire Resistance, Flash Temperature	5	5	4	4	4	5
Hydrolytic Stability	1	1	3	4	4	5
Corrosion Protection Properties	1	1	3	4	4	1
Seal Material Compatability	3	2	3	4	4	4
Paint and Lacquer Compatability	1	1	4	4	4	4
Miscibility with Mineral Oil	–	1	5	2	2	1
Solubility of Additives	1	2	4	2	2	3
Lubricating Properties, Load Carrying Capacity	3	3	2	2	2	1
Toxicity	3	1	3	3	3	1
Biodegradability	4	3/4	1/2	1/2	1/2	1
Price Relation against Mineral Oil	–	3–5	6–10	4–10	4–10	2–3

Figure 4.1. Decision matrix for different base oils (Bartz 1998)



	Life-cycle stages					
	Raw materials		Production		Use (and retail)	
Indicator	Product 1	Product 2	Product 1	Product 2	Product 1	Product 2
Environmental						
Energy use	5	4	5	3	2	1
CO_2 emissions	5	3	5	4	4	4
Other emissions to air	5	3	4	4	4	4
Impact on water supplies	3	4	3	3	5	3
Environmental fate and effect	3	2	4	3	4	1
Use of nonrenewable materials	5	2	NA	NA	NA	NA
Recyclability	5	5	5	5	5	5
Amount of waste to landfill/special waste	NA	NA	NA	NA	NA	NA
Biodiversity reduction*	3	4	NA	NA	4	2
By-product utility*	3	2	3	2	3	2
Environmental indicators summed	37	29	29	24	31	22
Percent of total unsustainability	82	64	83	69	78	55
Difference in percentage (sustainability measure):	18		14		23	
Social						
Perceived risk	4	3	3	3	4	2
Effect on public health	4	3	3	3	4	1
Effect on employment	1	0	NA	NA	NA	NA
Likelihood of employee injury	3	2	3	3	3	3
Restriction on product availability†	4	2	3	3	3	4
Impacts of changed usage behavior due to characteristics of product†	NA	NA	NA	NA	NA	NA
Need for employee training	3	3	3	3	3	4
Fulfillment of legislative requirements	NA	NA	NA	NA	NA	NA
Product benefit: convenience	NA	NA	NA	NA	NA	NA
Social indicators summed	19	13	15	15	17	14
Percent of total unsustainability	63	43	60	60	68	56
Difference in percentage (sustainability measure):	20		0		12	
Economic						
Cost of labor	5	3	3	3	NA	NA
Cost of material inputs	2	4	3	3	2	1
Effect of stakeholder intervention	4	2	3	3	3	2
Profit from the product (per 1,000 L sold)	NA	NA	NA	NA	3	2
Price of the product	NA	NA	NA	NA	1	5
Likelihood of reduced performance	NA	NA	NA	NA	2	3
Economic indicators summed	11	9	9	9	11	13
Percent of total unsustainability	73	60	60	60	44	52
Difference in percentage (sustainability measure):	13		0		–8	

Note: Product 1 is the mineral oil hydraulic fluid; product 2 is the environmentally acceptable hydraulic fluid. NA indicates that the indicator is not applicable to this stage of the life cycle.

* Biobased versus mineral-based only.

† Indicator relevant to other products.

Figure 4.2. Decision matrix for lubricants (Cunningham et al. 2004)

The LCA results from this study and the criteria utilized in the Bartz (1998) and Cunningham et al. (2004) studies were considered in the development of the decision matrix framework to be used for lubricant selection. LCA results are not the only metrics that can be used to evaluate bioproducts; therefore other criteria were integrated into the proposed decision matrix. In addition to LCA results, physical properties of a lubricant, lubricant cost, and other selected criteria were included in the decision matrix framework. Hypothetical rapeseed, soybean and mineral based lubricants were evaluated against the selected criteria to simplify discussion of the framework, the scoring process, and obtain a sample of results.

LCA results from this study were selected as criteria. The nine LCIA impact categories – GWP, AP, carcinogenics, non-carcinogenics, RE, EP, ODP, ecotoxicity, and PS – were included in the decision matrix and scores were assigned using the normalized results from Figure 3.17. For example, mineral had the highest contribution in the ODP category and was normalized to 100%. In the DM, ODP for the mineral lubricant was assigned a 1. Rapeseed and soybeans were assigned 0.44 and 0.07, respectively, based on the normalized percentages of approximately 44% and 7%. This scoring method for the ODP results was completed for all the LCIA categories.

Material safety data sheets (MSDS) and other technical datasheets provide a variety of physical and chemical properties that can be utilized as DM inputs. Viscosity, flash point, solubility, corrosion properties, compatibility with other materials, and evaporation loss are just a few categories that could be utilized. To score these properties, assign a 1 to the lubricant that has the highest value for the selected property and a 0 to the lubricant with the lowest value. If a third lubricant is being evaluated, as is the case in this example, interpolation is performed to obtain the DM score as shown in Figure 4.3. Other properties such as biodegradability, toxicity, water hazard impacts, and cost can also be scored using interpolation.

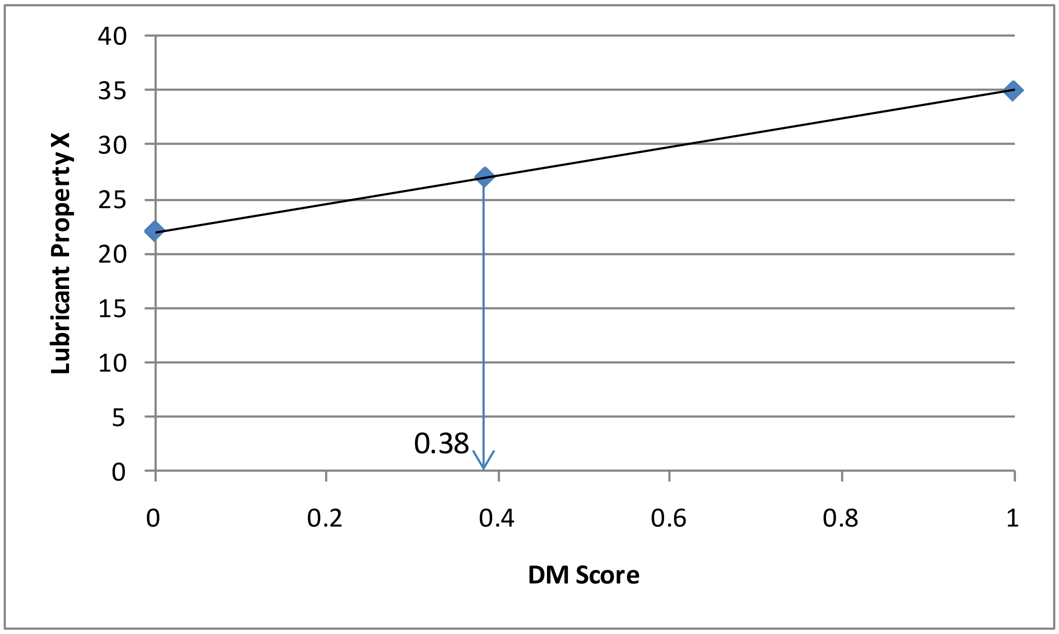


Figure 4.3. DM score interpolation

The USDA BioPreferred Program intends to increase the use of renewable, environmentally friendly biobased products by providing a database of bioproducts and bioproducts manufacturers that can be used by federal and contractor personnel to find products that meet federal regulations regarding green purchasing (USDA 2010). The BioPreferred Program has established a minimum biobased content percentage for more than 40 items such as: roof coatings, carpets, lip care products, greases, hydraulic fluids, and multiple types of lubricants (USDA 2010). Several lubricant products and their minimum biobased content required by the BioPreferred program are listed in Table 4.1. For the DM, a product in the BioPreferred catalog receives a score of 0, while a 1 is assigned to products not in the catalog. The hypothetical rapeseed and soybean lubricants evaluated in this DM were assumed to be in the BioPreferred catalog, while the mineral lubricant was not and received a score of 1. The sample results of the decision matrix are shown in Table 4.2.

Table 4.1. BioPreferred minimum biobased content for lubricant products

Biobased product	**Minimum biobased content**
Hydraulic fluids – mobile equipment	44%
Hydraulic fluids – stationary equipment	44%
2-Cycle engine oils	34%
Chain and cable lubricants	77%
Gear lubricants	58%
Greases	75%

The DM framework developed in this section can be customized by any user looking to evaluate different lubricant products. If the user does not have the resources or time to perform an LCA, the LCIA scores obtained in this study can be utilized. The other lubricant properties can be manipulated using MSDS, cost info, and other available information regarding the lubricants in question. For this study, each category criterion was equally weighted to eliminate subjectivity. However, the weighting factors can be modified if the user desires. After all scoring was performed, the results were added to determine the final score and rank the lubricants. In this DM, the lowest score indicates a better option, while a higher score is a worse option. Therefore, soybean resulted as the best option to utilize with a score of 0.02 followed by mineral lubricants with a score of 4.74 and then rapeseed with a score of 7.11. Lubricant properties were not scored, since specific data is required to assign values.

Table 4.2. Lubricant decision matrix

Criteria	Rapeseed	Soybean	Mineral	Weighting
LCIA categories				
GWP	-0.33	-0.64	1	1
AP	1	0.07	0.17	1
Carcinogenics	1	0.17	0.43	1
Non carcinogenics	1	0.06	0.26	1
RE	1	0.14	0.47	1
EP	1	0.38	0.03	1
ODP	0.44	0.07	1	1
Ecotoxicity	1	-0.40	0.24	1
PS	1	0.17	0.14	1
Lubricant properties				
Viscosity				1
Flash point				1
Evaporation loss				1
Biodegradability				1
Other				
BioPreferred	0	0	1	1
Cost				1
Sample Total Score	7.11	0.02	4.74	

5.0 IMPLEMENTATION IMPACTS

Mineral and biobased lubricants have different environmental impacts for GWP, EP, AP, and other impact categories as discussed in Chapter 4. A mix in environmental impact results can be obtained by utilizing a variety of these products. For example, based on the results of the LCA completed in this study, rapeseed lubricant had a higher AP than mineral based lubricants. However, in the case of ODP, mineral lubricants had the highest impact. Based on the total lubricant demand in the US in 2008, the total AP for the usage of 100% rapeseed lubricants versus the usage of 100% mineral lubricants is shown in Figure 5.1. A similar analysis was performed for ODP illustrating the tradeoff between the two types of lubricants, see Figure 5.2. Therefore, as depicted in Figure 5.1 and Figure 5.2, an increase in biolubricants would minimize ODP impacts, but also cause an increase in AP emissions. Knowing the environmental impacts caused by these products can be useful in determining how to regulate the lubricant market.

LCA results can also be affected by lubricant performance. Biolubricants have several limitations, including: sensitivity to high temperatures, poor low temperature stability, and poor oxidative stability (Vag et al. 2002; IENICA 2004). Some also argue that biolubricants need to be replaced more often than mineral based lubricants (McManus et al. 2004). Therefore, the LCA results could change significantly if these factors are considered. For instance, McManus et al. (2004) performed a sensitivity analysis considering mineral oil to be equal, 1.5, 2, or 3 times better than rapeseed oil (McManus et al. 2004). In all cases mineral oil had the greatest GWP impact. However, when comparing all the performance scenarios rapeseed oil surpassed mineral oil in all impact categories evaluated, except for carcinogens and ODP. This type of analysis was not performed in this study, but is recommended as future work.

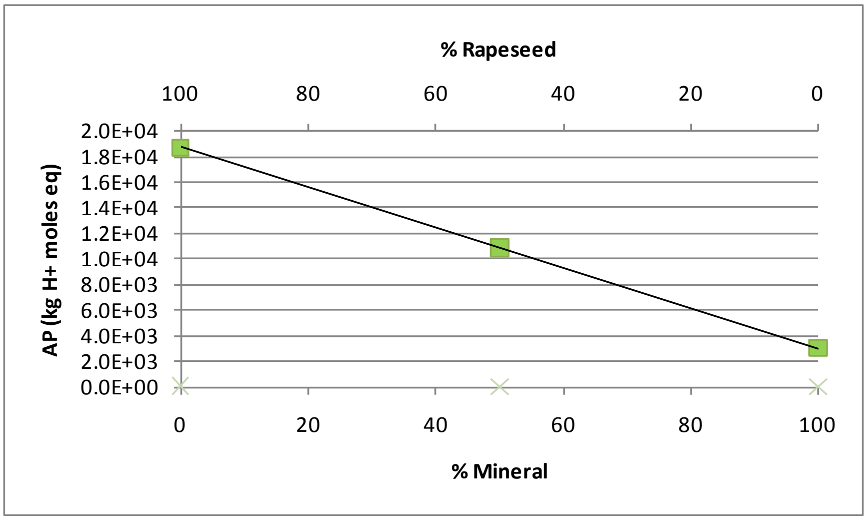


Figure 5.1. AP impacts based on % of lubricant used in the US

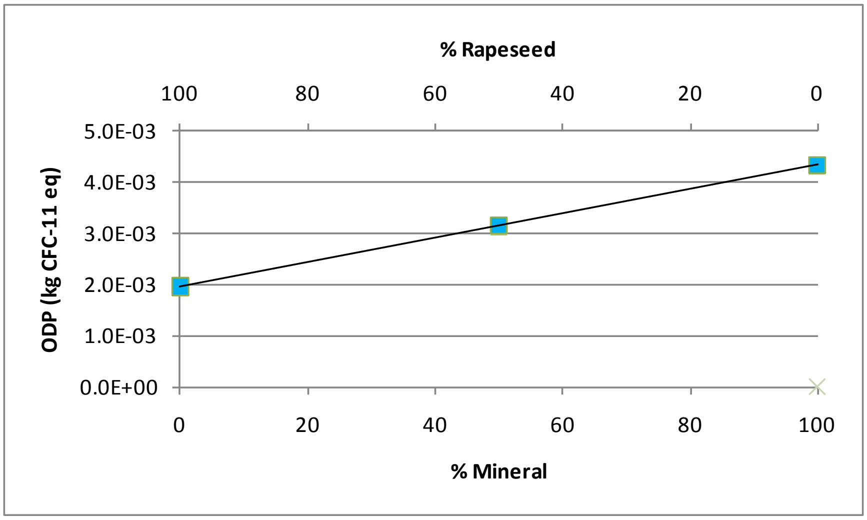


Figure 5.2. ODP impacts based on % of lubricant used in the US

5.1 LAND USE EVALUATION

In addition to environmental impacts, biolubricants also have a significant impact on land use. The U.S. has approximately 2.3 billion acres of land, which in 2002 were classified as 97% rural and 3% urban as shown in Figure 5.3 (USDA 2005). U.S. rural land includes several uses including cropland, grassland, and forest land (USDA 2005). Special use land, such as parks, and miscellaneous land, which considers deserts and wetlands, is also considered rural land (USDA 2005). Biolubricant use can cause changes in cropland, which is 19% of the U.S. total land (USDA 2005). Soybean and rapeseed, common crops used for biolubricant production, represent 9% and 0.2%, respectively, of U.S. cropland (USDA 2005; USDA 2009). Any change in biolubricant use will also typically cause an increase or decrease in other land categories. However, other measures can be taken to meet biolubricant demand, such as an increase in crop yield (Schmidt 2010).

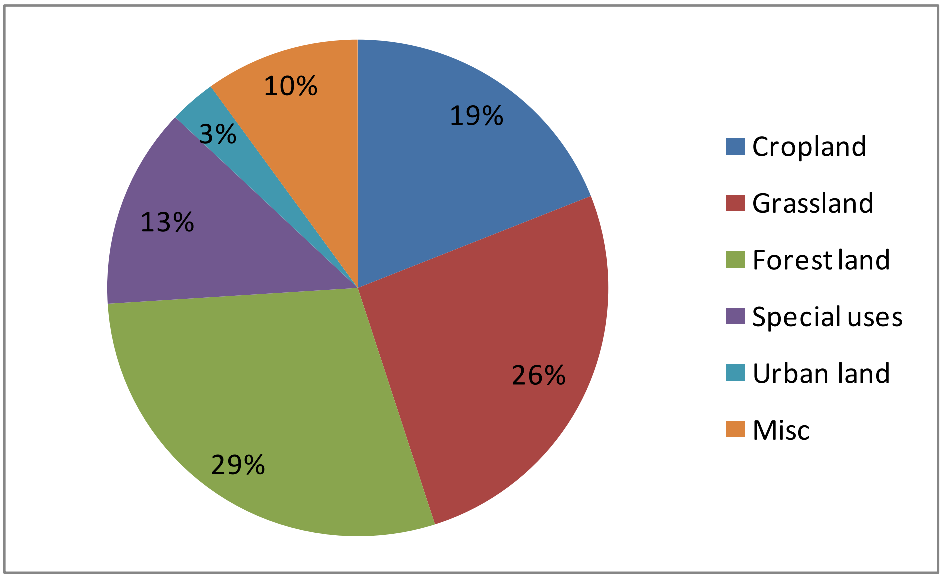


Figure 5.3. Major land uses in the U.S. - 2002

(Adapted from USDA 2005)

In 2008, 0.131 million barrels of mineral based lubricants were consumed in the U.S. per day (EIA 2010). That is approximately 2 billion gallons of lubricants per year. It is estimated that 8.2 million gallons of biolubricants are also consumed each year (Bremmer and Plonsker 2008). In this section, the direct land use impacts from producing 2 billion gallons of lubricants from biobased sources instead of mineral based sources were determined.

In the LCA community there has been numerous discussions about direct and indirect land use change. Direct land use change occurs within a specific supply chain for a specific production facility (Kim et al. 2009). On the other hand, indirect land use changes occur in land that is not part of a specific supply chain due to market forces, including hypothetical land use change on another continent (Kim et al. 2009). A simple evaluation of the direct land use impacts is performed, indirect land use is not considered, since it is beyond the scope of this study. Although land use for mineral based lubricants is not zero due to production plant location, it is not included in this evaluation. Biolubricant production plants are not considered either.

The following steps were performed to determine the land needed if soybean or rapeseed were used as the sole contributors for meeting U.S. lubricant demand, see Table 5.1:

1. Calculate U.S. yield average (metric tons/hectare) from 2006-2010 data.
2. Convert yield average from metric tons/hectare to lbs/acre.
3. Determine oil yield by converting yield in lbs/acre to gallons of oil/acre using seed oil content and oil density.
4. Determine land needed in acres to produce approximately 2 billion gallons of lubricant by multiplying the oil yield by 2 billion gallons.

Based on the land use evaluation, approximately 32 million acres of land would be required to produce 2 billion gallons of lubricants from soybeans. However, only approximately

25 million acres would be needed if the lubricants were produced from rapeseed. This difference in acreage is due mostly to rapeseed oil content, which is more than double the soybean oil content. Figure 5.4 depicts the land use results for meeting the U.S. lubricant demand of 2 billion gallons using soybean, rapeseed, and a mix of 50% soybean/50% rapeseed. In addition, an estimate of land needed to only replace a percentage of mineral based lubricants can be determined using this graph. For example, to replace 40% of the U.S. lubricant demand with the 50/50 mix would require approximately 12 million acres.

Table 5.1. Land use calculations

Parameters	**Unit**	**Soybean**	**Rapeseed**	**References**
U.S. Yields				
2006-2007		2.88	1.53	
2007-2008	metric tons/hectare	2.81	1.39	(USDA 2010)
2008-2009		2.67	1.64	
2009-2010		2.96	2.03	
Yield average	metric tons/hectare	2.83	1.65	Average
Yield	lbs/acre	2524.87	1469.87	1 ha = 2.47 acre 1 ton = 2,204.62 lbs
Oil content	%	19	42	(Frier and Roth 2006)
Oil density	g/mL @ 20°	0.9199	0.911	(Rice and Hamm 1988)
Oil yield	gallons/acre	62.49	81.20	1 lbs = 453.59 g 1 gallon = 3,785.42 cm^3
Land use	acres	32,137,298	24,731,613	(EIA 2010)

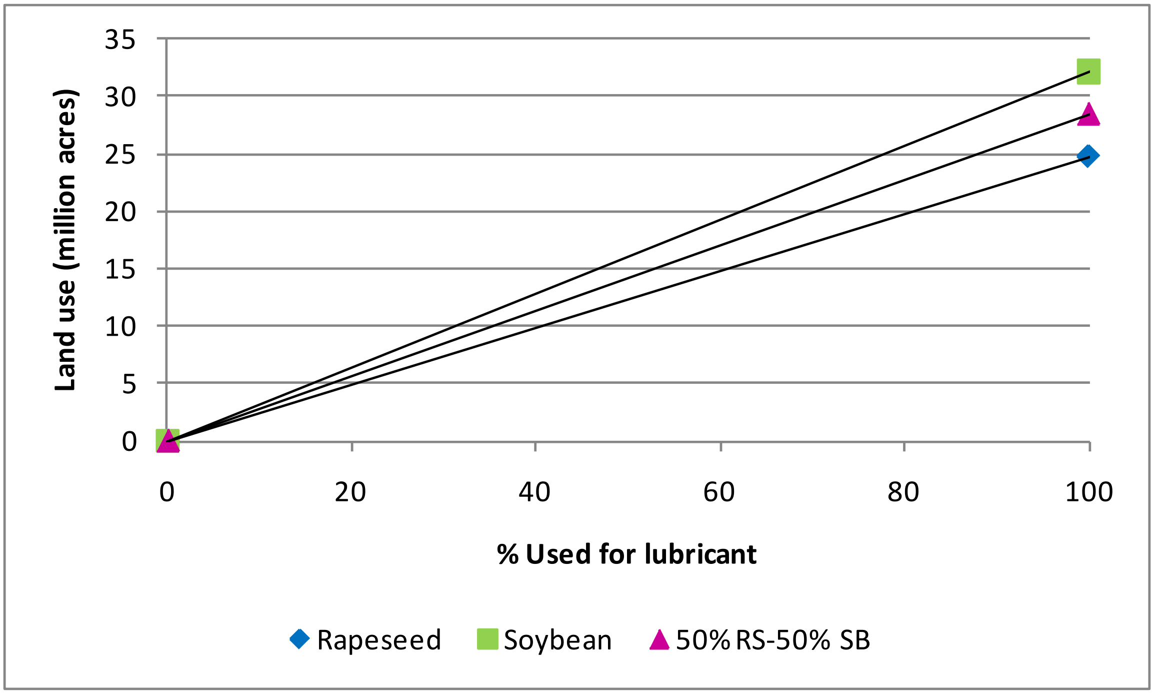


Figure 5.4. Land needed to meet U.S. lubricant demand

6.0 CONCLUSION

The objective of this study was to complete a life cycle assessment of biobased and mineral based lubricants, and to develop a decision matrix that incorporated the results of the LCA to screen and evaluate potential lubricants. The LCA was completed by collecting rapeseed inventory data from scientific journals, reports, life cycle databases and government resources, utilizing the TRACI characterization factors to obtain the life cycle impacts of rapeseed lubricants, and comparing the results to SimaPro – ecoinvent processes ‘Soybean oil, at oil mill/US U’ and ‘Lubricating oil at plant/RER U’. The rapeseed results were also compared to other LCA studies. Finally, the LCA results were utilized to develop the decision matrix framework and to determine direct land use impacts in the U.S.

LCA results showed rapeseed lubricants as the major contributor in the acidification potential, carcinogenics, non-carcinogenics, respiratory effects, eutrophication potential and photochemical smog impact categories when compared to soybean and lubricant oils. Mineral lubricants dominated the global warming potential and ozone depletion potential categories. However, it should be noted that if using weighting had been performed in an improvement analysis these results could have been different. In addition, all LCAs have limitations that could alter the outcome as seen with the missing inventory that required additional calculations to obtain more accurate eutrophication potential results.

When selecting a lubricant one must look at more than the viscosity and other physical properties, since the impacts caused by these products not only affect the environment but also economic and social outcomes. It is through a decision matrix that all these categories can be combined and evaluated to ensure an informed decision is made regarding the appropriate product to be utilized. Additional analyses, such as determining land use impacts, can also improve lubricant selection. LCA and decision making can be complex and time consuming, but these methods can improve how decisions are made by choosing the most appropriate products that will have the least negative impact on the environment, economy, and society.

7.0 FUTURE WORK

Research on biobased lubricants has generated varying conclusions regarding the environmental effects of these products. Ideally, an LCA of each product should be completed, but this would be very demanding and time consuming. The following recommendations should be considered to enhance the LCA performed in this study:

- Revise SimaPro fertilizer database to include additional fertilizers, herbicides and pesticides that are utilized on today's fields.
- Utilize different LCIA methods such as: IMPACT 2002, EDIP 2003, Eco-indicator 99, and others to evaluate lubricants.
- Analyze carbon sequestration.
- Calculate mass, energy, and market allocation.
- Evaluate lubricant performance.
- Establish end-of-life scenarios.
- Compare lubricants to new sources such as algae.
- Update the Appendix A - Biolubricant Database.
- Perform a life cycle costing (LCC).

APPENDIX A

BIOLUBRICANT DATABASE

Commercial Name[1]	Manufacturer/Distributor	Type	Website
Bio-Synthetic SHP Motor Oil SAE 0W20 PCMO	Renewable Lubricants, Inc.	High Performance Motor Oils	http://www.renewablelube.com/motoroilsHP.htm
Bio-Synthetic SHP Motor Oil SAE 0W30 PCMO	Renewable Lubricants, Inc.	High Performance Motor Oils	http://www.renewablelube.com/motoroilsHP.htm
Bio-Synthetic SHP Motor Oil SAE 5W20 PCMO	Renewable Lubricants, Inc.	High Performance Motor Oils	http://www.renewablelube.com/motoroilsHP.htm
Bio-Synthetic SHP Motor Oil SAE 5W30 PCMO	Renewable Lubricants, Inc.	High Performance Motor Oils	http://www.renewablelube.com/motoroilsHP.htm
Bio-Synthetic SHP Motor Oil SAE 10W30 PCMO	Renewable Lubricants, Inc.	High Performance Motor Oils	http://www.renewablelube.com/motoroilsHP.htm
Bio-Synthetic SHP Motor Oil SAE 10W40 PCMO	Renewable Lubricants, Inc.	High Performance Motor Oils	http://www.renewablelube.com/motoroilsHP.htm
Bio-Synthetic HD SHP SAE 5W40 Motor Oil	Renewable Lubricants, Inc.	High Performance Motor Oils	http://www.renewablelube.com/motoroilsHP.htm
Bio-Synthetic HD SHP SAE 10W30 Motor Oil	Renewable Lubricants, Inc.	High Performance Motor Oils	http://www.renewablelube.com/motoroilsHP.htm
Bio-Synthetic HD SHP SAE 15W40 Motor Oil	Renewable Lubricants, Inc.	High Performance Motor Oils	http://www.renewablelube.com/motoroilsHP.htm
Bio-Synthetic HD SHP SAE 15W50 Motor Oil	Renewable Lubricants, Inc.	High Performance Motor Oils	http://www.renewablelube.com/motoroilsHP.htm
Bio-Synthetic HD SHP SAE 20W50 Motor Oil	Renewable Lubricants, Inc.	High Performance Motor Oils	http://www.renewablelube.com/motoroilsHP.htm
Bio-Synthetic HD SHP SAE 30 Motor Oil	Renewable Lubricants, Inc.	High Performance Motor Oils	http://www.renewablelube.com/motoroilsHP.htm
Bio-Synthetic HD SHP SAE 40 Motor Oil	Renewable Lubricants, Inc.	High Performance Motor Oils	http://www.renewablelube.com/motoroilsHP.htm
Bio-Synthetic 80W90 GL-5 Gear Oil	Renewable Lubricants, Inc.	High Performance Transmission & Gear Oils	http://www.renewablelube.com/motoroilsHPgear.htm
Bio-Synthetic 75W90 GL-5 LS Gear Oil	Renewable Lubricants, Inc.	High Performance Transmission & Gear Oils	http://www.renewablelube.com/motoroilsHPgear.htm
Bio-Synthetic ATF Automatic Transmission Fluid	Renewable Lubricants, Inc.	High Performance Transmission & Gear Oils	http://www.renewablelube.com/motoroilsHPgear.htm
Bio-Super High Performance Transmission Fluids SAE: 20	Renewable Lubricants, Inc.	High Performance Transmission & Gear Oils	http://www.renewablelube.com/motoroilsHPgear.htm
Bio-Penetrating Lubricant™ (BPL) with Anti-Wear	Renewable Lubricants, Inc.	Penetrating lubricant	http://www.renewablelube.com/biopenetratinglubricant.htm
BPL™ Food Grade Bio-Penetrating Lubricant™	Renewable Lubricants, Inc.	Penetrating lubricant	http://www.renewablelube.com/biopenetratinglubricant.htm
Bio-Blast™ Penetrant (Low Surface Tension)	Renewable Lubricants, Inc.	Penetrating lubricant	http://www.renewablelube.com/biopenetratinglubricant.htm
Bio-Penetrating Lubricant Plus Tack™	Renewable Lubricants, Inc.	Lubricant & Corrosion Inhibitor	http://www.renewablelube.com/biopenetratinglubricant.htm
Bio-Penetrating Lubricant Plus Moly + Tack™	Renewable Lubricants, Inc.	Chain & Cable Lubricant	http://www.renewablelube.com/biopenetratinglubricant.htm
Bio-Penetrating Lubricant Plus Moly™	Renewable Lubricants, Inc.	Chain & Cable Lubricant	http://www.renewablelube.com/biopenetratinglubricant.htm
Bio-Power™ Soy-Based Summer Diesel Fuel Conditioner	Renewable Lubricants, Inc.	Gas & Diesel Fuel Conditioner	http://www.renewablelube.com/fuelconditioner.htm
Bio-Power™ Soy-Based Winter Diesel Fuel Conditioner	Renewable Lubricants, Inc.	Gas & Diesel Fuel Conditioner	http://www.renewablelube.com/fuelconditioner.htm
Bio-Bunker™ Biobased Marine & Industrial Fuel Conditioner	Renewable Lubricants, Inc.	Gas & Diesel Fuel Conditioner	http://www.renewablelube.com/fuelconditioner.htm
Bio-Diesel System	Renewable Lubricants, Inc.	Gas & Diesel Fuel Conditioner	http://www.renewablelube.com/fuelconditioner.htm
Bio-Diesel Clean/Clear B-100	Renewable Lubricants, Inc.	Gas & Diesel Fuel Conditioner	http://www.renewablelube.com/fuelconditioner.htm
Bio-Booster Soy-based Cetane Improver	Renewable Lubricants, Inc.	Gas & Diesel Fuel Conditioner	http://www.renewablelube.com/fuelconditioner.htm
Bio-Plus™ Injector Cleaner Gas Conditioner	Renewable Lubricants, Inc.	Gas & Diesel Fuel Conditioner	http://www.renewablelube.com/fuelconditioner.htm
Bio-Valve Lube™ Gas Conditioner (for off highway use)	Renewable Lubricants, Inc.	Gas & Diesel Fuel Conditioner	http://www.renewablelube.com/fuelconditioner.htm
Bio-Ultimax 1000- 2000 Hydraulic Fluids ISO 32	Renewable Lubricants, Inc.	Hydraulic Fluid	http://www.renewablelube.com/hyrdraulic.htm
Bio-Ultimax 1000- 2000 Hydraulic Fluids ISO 48	Renewable Lubricants, Inc.	Hydraulic Fluid	http://www.renewablelube.com/hyrdraulic.htm
Bio-Ultimax 1000- 2000 Hydraulic Fluids ISO 68	Renewable Lubricants, Inc.	Hydraulic Fluid	http://www.renewablelube.com/hyrdraulic.htm
Bio-Ultimax Hydraulic Fluids AW 1000 SAE 10W40	Renewable Lubricants, Inc.	Hydraulic Fluid	http://www.renewablelube.com/hyrdraulic.htm
Bio-Ultimax 1200LT Hydraulic Fluids (ISO 15, 22, 32)	Renewable Lubricants, Inc.	Hydraulic Fluid	http://www.renewablelube.com/hyrdraulic.htm
Bio-Ultimax 1500 Dielectic Hydraulic Fluids (ISO 22, 32, 46, 68)	Renewable Lubricants, Inc.	Hydraulic Fluid	http://www.renewablelube.com/hyrdraulic.htm
Bio-HVO Hydraulic Fluids (ISO 46, 68, FR)	Renewable Lubricants, Inc.	Hydraulic Fluid	http://www.renewablelube.com/hyrdraulic.htm
Bio-HVO2 Hydraulic Fluids (ISO 46, 68, FR)	Renewable Lubricants, Inc.	Hydraulic Fluid	http://www.renewablelube.com/hyrdraulic.htm
Bio-Hydraulic™ Fluids (ISO 32, 46, 68)	Renewable Lubricants, Inc.	Hydraulic Fluid	http://www.renewablelube.com/hyrdraulic.htm
Bio-MIL-PRF-32073 Hydraulic Fluids (ISO 15, 22, 32, 46, 68)	Renewable Lubricants, Inc.	Hydraulic Fluid	http://www.renewablelube.com/hyrdraulic.htm
Bio-AW/AL Hydraulic Press Oils (ISO 32, 46, 68)	Renewable Lubricants, Inc.	Hydraulic Fluid	http://www.renewablelube.com/hyrdraulic.htm

Commercial Name[1]	**Manufacturer/Distributor**	**Type**	**Website**
Bio-AW Turbine R & O Fluids (ISO 32, 46, 68, 100)	Renewable Lubricants, Inc.	Hydraulic Fluid	http://www.renewablelube.com/hyrdraulic.htm
Bio-SYN Trans Hydraulic Fluid	Renewable Lubricants, Inc.	Trans-hydraulic	http://www.renewablelube.com/transhydraulic.htm
Bio-Hydrostatic Fluid Low Viscosity	Renewable Lubricants, Inc.	Trans-hydraulic	http://www.renewablelube.com/transhydraulic.htm
Bio-E.P. Gear Oils (ISO 46, 68, 100, 150, 220, 320, 460)	Renewable Lubricants, Inc.	Gear, Slideway and Spindle Oils	http://www.renewablelube.com/gear.htm
Bio-80W90 Gear Oils GL-4	Renewable Lubricants, Inc.	Gear, Slideway and Spindle Oils	http://www.renewablelube.com/gear.htm
Bio-Gearhead Oil (SAE 10W30 SAE 15W40)	Renewable Lubricants, Inc.	Gear, Slideway and Spindle Oils	http://www.renewablelube.com/gear.htm
Bio-E.P. Press Oils (ISO 46, 68, 100, 150, 220)	Renewable Lubricants, Inc.	Gear, Slideway and Spindle Oils	http://www.renewablelube.com/gear.htm
Bio-Spindle Oils (ISO 22)	Renewable Lubricants, Inc.	Gear, Slideway and Spindle Oils	http://www.renewablelube.com/gear.htm
Bio-Air Compressor Fluid (SAE 30)	Renewable Lubricants, Inc.	Gear, Slideway and Spindle Oils	http://www.renewablelube.com/gear.htm
Bio-Air Tool Lubricants (ISO 22, 32)	Renewable Lubricants, Inc.	Gear, Slideway and Spindle Oils	http://www.renewablelube.com/gear.htm
Bio-Drip Oils (SAE 10W20, SAE 10W30)	Renewable Lubricants, Inc.	Gear, Slideway and Spindle Oils	http://www.renewablelube.com/gear.htm
Bio-Vacuum Pump Oil (SAE 10W30)	Renewable Lubricants, Inc.	Gear, Slideway and Spindle Oils	http://www.renewablelube.com/gear.htm
Bio-Slide Way Lubricant (ISO 32, 68, 220)	Renewable Lubricants, Inc.	Gear, Slideway and Spindle Oils	http://www.renewablelube.com/gear.htm
Bio-Rock Drill Oils (10W20, 10W30, 15W50, 20W60)	Renewable Lubricants, Inc.	Rock Drill and Air Tool Oils	http://www.renewablelube.com/rockdrill.htm
Bio-Air Tool Lubricants (ISO 22, 32)	Renewable Lubricants, Inc.	Rock Drill and Air Tool Oils	http://www.renewablelube.com/rockdrill.htm
Bio-TC-W3 2-Cycle Engine Oil	Renewable Lubricants, Inc.	2 cycle oils	http://www.renewablelube.com/2-cycle.htm
Bio-TC-W 2-Cycle Engine Oil	Renewable Lubricants, Inc.	2 cycle oils	http://www.renewablelube.com/2-cycle.htm
Bio-Pro Bar & Chain Oils SAE 10W30	Renewable Lubricants, Inc.	Bar & Chain Oils	http://www.renewablelube.com/2-cycle.htm
Bio-Pro Bar & Chain Oils SAE 15W50	Renewable Lubricants, Inc.		http://www.renewablelube.com/cable.htm
Bio-Chain & Cable Lubricants (SAE 10W20, SAE 10W30, SAE 15W50, SAE 20W60)	Renewable Lubricants, Inc.	Cable and Saw Guide	http://www.renewablelube.com/cable.htm
Bio-Saw Guide Lubricants (SAE 10W20, SAE 10W30, SAE 15W50, SAE 20W60)	Renewable Lubricants, Inc.	Cable and Saw Guide	http://www.renewablelube.com/cable.htm
Bio-Soy Orange™ All-Purpose Degreaser/Cleaner	Renewable Lubricants, Inc.	Degreasers/Cleaners	http://www.renewablelube.com/degreaser.htm
Bio-Parts Cleaner/Degreaser™	Renewable Lubricants, Inc.	Degreasers/Cleaners	http://www.renewablelube.com/degreaser.htm
Bio-Cleaner/Degreaser (plus Corrosion Protection)	Renewable Lubricants, Inc.	Degreasers/Cleaners	http://www.renewablelube.com/degreaser.htm
Bio-General Purpose™ Cleaner/Degreaser (Water Emulsifiable)	Renewable Lubricants, Inc.	Degreasers/Cleaners	http://www.renewablelube.com/degreaser.htm
Bio-Metal Cool GP	Renewable Lubricants, Inc.	Metal Working	http://www.renewablelube.com/metal.htm
Bio-Metal Cool HD	Renewable Lubricants, Inc.	Metal Working	http://www.renewablelube.com/metal.htm
Bio-Aluminum Cutting Oil	Renewable Lubricants, Inc.	Metal Working	http://www.renewablelube.com/metal.htm
Bio-Aluminum Cutting Oil cSt 4 & 18 (USDA H1)	Renewable Lubricants, Inc.	Metal Working	http://www.renewablelube.com/metal.htm
Bio-Process Oils (SUS-50, 70, 100, 150, 200)	Renewable Lubricants, Inc.	Metal Working	http://www.renewablelube.com/metal.htm
Bio-General Purpose Cut 30 & 40	Renewable Lubricants, Inc.	Metal Working	http://www.renewablelube.com/metal.htm
Bio-Syntra & SynXtra MW (ISO 22, 32, 46)	Renewable Lubricants, Inc.	Metal Working	http://www.renewablelube.com/metal.htm
Bio-Syntra LM Honing and Cutting Oil	Renewable Lubricants, Inc.	Metal Working	http://www.renewablelube.com/metal.htm
Bio-Heavy and Extra Heavy S Cut (ISO 32, 46, 68)	Renewable Lubricants, Inc.	Metal Working	http://www.renewablelube.com/metal.htm
Bio-Heavy Duty Cutting Oil (ISO 46)	Renewable Lubricants, Inc.	Metal Working	http://www.renewablelube.com/metal.htm
Bio-MultiPurpose Cutting (ISO- 32, 46, 68)	Renewable Lubricants, Inc.	Metal Working	http://www.renewablelube.com/metal.htm
Bio-Mist EP Cutting Oil (ISO 32)	Renewable Lubricants, Inc.	Metal Working	http://www.renewablelube.com/metal.htm
Bio-Corrosion Inhibitor™ (BCI™)	Renewable Lubricants, Inc.	Corrosion Inhibitors	http://www.renewablelube.com/corrosion.htm
Bio-Medium Preservative Lubricant (Mil-PRF-3150D)	Renewable Lubricants, Inc.	Corrosion Inhibitors	http://www.renewablelube.com/corrosion.htm
Bio-Acid Fume Rust Preventative Fluids	Renewable Lubricants, Inc.	Corrosion Inhibitors	http://www.renewablelube.com/corrosion.htm
Bio-Water Emulsifiable Corrosion Inhibitor	Renewable Lubricants, Inc.	Corrosion Inhibitors	http://www.renewablelube.com/corrosion.htm
Bio-Volatile Corrosion Inhibitors (BVCI Ultra Thin Film)	Renewable Lubricants, Inc.	Corrosion Inhibitors	http://www.renewablelube.com/corrosion.htm

Commercial Name[1]	Manufacturer/Distributor	Type	Website
Bio-Concrete Mold Release Fluids (Soy-Based)	Renewable Lubricants, Inc.	Corrosion Inhibitors	http://www.renewablelube.com/corrosion.htm
Bio-Assembly Oils (ISO 7, 15, 22, 32, 46, 68, 100, 150, 220)	Renewable Lubricants, Inc.	Corrosion Inhibitors	http://www.renewablelube.com/corrosion.htm
Bio Penetrating Lubricant™ Food Grade Bio-Penetrating Lubricant™	Renewable Lubricants, Inc.	Food Grade	http://www.renewablelube.com/foodgrade.htm
Bio-Food Grade Hydraulic Fluids (ISO 32, 46, 68, 100)	Renewable Lubricants, Inc.	Food Grade	http://www.renewablelube.com/foodgrade.htm
Bio-Food Grade General Purpose Lubricant SAE 20	Renewable Lubricants, Inc.	Food Grade	http://www.renewablelube.com/foodgrade.htm
Bio-Food Grade Gear Oil (ISO 32-460)	Renewable Lubricants, Inc.	Food Grade	http://www.renewablelube.com/foodgrade.htm
Bio-Food Grade Air Tool Lubricant ISO 32 (USDA H1)	Renewable Lubricants, Inc.	Food Grade	http://www.renewablelube.com/foodgrade.htm
Bio-Food Grade GP Lubricant ISO 10-220 (USDA H1)	Renewable Lubricants, Inc.	Food Grade	http://www.renewablelube.com/foodgrade.htm
Bio-Extreme High Temperature Oven Lubricants ISO 46, 68, 100, 150, 220	Renewable Lubricants, Inc.	Food Grade	http://www.renewablelube.com/foodgrade.htm
Bio-High Temperature Oven Lubricants ISO 68, 100, 150, 220 (USDA H1)	Renewable Lubricants, Inc.	Food Grade	http://www.renewablelube.com/foodgrade.htm
Bio-Food Grade E.P. Grease NLGI #0, #1, #2 (High Temperature)	Renewable Lubricants, Inc.	Greases	http://www.renewablelube.com/greases.htm
Bio-High Temp 180 E.P. Grease NLGI #2 (Multipurpose Lithium Complex)	Renewable Lubricants, Inc.	Greases	http://www.renewablelube.com/greases.htm
Bio-Graphite E.P. Grease NLGI #1	Renewable Lubricants, Inc.	Greases	http://www.renewablelube.com/greases.htm
Bio Gear CO220	BioBlend	Gear Oils	http://www.bioblend.com/content/view/97/87/
Bio Gear EP	BioBlend	Gear Oils	http://www.bioblend.com/content/view/97/87/
Syn Gear FG	BioBlend	Gear Oils	http://www.bioblend.com/content/view/97/87/
Tru Gear FG	BioBlend	Gear Oils	http://www.bioblend.com/content/view/97/87/
Bio Grease EP2	BioBlend	Grease	http://www.bioblend.com/content/view/98/88/
Tru Grease AP2	BioBlend	Grease	http://www.bioblend.com/content/view/98/88/
Bio Grease DR3	BioBlend	Grease	http://www.bioblend.com/content/view/98/88/
Bio Flo AW	BioBlend	Hydraulic Fluid	http://www.bioblend.com/content/view/99/89/
Bio Flo AWS	BioBlend	Hydraulic Fluid	http://www.bioblend.com/content/view/99/89/
Bio Flo EO	BioBlend	Hydraulic Fluid	http://www.bioblend.com/content/view/99/89/
Bio Flo FG	BioBlend	Hydraulic Fluid	http://www.bioblend.com/content/view/99/89/
Bio Flo THF^{Arctic}	BioBlend	Hydraulic Fluid	http://www.bioblend.com/content/view/99/89/
Bio Flo UTF	BioBlend	Hydraulic Fluid	http://www.bioblend.com/content/view/99/89/
Syn Flo FG	BioBlend	Hydraulic Fluid	http://www.bioblend.com/content/view/99/89/
Tru Flo FG	BioBlend	Hydraulic Fluid	http://www.bioblend.com/content/view/99/89/
Bio Lube R & O	BioBlend	Rust & Oxidation	http://www.bioblend.com/content/view/102/92/
Bio Motive^{2c}	BioBlend	2 cycle engine oil	http://www.bioblend.com/content/view/105/95/
BioBlend Multi-Purpose Oil	BioBlend	Aerosol	http://www.bioblend.com/content/view/92/82/
BioLube C&C-FFG	BioBlend	Chain & Cable - Aerosol	http://www.bioblend.com/content/view/92/82/
BioLube Food Release	BioBlend	Aerosol	http://www.bioblend.com/content/view/92/82/
BioBlend PO	BioBlend	Penetrating Oil - Aerosol	http://www.bioblend.com/content/view/92/82/
SynLube SS^{FG}	BioBlend	Aerosol	http://www.bioblend.com/content/view/92/82/
BioLube C&C32P	BioBlend	Chain & Cable Lubricants	http://www.bioblend.com/content/view/94/84/
BioLube C&C46	BioBlend	Chain & Cable Lubricants	http://www.bioblend.com/content/view/94/84/
BioLube C&CFG	BioBlend	Chain & Cable Lubricants	http://www.bioblend.com/content/view/94/84/
SynLubeCOFG	BioBlend	Compressor Oils	http://www.bioblend.com/content/view/95/85/
BioLube CFR	BioBlend	Form Release	http://www.bioblend.com/content/view/96/86/
BioCool SO ^{100}	BioBlend	Metal Working Fluids	http://www.bioblend.com/content/view/100/90/
BioCool SSC	BioBlend	Metal Working Fluids	http://www.bioblend.com/content/view/100/90/

Commercial Name[1]	**Manufacturer/Distributor**	**Type**	**Website**
BioCut ^{1500,2200,3600,4600}	BioBlend	Metal Working Fluids	http://www.bioblend.com/content/view/100/90/
BioCut FG ^{2000}	BioBlend	Metal Working Fluids	http://www.bioblend.com/content/view/100/90/
BioLube RD	BioBlend	Rock drilling	http://www.bioblend.com/content/view/103/93/
BioLube RDP	BioBlend	Rock drilling	http://www.bioblend.com/content/view/103/93/
BioLube RDS	BioBlend	Rock drilling	http://www.bioblend.com/content/view/103/93/
BioLube AT^{FG}	BioBlend	Specialty products	http://www.bioblend.com/content/view/104/94/
SynLube SS^{FG}	BioBlend	Specialty products	http://www.bioblend.com/content/view/104/94/
SynLube VP^{FG}	BioBlend	Specialty products	http://www.bioblend.com/content/view/104/94/
TruLube WD^{FG}	BioBlend	Specialty products	http://www.bioblend.com/content/view/104/94/
TruLube WOFG^{100}	BioBlend	Specialty products	http://www.bioblend.com/content/view/104/94/
Bio 2-Cycle Engine Oil TC-W	United Bio Lube	2 cycle engine oil	http://www.bio2cycleengineoils.com/
Bio 2-Cycle Engine Oil TC-W3	United Bio Lube	2 cycle engine oil	http://www.bio2cycleengineoils.com/
Bio Assembly Oil - ISO 7,15,22,32,46,68,100,150,220	United Bio Lube	Assembly Oil	http://www.bioassemblyoils.com/
Bio Bar & Chain Oil - SAE 15W50, SAE 10W30	United Bio Lube	Bar & Chain Oils	http://www.biobarchainoils.com/
Bio Chain & Cable Oil - SAE 10W20, 10W30, 15W50, 20W60	United Bio Lube	Chain & Cable Oils	http://www.biochaincableoils.com/
Bio Medium Preservative Oil	United Bio Lube	Corrosion Inhibitors	http://www.biocorrosioninhibitors.com/
Bio Acid Fume Rust Preventative Fluids (Light)	United Bio Lube	Corrosion Inhibitors	http://www.biocorrosioninhibitors.com/
Bio Acid Fume Rust Preventative Fluids (Med)	United Bio Lube	Corrosion Inhibitors	http://www.biocorrosioninhibitors.com/
Bio Water Emulsifiable Corrosion Inhibitor	United Bio Lube	Corrosion Inhibitors	http://www.biocorrosioninhibitors.com/
Bio Volatile Corrosion Inhibitors - BVCI™	United Bio Lube	Corrosion Inhibitors	http://www.biocorrosioninhibitors.com/
Bio SoyOrange™ All Purpose Degreaser-Cleaner	United Bio Lube	Degreasers/Cleaners	http://www.biodegreasers.com/
Bio General Purpose Degreaser-Cleaner	United Bio Lube	Degreasers/Cleaners	http://www.biodegreasers.com/
Bio Parts Degreaser	United Bio Lube	Degreasers/Cleaners	http://www.biodegreasers.com/
Bio Parts Degreaser + Bio Corrosion Inhibitors	United Bio Lube	Degreasers/Cleaners	http://www.biodegreasers.com/
Bio Multi-Purpose High Temp EP Grease - NLGI 2	United Bio Lube	Greases	http://www.biogreases.com/
Bio Graphite EP Grease - NLGI 1	United Bio Lube	Greases	http://www.biogreases.com/
Bio Food Grade Gear Oil - ISO 32,46,68,100,150,220,320,460	United Bio Lube	Food Grade Gear Oils	http://www.biofoodgradegearoils.com/
Bio Food Grade EP Grease - NLGI 2	United Bio Lube	Food Grade Greases	http://www.biofoodgradegreases.com/
Bio Food Grade EP Grease - NLGI 1	United Bio Lube	Food Grade Greases	http://www.biofoodgradegreases.com/
Bio Food Grade EP Grease - NLGI 0	United Bio Lube	Food Grade Greases	http://www.biofoodgradegreases.com/
Bio Food Grade Hydraulic Fluid - ISO 32, 46, 68	United Bio Lube	Food Grade Hydraulic Fluids	http://www.biofoodgradehydraulicfluids.com/
Bio Food Grade Penetraing Lubricant - BPL™	United Bio Lube	Food Grade Lube	http://www.biofoodgradelubes.com/
Bio Food Grade Air Tool Oil - ISO 32	United Bio Lube	Food Grade Lube	http://www.biofoodgradelubes.com/
Bio Food Grade Al Cutting Oil - 4 cSt	United Bio Lube	Food Grade Lube	http://www.biofoodgradelubes.com/
Bio Food Grade Al Cutting Oil - 18 cSt	United Bio Lube	Food Grade Lube	http://www.biofoodgradelubes.com/
Bio Food Grade Edible GP Lube - SAE 20	United Bio Lube	Food Grade Lube	http://www.biofoodgradelubes.com/
Bio Food Grade GP Lubricant - ISO 10,15,22,32,46,68,100,150,220	United Bio Lube	Food Grade Lube	http://www.biofoodgradelubes.com/
BioHydran TMP 32,46,68	Total	Hydraulic Oils	http://www.lubricants.total.com
BioHydran TMP 100	Total	Hydraulic Oils	http://www.lubricants.total.com
BioHydran SE 32,46,68	Total	Hydraulic Oils	http://www.lubricants.total.com
BioHydran FG	Total	Hydraulic Oils	http://www.lubricants.total.com
BioHydran RS 38B	Total	Hydraulic Oils	http://www.lubricants.total.com

Commercial Name[1]	**Manufacturer/Distributor**	**Type**	**Website**
BioTrans FX	Total	UTTO Transmissions	http://www.lubricants.total.com
Carter Bio 150,220,320,460	Total	UTTO Transmissions	http://www.lubricants.total.com
ChainBio 100,160	Total	Chainsaw & Chain oils	http://www.lubricants.total.com
Neptuna Bio-Jet	Total	2 stroke engine oils	http://www.lubricants.total.com
BioMultis SEP 2	Total	Greases	http://www.lubricants.total.com
BioMerkan RS	Total	Greases	http://www.lubricants.total.com
BioMoldol S	Total	Specialty	http://www.lubricants.total.com
Mobil EAL Envirosyn H Series	Mobil	Hydraulic Oils	http://www.mobil.com/USA-English/Lubes/PDS/GLXXENINDMOMobil_EAL_Envirosyn_H.asp
Mobil EAL 224H	Mobil	Hydraulic Oils	http://www.mobil.com/USA-English/Lubes/PDS/GLXXENINDMOMobil_EAL_224_H.asp
Mobil SHC Grease 100 EAL Series	Mobil	Greases	http://www.mobil.com/USA-English/Lubes/PDS/GLXXENGRSMOMobil_SHC_Grease_100_EAL_Series.asp
Mobil EAL Arctic Series	Mobil	Refrigeration compressors	http://www.mobil.com/USA-English/Lubes/PDS/GLXXENINDMOMobil_EAL_Arctic.asp
Mobil EAL Arctic Series (Marine)	Mobil		http://www.exxonmobil.com/USA-English/Marine/PDS/GLXXENMRNEMMobil_EAL_Arctic_SHC.asp
Mobil EAL Arctic Series (Marine)	Mobil		http://www.exxonmobil.com/USA-English/Marine/PDS/GLXXENMRNEMMobilEALArcticSeries.asp
CHEVRON CLARITY® HYDRAULIC OILS AW ISO 32, 46, 68	Chevron	Hydraulic Oils	http://www.chevronlubricants.com/worldwide/northamerica/na_lubricantsforbiz/na_chevron_prodindex/default.asp
G-Oil 2 cycle Green engine Oil	Green Earth Solutions LLC.	2 cycle engine oils	http://www.getgreenearthsolutions.com/
PROECO 2818-A TCW-3 2-CYCLE Engine Lubricant	Cognis Corporation	2 cycle engine oils	
Bar & Chain Lubricant (1 GAL)	Bio-Gem Services Inc.	Chain and cable lubricants	
SoyEasy Bike Chain Lubricant	Bio-Gem Services Inc.	Chain and cable lubricants	
SoyEasy Draw- Biodegradable Drawing Fluid	Bio-Gem Services Inc.	Forming lubricants	
SoyEasy Quench- Biodegradable Quench Oil	Bio-Gem Services Inc.	Forming lubricants	
80W90 Multi- Purpose Gear Lubricant	Bio-Gem Services Inc.	Gear lubricants	
SoyEasy Open Gear Lubricant	Bio-Gem Services Inc.	Gear lubricants	
Eco Biodegradable Gear Oils	DSI Ventures, Inc.	Gear lubricants	
5th Wheel Biobased Grease	Creative Composites, LTD.	Greases	
5th Wheel Trailer Grease	Plews/Edelmann	Greases	
Disc/Drum Wheel Bearing Grease	Plews/Edelmann	Greases	
Ecoline Food Machinery Grease	Cortec Corporation	Greases	
Ecoline Heavy Duty Grease	Cortec Corporation	Greases	
ELM Cotton Picker Spindle Grease	Environmental Lubricants Manufacturing, Inc.	Greases	
ELM Textile Grease	Environmental Lubricants Manufacturing, Inc.	Greases	
EP Lithium Grease	Environmental Lubricants Manufacturing, Inc.	Greases	
EP Plus Grease	SoyClean	Greases	
Grease EP	RyDol Prodcuts, Inc	Greases	
LMX TM Red Grease	Plews/Edelmann	Greases	
Moly EP Grease	Plews/Edelmann	Greases	
Multi-Purpose Grease	Plews/Edelmann	Greases	
SoyGrease Food Machinery (NLGI Grade 1 & 2)	Environmental Lubricants Manufacturing, Inc.	Greases	
SoyGrease Heavy Duty Truck	Environmental Lubricants Manufacturing, Inc.	Greases	
SoyGrease Multi-Purpose EP	Bio-Gem Services Inc.	Greases	
SoyGrease Semi-Truck Fifth Wheel	Environmental Lubricants Manufacturing, Inc.	Greases	
SoyGrease EP Plus	Environmental Lubricants Manufacturing, Inc.	Greases	
SoyGrease EP Premium	Environmental Lubricants Manufacturing, Inc.	Greases	

Commercial Name[1]	Manufacturer/Distributor	Type	Website
SoyGrease™ Multipurpose Equipment Grease, TF 0-100 winter	Environmental Lubricants Manufacturing, Inc.	Greases	
SoyGrease™ Multipurpose Equipment Grease, TF 35-160 Summer	Environmental Lubricants Manufacturing, Inc.	Greases	
SoyGrease™ Multipurpose Equipment Grease, TFHD 35-160 Summer w/moly	Environmental Lubricants Manufacturing, Inc.	Greases	
SoyGrease™ Multipurpose Equipment Grease, TFHD Winter 0-100 w/moly	Environmental Lubricants Manufacturing, Inc.	Greases	
SoyTrak Arctic Blend Grease	Bio-Gem Services Inc.	Greases	
SoyTrak Multi-Season Grease	Bio-Gem Services Inc.	Greases	
SoyTrak Summer Grease	Bio-Gem Services Inc.	Greases	
SoyTrak Winter Grease	Bio-Gem Services Inc.	Greases	
TempFlex™ 0-100 Rail Curve Lubricant	Environmental Lubricants Manufacturing, Inc.	Greases	
TempFlex™ 0-100 w/MoS2 Rail Curve Lubricant	Environmental Lubricants Manufacturing, Inc.	Greases	
TempFlex™ 35-160 Rail Curve Lubricant	Environmental Lubricants Manufacturing, Inc.	Greases	
TempFlex™ 35-160 w/MoS2 Rail Curve Lubricant	Environmental Lubricants Manufacturing, Inc.	Greases	
ThermaPlex Bio Green Bearing Grease	LPS Laboratories	Greases	
Vane Spindle Grease (VSG)	Eco Fluid Center Ltd.	Greases	
White Lithium Grease	Plews/Edelmann	Greases	
BiotechBased Industrial Hydraulic Oil	Environmental Lubricants Manufacturing, Inc.	Hydraulic Fluids	
Castrol CareLube HTG	McNovick inc.	Hydraulic Fluids	
Cosmolubric B-230	Houghton International, Inc.	Hydraulic Fluids	
Cosmolubric B-68	Houghton International, Inc.	Hydraulic Fluids	
Cosmolubric FG-46	Houghton International, Inc.	Hydraulic Fluids	
Cosmolubric HF-122	Houghton International, Inc.	Hydraulic Fluids	
Cosmolubric HF-130	Houghton International, Inc.	Hydraulic Fluids	
Cosmolubric HF-144	Houghton International, Inc.	Hydraulic Fluids	
Cosmolubric HF-1530	Houghton International, Inc.	Hydraulic Fluids	
Desigreen 300	Desilube Technology, Inc.	Hydraulic Fluids	
DOW™ SYMBIO Bio-Hydraulic Fluid	The Dow Chemical Company	Hydraulic Fluids	
EcoSafe V-200	American Chemical Technologies	Hydraulic Fluids	
EnviroLift™ Elevator Hydraulic Oil	Environmental Lubricants Manufacturing, Inc.	Hydraulic Fluids	
GRIFLUBE Bio-Syn	Hill and Griffith Company	Hydraulic Fluids	
BioFlo LT	BioBlend	Hydraulic Fluids	
BioSOY All-Season Hydraulic Oil	SoyClean	Hydraulic Fluids	
AgriTech Hydraulic Fluid	Bunge oils	Hydraulic Fluids	
Bio-Biodegradable Hoist Oil (BHHO)	Renewable Lubricants, Inc.	Hydraulic Fluids	
Bio-trans Hydraulic (Universal Tractor Fluid)	Renewable Lubricants, Inc.	Hydraulic Fluids	
Hydro Safe ISO VG 32	Hydro Safe Oil Division, Inc.	Hydraulic Fluids	
Hydro Safe ISO VG 46	Hydro Safe Oil Division, Inc.	Hydraulic Fluids	
Hydro Safe ISO VG 46FR	Hydro Safe Oil Division, Inc.	Hydraulic Fluids	
Hydro Safe ISO VG 46FR	Hydro Safe Oil Division, Inc.	Hydraulic Fluids	
Hydro-Drive B-100	Houghton International, Inc.	Hydraulic Fluids	
Hydro-Drive B-150	Houghton International, Inc.	Hydraulic Fluids	
MIL-PRF-32073 Grade 1 Hydro Safe ISO VG-15M1	Hydro Safe Oil Division, Inc.	Hydraulic Fluids	
MIL-PRF-32073 Grade 2 Hydro Safe ISO VG-22M2	Hydro Safe Oil Division, Inc.	Hydraulic Fluids	

Commercial Name[1]	Manufacturer/Distributor	Type	Website
MIL-PRF-32073 Grade 2 Hydro Safe ISO VG-22M2	Hydro Safe Oil Division, Inc.	Hydraulic Fluids	
MIL-PRF-32073 Grade 4 Hydro Safe ISO VG 46-M4	Hydro Safe Oil Division, Inc.	Hydraulic Fluids	
MIL-PRF-32073 Grade 5 Hydro Safe ISO VG-68M5	Hydro Safe Oil Division, Inc.	Hydraulic Fluids	
No-Ox-Id Liquid Elevator Casing Filler E-800	Hydro Safe Oil Division, Inc.	Hydraulic Fluids	
Novus 300 ISO 46	Cargill Industrial Oils and Lubricants	Hydraulic Fluids	
Novus THF (Tractor Hydraulic Fluid)	Cargill Industrial Oils and Lubricants	Hydraulic Fluids	
PANOLIN HLP SYNTH E 15, 22, 32, 46, 68	Panolin America, Inc.	Hydraulic Fluids	
PANOLIN TURWADA SYNTH E 46	Panolin America, Inc.	Hydraulic Fluids	
Plantohyd 40N	Fuchs Lubricants Co.	Hydraulic Fluids	
ProEco HE 801-22, 32, 46, 68	Cognis Corporation	Hydraulic Fluids	
ProEco® EAF™ 346, 368 Biodegradable Hydraulic Fluid	Cognis Corporation	Hydraulic Fluids	
ProEco® EAF™ 446, 468 LL "Long Life" Biodegradable Hydraulic Fluid	Cognis Corporation	Hydraulic Fluids	
Pure Lube AW 32 and AW 46	G-C Lubricants	Hydraulic Fluids	
SAFE LUBE Hydraulic Fluid - ISO 32, 46, 68	GEMTEK Products	Hydraulic Fluids	
SoyFluid™ Hydraulic Food Grade ISO 32, 46	Environmental Lubricants Manufacturing, Inc.	Hydraulic Fluids	
SoyFluid™ Hydraulic Industrial ISO 32, 46, 68 All Season	Environmental Lubricants Manufacturing, Inc.	Hydraulic Fluids	
SoyFluid™ Hydraulic Universal Tractor	Environmental Lubricants Manufacturing, Inc.	Hydraulic Fluids	
Universal Tractor Hydraulic Oil	Environmental Lubricants Manufacturing, Inc.	Hydraulic Fluids	
Starbrite ECO AW 32, 46, 68 Hydraulic Oil	Starbrite Distributing	Hydraulic Fluids	
CIMFREE ® VG-3900H	Milacron LLC	Metalworking Fluids	
CIMFREE ® VG-703ES	Milacron LLC	Metalworking Fluids	
CIMFREE ® VG-901ZH	Milacron LLC	Metalworking Fluids	
CIMFREE ® VG-MF5350	Milacron LLC	Metalworking Fluids	
CIMFREE ® VG-S175	Milacron LLC	Metalworking Fluids	
Coolube 2210	UNIST, Inc.	Metalworking Fluids	
Defoamer Soy Easy Cool-XXL	Bio-Gem Services Inc.	Metalworking Fluids	
Defoamers SoyEasy UNI-Cut and SoyEasy UNI-Cut Lite	Bio-Gem Services Inc.	Metalworking Fluids	
Desigreen 100	Desilube Technology, Inc.	Metalworking Fluids	
Desigreen 12	Desilube Technology, Inc.	Metalworking Fluids	
Desigreen 120	Desilube Technology, Inc.	Metalworking Fluids	
Desigreen 215B	Desilube Technology, Inc.	Metalworking Fluids	
Desigreen Penetrant	Desilube Technology, Inc.	Metalworking Fluids	
Ecoline 3220	Cortec Corporation	Metalworking Fluids	
Ecoline All-Purpose Lubricant	Cortec Corporation	Metalworking Fluids	
Ecoline Bearing, Chain & Roller Lubricant	Cortec Corporation	Metalworking Fluids	
Ecoline Cutting Fluid	Cortec Corporation	Metalworking Fluids	
KG3X Honing Oil	Sunnen Products Company	Metalworking Fluids	
MAN-863 Honing Oil	Sunnen Products Company	Metalworking Fluids	
pH Booster- Maintains pH Conditions for Coolant Longevity	Bio-Gem Services Inc.	Metalworking Fluids	
Pure Kut 50	G-C Lubricants	Metalworking Fluids	
SAFE LUBE Cutting & Forming Fluid NF	GEMTEK Products	Metalworking Fluids	
SAFE LUBE Cutting Fluid TD	GEMTEK Products	Metalworking Fluids	

Commercial Name[1]	Manufacturer/Distributor	Type	Website
SAFE LUBE Grinding Fluid	GEMTEK Products	Metalworking Fluids	
SAFE LUBE Rolling Fluid	GEMTEK Products	Metalworking Fluids	
SAFE LUBE Tapping Fluid	GEMTEK Products	Metalworking Fluids	
Soy Easy Cool GHP-Biodegradable High Speed Grinder Coolant	Bio-Gem Services Inc.	Metalworking Fluids	
SoyEasy Cool- XXL- Biodegradable Semi-Synthetic Coolant	Bio-Gem Services Inc.	Metalworking Fluids	
SoyEasy Draw- Biodegradable Drawing Fluid	Bio-Gem Services Inc.	Metalworking Fluids	
SoyEasy Form C60- Biodegradable Metal Forming Fluid	Bio-Gem Services Inc.	Metalworking Fluids	
SoyEasy Form HM- Biodegradable Metal Stamping Fluid	Bio-Gem Services Inc.	Metalworking Fluids	
SoyEasy Form HM- Biodegradable Metal Stamping Fluid	Bio-Gem Services Inc.	Metalworking Fluids	
SoyEasy Form R40- Biodegradable Metal Forming Fluid	Bio-Gem Services Inc.	Metalworking Fluids	
SoyEasy Quench- Biodegradable Quench Oil	Bio-Gem Services Inc.	Metalworking Fluids	
SoyEasy UNI-Cut -Tri-purpose Cutting Oil	Bio-Gem Services Inc.	Metalworking Fluids	
SoyEasy UNI-Cut Lite- Light Weight Cutting Oil	Bio-Gem Services Inc.	Metalworking Fluids	
SoyEasy- Cut II- Dual-purpose Cutting Oil	Bio-Gem Services Inc.	Metalworking Fluids	
Soy Easy Cut	Environmental Lubricants Manufacturing, Inc.	Metalworking Fluids	
SoyEasy Form HM- Biodegradable Metal Stamping Fluid	Environmental Lubricants Manufacturing, Inc.	Metalworking Fluids	
SPINDKOOL CARBIDE GRIND	RS Farm and Harvest Supply, Inc	Metalworking Fluids	
SunLub Cut 10-46	NATOIL AG	Metalworking Fluids	
Tapmatic Edge Crème	LPS Laboratories	Metalworking Fluids	
Tapmatic Edge Liquid	LPS Laboratories	Metalworking Fluids	
Tapmatic Edge Lube	LPS Laboratories	Metalworking Fluids	
Tapmatic Natural	LPS Laboratories	Metalworking Fluids	
EnviroLogic 31	Terresolve Technologies	Penetrating Lubricants	
Lubricant/Cleaner.Preservative	RyDol Products, Inc.	Penetrating Lubricants	
LubriMagic™ Multi-Purpose Lubricant & Penetrant	Plews/Edelmann	Penetrating Lubricants	
Naturelube 700	BioPlastic Polymers and Composites LLC	Penetrating Lubricants	
Penetrant and lubricant	SoyClean	Penetrating Lubricants	
Simply Soy	Nutek, LLC	Penetrating Lubricants	
Soy Lube SL-100	Bi-O-Kleen Industries, Inc	Penetrating Lubricants	
SoyLube	Environmental Lubricants Manufacturing, Inc.	Penetrating Lubricants	
Zep 70	Acuity Specialty Products, Inc.	Penetrating Lubricants	

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[1] Blue highlighted cells indicate that the product is included in the BioPreferred catalog.

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