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ORGANIC MUNICIPAL SOLID WASTE (MSW) AS FEEDSTOCK FOR
BIODIESEL PRODUCTION:
A FINANCIAL FEASIBILITY ANALYSIS

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Dissertação apresentada ao Programa de Pós-Graduação em Energia – Escola Politécnica / Faculdade de Economia, Administração e Contabilidade / Instituto de Eletrotécnica e Energia / Instituto de Física – da Universidade de São Paulo como parte dos requisitos para obtenção do título de Mestre em Ciências.

Orientação: Prof^a. Dr^a. Virginia Parente

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*“The energy industry is a multi-trillion
dollars per year, highly capitalized,
commodity business, with exquisite supply
chains, providing essential services at all
levels of society. This leads to a system with
considerable inertia, aversion to risk,
extensive regulation and complex politics”*

Ernie Moniz

ABSTRACT

GAETA-BERNARDI, André. **Organic municipal solid waste (MSW) as feedstock for biodiesel production**: a financial feasibility analysis. . 2014. 129f .Master's Dissertation - Graduate Program on Energy, Universidade de São Paulo, São Paulo, 2014.

The pursuit towards an alternative solution to fossil fuel has facilitated science investigation initiatives that compare various options leading to biodiesel production. Besides conventional feedstock derived from vegetable oils, alternative sources that could be produced in large scale at competitive costs are the main scope of research in this field. This dissertation investigates the financial feasibility using organic solid waste as a feedstock, which results in the production of biodiesel through the conversion of volatile fatty acids (VFA) into lipids. As a result, based on existing references of: (i) capital and operating costs; (ii) internal rate of return; (iii) production and extraction yields for volatile fatty acids and lipids, we concluded that biodiesel production is competitive compared to subsidized biodiesel traded in regions of Europe and the United States. The sensitivity analysis took into consideration independent variables associated with: (i) investments in the plant; (ii) selling price of the biodiesel; (iii) costs of feedstock; and (iv) production yield. The results of such analysis showed the feasibility of using organic solid waste as a feedstock in 86.4% of the total 10,000 simulations, at the required internal rate of return. These results encourage research aims to examine this technology at a larger scale. The adoption of public policies for the urban waste's disposal and collection is also important for the implementation of such technologies.

Key words: biodiesel, volatile fatty acids, municipal solid waste, energy and feasibility.

RESUMO

GAETA-BERNARDI, André. **Organic municipal solid waste (MSW) as feedstock for biodiesel production: a financial feasibility analysis.** . 2014. 129f .Master's Dissertation - Graduate Program on Energy, Universidade de São Paulo, São Paulo, 2014.

A busca por soluções alternativas aos combustíveis fósseis tem impulsionado as iniciativas de pesquisa científica que comparam várias opções para a produção de biodiesel. Além das tradicionais fontes de matéria-prima provenientes de óleos vegetais, fontes alternativas, que possam ser produzidas em grande escala a custo competitivo, figuram como o principal escopo nesse campo de pesquisa. Essa dissertação investiga a viabilidade financeira da utilização de resíduo sólido orgânico como matéria-prima para a produção de biodiesel, através da conversão de ácidos graxos voláteis em lipídios. Como resultado, baseando-se em dados sobre: (i) investimentos e custos de operação; (ii) taxa interna de retorno requerida; (iii) taxas de extração e produção de ácidos graxos voláteis e de lipídios, conclui-se que a produção de biodiesel é competitiva quando comparada ao biodiesel subsidiado, que é negociado em regiões dos Estados Unidos e da Europa. A análise de sensibilidade realizada levou em consideração variáveis independentes tais como: (i) investimentos na planta; (ii) preço de venda do biodiesel, (iii) custos da matéria-prima e (iv) produtividade. O resultado de tal análise mostrou a viabilidade da utilização de ácidos graxos voláteis para a produção de biodiesel em 86,4% das 10.000 simulações, assumindo a taxa interna de retorno requerida. Esses resultados encorajam pesquisas adicionais para teste da tecnologia em maior escala. A adoção de políticas públicas para o descarte e coleta adequados dos resíduos sólidos urbanos também é importante para o desenvolvimento dessa tecnologia.

Palavras-chave: biodiesel, ácidos graxos voláteis, resíduo orgânico sólido, energia e viabilidade.

LIST OF ABBREVIATIONS

AACE	Association for the Advancement of Cost Estimating International
AGA	American Gas Association
ANP	<i>Agência Nacional do Petróleo, Gás Natural e Biocombustíveis</i>
API	American Petroleum Institute
APV	Adjusted Preset Value
BTU	British Thermal Unit
BVS	Biodegradable Volatile Solids
CAGR	Compound Annual Growth Rate
CAPM	Capital Asset Pricing Model
DIN	<i>Deutsches Institut für Normung</i>
EIA	Energy Information Administration
EPA	United States Environmental Protection Agency
EPC	Engineering Procurement Contract
FAME	Fatty Acids Methyl Ester
FCFE	Free Cash Flow to Equity
FCFF	Free Cash Flow to Firm
FOB	Free On Board
FRN	<i>Fachagentur Nachwachsende Rohstoffe</i>
IEA	International Energy Agency
IICA	<i>Instituto Interamericano de Cooperación para la Agricultura</i>
IRR	Internal Rate of Return
ISBL	Inside Battery Limits
LCA	Life Cycle Analysis
MSW	Municipal Solid Waste
NPV	Net Present Value
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization of Petroleum Export Countries
OSBL	Offsite Battery Limits
P	Production
PAHO	Pan-American Health Organization
PPA	Purchase Power Agreement

R	Reserves
RFS	Renewable Fuel Standard
RME	Rapeseed Methyl Ester
ROIC	Return on Investment
RVS	Refractory Volatile Solids
SME	Soy Methyl Esters
SPE	Society of Petroleum Engineers
TC	Total Carbons
TS	Total Solids
TOPO	Trioctyl-Phosphine Oxide
TVS	Total Volatile Solids
U.S.	United States of America
UCOME	Used Cooked Oil Methyl Esters
ULSD	Ultra Low Sulfur Diesel
USDA	United States Department of Agriculture
VFA	Volatile Fatty Acid
WACC	Weighted Average Cost of Capital

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1. Introduction

The increased generation of solid urban waste combined with the utilization of non-renewable fuels as the main energy source for transportation, specifically the negative consequences thereof, may be considered the main concerns of today's society. This dissertation investigates the financial feasibility of biodiesel production from municipal solid waste (MSW) by an integrated solution, which addresses the challenges associated with waste generation and our dependency on a limited supply of fossil fuels.

Urban waste, or municipal solid waste (MSW), has led to environmental pollution and high costs to the municipality (MADU; KUEI, 2012). The World Bank (2012) expects MSW generation to attain 2.2 billion tons by 2025. When compared to the current estimate of MSW generation at 1.3 billion tons per year, many policies have suggested investments, especially in low income countries, where most of this waste is deposited in dumps and landfills. The improper management of MSW has severe environmental consequences, such as contaminants polluting water sources, as well as the emission of large amounts of greenhouse gases (GHG) that contribute to global warming¹(MADU; KUEI, 2012).

The disposal of MSW is a serious concern facing societies around the world. Despite recent technological improvements to optimize waste management procedures and reduce negative externalities², MSW generation per capita continues to escalate. Furthermore, the commonly used methodologies for waste treatment to mitigate environmental risks are costly (CHEREMISINOFF, 2003). For example, the cost of landfill disposal varies from \$10 per ton to \$30 per ton, but the disposal in more advanced engineered landfills could reach up to \$100 per ton (The World Bank, 2012).

¹ Greenhouse gases (GHG) contribute to global warming. The physical characteristics of greenhouse gases are the potential to absorb infra-red radiation via a specific vibrational modes and its lifetime in the earth's atmosphere. The main contributors to global warming are carbon dioxide (CO₂) and methane (CH₄) (LECTHER; 2009).

² Sometimes markets fail to capture all the costs of a market transaction, when a third party is negatively affected by the production or consumption of a commodity, for example. If the external effect generates a cost to a third party, it is considered a negative externality. Environmental economists are interested in the negative externalities that damage the atmosphere, natural resources and quality of life (CALLAN, THOMAS; 2010).

The detrimental effects associated with oil utilization comprise energy security risks. Supply is concentrated to politically instable regions, and, as such, energy affordability during peak and volatile price periods are negative to economies. Furthermore, environmental problems associated with oil production, GHG emissions from fossil fuel consumption (PASCUAL; ELKIND, 2010) and petroleum's non-renewable nature (GROSH; PRELAS, 2009) also represent intrinsic problems in fossil fuel utilization.

Concerns about petroleum's non-renewable nature are not new. At the beginning of 1970, the Club of Rome raised awareness and potential consequences of exponentially growing population combined with finite hydrocarbon-based energy sources like petroleum (DIETER; WITZEL, 2010). In regards to energy security, Arab and Israel war conflicts, Iran-Arab and Arab-Arab conflicts, US-Gulf war conflicts of Kuwait and Iraq, radicalism and terrorist attacks have affected the region and the world's oil supply since the Middle East holds 65% to 70% of world's oil reserves (ŞEN; BABALI, 2007).

Although the diesel engine was invented in 1900s, the commercial-scale exploration of biodiesel surged only many decades later in the 1970s as an increased interest to alleviate the depletion of fossil fuel resources, mitigating oil shocks risks and reducing greenhouse gas emissions became apparent (JANAUN; ELLIS, 2010). Governments are determined to promote an alternative to fossil fuels by implementing policy that supports biofuel technology and production, mostly with respect to biodiesel and ethanol. Nevertheless, "green" business models could be further fostered by policy makers (NAIR; PAULOSE, 2014). The governments of the United States, Brazil, Colombia, European Union Member States and Australia have promoted these public policies (CHARLES; RYAN; RYAN; OLORUNTOBA, 2007).

Economic and geopolitical factors, including high petroleum prices, environmental concerns such as GHG emissions, and supply instability from oil producing countries have facilitated a greater emphasis on renewable energy policy initiatives (STEPHANOPOULOS, 2007). However, biodiesel production faces limitations to thrive as a renewable source. The low conversion yield to produce biodiesel and the high costs associated with feedstock remain the main challenges to sustainable biodiesel production (JANAUN; ELLIS, 2010).

The cost of feedstock corresponds to 75% of the total cost of biodiesel produced from edible and non-edible vegetable oils. As a consequence, the world's average cost of producing biodiesel is usually \$0.50 per liter versus \$0.35 per liter of fuel diesel (ATABANI; SILITONGA; BADRUDDIN; MAHLIA; MASJUKI; MEKHILEF, 2012).

The cost of producing biodiesel in developed countries could be 1.5 – 3.0 times more expensive than producing diesel. Consequently, biodiesel is not feasible economically and policies that support advancements leading to competitive prices with fossil fuels are required (ATABANI; SILITONGA; BADRUDDIN; MAHLIA; MASJUKI; MEKHILEF, 2012).

In spite of the use of vegetable oils to produce biodiesel, initiatives that analyze the economic competitiveness of other sources are found in literature. For example, Dufreche et al. (2007) concluded that the cost of producing biodiesel from municipal sewage sludge was \$3.11 per gallon (\$0.88 per liter), due to low yields. As such, these results are not competitive when compared to the production cost at \$2.5 per gallon (\$0.66 per liter) when soy is used as a feedstock. Research on biodiesel production from microalgae has showed the advantages of this source in terms of the high oil content, later converted in biodiesel. The rapid biomass production from microalgae and the maintenance of agricultural land for food production are additional benefits. However, production cost remains \$20 to \$30 per gallon (\$5.3 to \$ 8.0 per liter), thus not economically feasible (BALAT, 2011).

The IEA (International Energy Agency, 2012) predicts that biofuels, which comprise biodiesel and ethanol, will receive \$46 billion in subsidies³ by 2020 and \$59 billion by 2035 versus \$24 billion received in 2011 – an increase in 92% and 146% respectively. Biofuel subsidies are largely concentrated in the European Union, which allocated \$11 billion to biofuels in 2011, mostly in biodiesel. In the same year, the U.S. allocated \$8 billion to biofuels that targeted ethanol production.

The production of biofuels on an agricultural scale raises additional concerns among environmental and conservation groups, including the use of fertile land to produce fuel products instead of food production, as well as potential deforestations of tropical regions.

³ Subsidies to renewables are generally paid to producers directly or indirectly. The direct subsidy includes tax credits for investment or production, price premiums or feed-in tariffs. The indirect subsidy comprises mandates, quotas or portfolio standards (IEA, 2012).

These aspects have weakened the political support for biofuels' subsidies (CHAPMAN, 2013).

Continuous efforts to develop and produce biofuels, as part of governments' environmental and energy policies, should continue to increase demand, yet a growing global population and limited availability of cultivated land limit the production of biodiesel from agricultural crops (ATABANI; SILITONGA; BADRUDDIN; MAHLIA; MASJUKI; MEKHILEF, 2012). As a result, the use of alternative feedstock for biodiesel production, such as organic residues from municipal solid waste (MSW), rather than vegetable oils may facilitate the development of a sustainable fuel source (SATYANARAYANA; JOHRI; PRAKASH, 2012).

Additional to the cost advantages due to using a less expensive carbon feedstock include the utilization of organic waste as an alternative feedstock. As a result, the production of biodiesel eliminates the controversial debate of using edible carbons to produce fuel as opposed to food, as well as the need for additional agricultural land to increase biodiesel production (SATYANARAYANA; JOHRI; PRAKASH, 2012). Notably, solar radiation is the most abundant energy source available (MARSHALL; KAUFMAN, 2013). Organic waste conversion to biofuels, not only addresses environmental problems, but also maximizes the energy utilization from solar radiation, by recycling organic matter.

1.1 Objective

This dissertation's primary objective is to evaluate the financial feasibility of organic municipal solid waste (MSW) conversion, through industrial biotechnology⁴, in fatty acids methyl esters (FAME), the primary molecule in biodiesel (BISEN; DEBNACHT; PRASAD, 2012).

Existing literature about this research field is limited and generally focused on the segmented parts of the process to convert organic MSW in biodiesel. D'Addario et al (1993) and Sans et al (1995) published the results of several experiments on VFA production from organic MSW. Alkaya et al (2009) and Mostafa (1999) published results on VFA extraction from

⁴ Industrial biotechnology is the conversion of biomass via bio catalysis, microbial fermentation, or cell culture to produce chemicals, materials and/or energy (OLSSON, L.; SCHEPER, T., 2007).

fermentation broth and Fontainelle et al (2012) and Fei et al (2010) on VFA conversion to lipids.

Secondary objectives in this dissertation are:

1. To assess existing literature about the MSW composition and its main characteristics from a physical-chemical and economic standpoint, as well as, to analyze existing methods for MSW's collection, disposal and treatment. MSW increase in volume over the decades and its toxicity represent the main challenges to modern society (KREITH; TCHOBANOGLIOUS, 2002).
2. To estimate the amount of potential organic MSW that could be degradable by acidogenesis, such as waste food, leaves and grass trimming, which will be the main feedstock for FAME production.
3. To revise existing methods to convert organic matter from different sources to volatile fatty acids (VFA), which will later converted to FAME. Most studies on FAME production have been carried out with oleaginous as the carbon source, but alternative sources, such as starch and ethanol, pectin and lactose, waste and glycerol have also been tested (FEI; CHANG; SHANG; CHOI; KIM; KANG, 2011).
4. To review main methods for evaluating investments and the decision making process, with particular focus on net present value (NPV) from a stream of cash flow and internal rate of return (IRR) methodology. These methodologies and tools incorporate the concept of the time value of money, which has been known and evolved since the early 1800s (CRUNDWELL, 2008).

1.2 Central Question and Hypothesis

The central question to be pursued in this dissertation is:

At what diesel or conventional biodiesel price, would biodiesel produced from organic MSW be economically competitive?

The hypothesis is to be investigated is that petroleum prices above \$100 per barrel and existing subsidies would make biodiesel produced from organic MSW competitive to diesel and conventional biodiesel.

While raw material costs correspond to 80% to 90% of the cash cost production in chemicals and petrochemical processes that use vegetable oils (TOWLER; SINNOT, 2013), MSW feedstock cost should be significantly lower, if not positive. Municipalities disburse \$5/ton to \$200/ton (The World Bank, 2012) in MSW treatment, depending on the selected treatment method. Thus, the use of MSW as a feedstock should have a significant lower cost compared to other biodiesel feedstock.

Petroleum prices have been escalating over the past two decades with extraordinary volatile in recent years. Literature describing the “third oil price shock” attributes the recent increase in petroleum prices to increase in demand from emerging market countries, expansionary monetary policies, flat petroleum production and increase in futures market’s speculations (MORANA, 2013).

Research has also been conducted to describe the potential impact of a “peak oil”⁵ scenario, which could be associated to political disruptions, military conflicts or terrorist attacks. The conclusion is higher volatility for only small changes in supply and higher petroleum prices, connected to negative economic impacts (LUTZ; LEHR; WIEBE, 2012).

Chapman (2013) argues the discussions about a factual “peak oil” overshadows the debate on the decreasing long-term supply of petroleum, which should focus on the acknowledgment that cheap fuel is no longer available. The debate should conduct to serious discussions about ways to reduce energy utilization at production, distribution and consumption phases of the economy.

Research experiments aimed to present an economic analysis of biodiesel prices by using different raw material as a feedstock for production and indicate that VFA could be financially feasible under certain feedstock cost scenarios. The conclusion is based on the fact

⁵ Peak oil is the point at which global production of petroleum reaches the maximum level and flow rates decline (BOWDEN et al. 1985 apud CHAPMAN, 2013).

that the biodiesel price is higher than the raw material price, as depicted in Table 1 (FEI; CHANG; SHANG; CHOI; KIM; KANG, 2011).

Table 1 – Biodiesel raw material cost and equivalent biodiesel price

Raw material for biodiesel production	Raw material price (\$/kg)	Biodiesel price (\$/L)
Soy oil	1.36	1.28
Castor oil	1.16	1.52
Lipid (VFA as \$-20/ton)	0.16	0.30
Lipid (VFA as \$30/ton)	0.49	0.70
Lipid (VFA as \$100/ton)	0.95	1.26
Lipid (glucose as \$490/ton)	3.15	3.79
Microalgae (in photobioreactor)	0.47	1.08
Microalgae (in raceway pounds)	0.60	1.34

Source: FEI; CHANG; SHANG; CHOI; KIM; KANG, 2011.

Although this analysis suggests a potential financial feasibility, results lack of an integrated analysis in terms of the internal rate of return (IRR) and net present value (NPV) associated to the project. These concepts are further discussed in the methodology section.

1.3 Methodology

The adopted methodology could be divided in two central parts, which aims to answer the central question of this dissertation.

The first part comprises the analysis and definition of the necessary structure and costs to produce biodiesel from MSW, based on existing literature and operating units with the same or similar physical and chemical characteristics. The information defines basic standards for cost and size in a theoretical facility.

The last part consists of building a financial model to evaluate the facility's financial feasibility by incorporating the information previously collected. The financial model allows the assessment of the profitability of the plant through the interpretation of financial indicators used in this type of analysis, which are the net present value (NPV) method and the internal rate of return (IRR) method.

Together with the NPV method, the internal rate of return (IRR) method is widely used in investments' decisions as a measure of profitability expressed as percentage rate of return. NPV and IRR are consistent with a company's goal to maximize shareholder's wealth; therefore most firms largely use NPV and IRR (BESLEY; BRIGHAM, 2009).

The IRR serves as a fixed and minimum parameter to define the implicit biodiesel's selling price of the facility, which compared to the equivalent diesel prices and biodiesel prices available, will provide the answer to the dissertation's central question and deny or confirm the proposed hypotheses.

Although there is limited consensus in the required IRR to equity in real terms for a project and terminology is imprecise in detailing real or nominal return, Birgisson (2011) defined a required real IRR to equity of 15% when calculating the feasibility of producing biodiesel from rapessed.

Pandey et. al (2011) also describe another example of economic feasibility studies for ethanol plant suggesting an IRR of 15%. Schmidt (2012) also suggests, in another microalgae-biofuel project, that the IRR has to be above 15% for the investment to be profitable. Therefore, this dissertation assumes a 15% real IRR as a minimum level to defined the feasibility of the study.

1.4 Dissertation structure

The first part of the dissertation introduces the general theme, with considerations about MSW and fuel energy. This section also narrows the scope of the research, as well as defines a methodology in order to accept or reject the proposed central question

In the second part, the dissertation presents an overview of fuel energy, with particular focus in society's appropriation of fossil fuels and biofuels, from supply and production to final consumption. This section also explores renewable fuels production and characteristics, with focus on biodiesel, which is the end energy fuel source analyzed in this dissertation.

The third part discusses MSW from a feedstock perspective to biodiesel production. In this section, the dissertation explores the nature of MSW in different countries according to their income generation, as well as, analyses the methods for MSW treatment and MSW composition. This understanding of the MSW generation and composition are crucial to understand the feedstock availability for biodiesel production.

The fourth part analysis the conversion processes required to convert MSW to FAME, from a chemical perspective, using existing literature to base the incorporation of conversion rates and yields. This output serves as an input to define the biodiesel production and the feedstock needed.

In the fifth part, the dissertation presents a review of existing literature regarding project evaluation in order to define the methods for the biodiesel plant project evaluation. In this section, the NPV and the IRR for the project are calculated using existing literature for estimating yields, operating costs, financial costs and capital costs. A sensitivity analysis is conducted to contribute to the final conclusions.

The final part of the dissertation presents conclusions and recommendations for researchers and entrepreneurs interested in developing biodiesel production from MSW and also for potential government action in light of environmental, social and economic challenges involving MSW treatment and fossil fuel utilization.

2. Liquid Fuels

This chapter aims to describe and analyze the main characteristics of the petroleum and biodiesel as an energy source. The first part of this chapter investigates the production and refining of petroleum, the supply-demand drivers of oil and its supply concerns. The second part analyzes the historical development of the biodiesel industry, as well as its production methods and feedstock, supply-demand characteristics and similarities to diesel. The last part investigates public policies aiming to foster the development of the biodiesel industry.

2.1 Petroleum – A Historical Perspective

The Petroleum Age was established by 1859 in Pennsylvania, a state located in the northeast region of the United States of America. Edwin Drake and George Bissell were pioneers in petroleum production and their intention was to produce an illuminant to replace difficult to obtain whale oil (SPEIGHT, 2011). Whale oil production was already declining when petroleum started to be explored. The peak production in whale oil was 15 million gallons in 1840, which was reduced to 10 million in 1860 due to intensity in competition for supply and increase in the cost of expeditions (VACTOR; 2010).

The essential insight of Bissel was to adapt drilling techniques generally used within salt production to oil and transfer this technology to produce oil. Given that the techniques for kerosene production were known, with Abraham Gesner applying for the first patented by in 1854 to produce kerosene from asphalt, and the right type of lamp for it was available, production increased significantly (YERGIN; 2008).

In the following decades, several companies emerged internationally aiming to explore, produce and sell kerosene as an illuminant. Standard Oil founded by John Rockefeller in 1865 built oil pipes to overcome high costs of delivering the product in wooden barrels. An organized production emerged in Russia in 1873. Marcus Shell and the Rothschild family founded Royal Dutch Shell to explore oil and ship illuminants to Asia (SPEIGHT, 2011).

The progress towards electric generation by coal and the development of light bulbs favored the replacement of kerosene as an illuminant. Nevertheless, the decline in petroleum consumption as source of light was replaced by the technological advancement of internal combustion engines for transportation. By 1905, the gasoline power engines had surpassed steam and electricity in the automotive industry (YERGIN; 2008).

2.1.1 Production and Refining

Even after the spectacular technological advancements used to explore oil over the past 150 years, the unpredictability profile of exploration should not be neglected. For example, oil resources are now becoming increasingly difficult to discover, requiring sophisticated technology and capital. The challenges to explore oil reflect the remote locations of new resources, at a depth of 5,000 or 6,000 meters in the oceans (DOS SANTOS, 2011).

In spite of increasing difficulty to explore oil, chances of success in drilling exploratory campaigns increased over the last 50 years. The world's average success rate per well is 33% compared to a lower success rate per well of 17% in 1960. Even with new technological advancements in the exploratory research, which provides the potential localization of oil reservoirs, the only way to determine the presence of oil is by drilling. Thus making oil exploration a high risk business activity by definition (TORDO; JOHNSTON; JOHNSTON; 2010).

Over the years, many different theories about the formation of oil have emerged. Among them, the organic theory is the most accredited. The organic theory states that the carbonization of organic matter by bacteria, in the absence of oxygen and over millions of years, produces oil (CLÔ, 2000).

Several conditions should be present for kerogen⁶ to be converted in oil. The first is the sedimentary base, which is the area where rocks accumulated through geological processes. Another condition is the presence of organic matter, algae or marine fauna, and in specific

⁶ Kerogen is organic rich material that produces hydrocarbon on heating (JAHN; COOK; GRAHAM, 2008).

elevated temperature and pressure for chemical reaction. A favorable impermeable shaped formation to trap the generated oil is also required (JAHN; COOK; GRAHAM, 2008)

Temperature is an important factor in the oil generation process, given that it affects the final outcome in different products other than oil. If temperature rises above 100°C, kerogen will be cracked and gas will start to be produced. Kerogen turns into oil in temperatures from 50°C to 100°C, with peak conversion at 100°C, into condensate or wet gas 130°C and into methane or dry gas when temperature is above 130°C (JAHN; COOK; GRAHAM, 2008).

In chemical terms, oil is composed largely by carbon and hydrogen, with traces or residual elements of sulfur, vanadium, nickel, among others, as depicted in Table 2. Besides of its basic chemical composition, oil generated in different sedimentary basins are not identical and will be different in terms of the chemical composition, as well as in the proportion of the chemical elements present (SELLEY, 1998).

Table 2 – Elemental composition of crude oil in % of total

Element	Minium	Maximum
Carbon	82.2	87.1
Hydrogen	11.8	14.7
Sulfur	0.1	5.5
Oxygen	0.1	4.5
Nitrogen	0.1	1.5
Other	Trace	0.1

Source: FREEMAN et. al 1967 apud SELLY 1998.

After explored and produced, oil is refined to generate a variety of different products, including fuels. Refining is the key link in the oil supply-demand organization, as this activity transforms oil into products that can be used in transport and industrial fuels, and as feedstock to chemical and petrochemical industries (FAVENNEC, 1998).

The refining process starts by fractional distillation of oil into three principal products, according to their boiling point, which are the straight-run gasoline, kerosene, heating oil or diesel fuel. In addition, under reduced pressure and higher temperature, distillation also produces lubricating oils and waxes. The residue that cannot be distilled is asphalt (MCMURRY, 2011).

Table 3 represents the fraction generated in the distillation tower, as oil is exposed to specific temperature and pressure conditions. The ultimate product becomes available after a variety of different process, which includes including cracking, hydrocracking and catalytic reforming.

Table 3 – Fraction, boiling rate and ultimate product oil refining

Fraction	Boiling range		Ultimate product(s)
	°C	°F	
Liquefied Petroleum Gas	-40 to 0	-40 to 31	Propane fuel
Light Naphta	39 - 85	80 - 185	Gasoline
Heavy Naphta	85 - 200	185 - 390	Gasoline and aromatics
Kerosene	170 - 270	340 - 515	Jet fuel and diesel
Gas Oil	180 - 340	350 - 650	Heating oil and diesel
Vaccum Gas Oil	340 - 566	650 - 1,050	Gasoline, fuel oil, diesel and others
Vaccum Residue	> 540	> 1,000	Coke, asphalt and others

Source: HSU; ROBINSON, 2006.

According to EIA (2013), total oil refined in the U.S. during 2012 yielded to 44.1% in finished motor gasoline, and 22.8% in distillate fuel oil, which includes diesel for transportation, heating and electric power generation. This percentage refers to the refinery yield in the U.S. Nevertheless, the output from oil refining depends on the quality of oil input and on the configuration of the refinery facility. One of the methods to define oil quality is calculating its density and sulfur content. Oil density's indication provides the potential gasoline and kerosene output that could be generated during oil refining and is largely used by the refining industry (SPEIGHT, 2011).

The oil industry widely uses the density measure API (American Petroleum Institute) gravity scale or API° as an indication for oil quality. This measure was first introduced by the American Petroleum Institute in 1921 as a methodology to calculate the specific gravity of liquids less dense than water (HUC, 2011).

According to Selley (1998), the general formula of API° is

$$\text{API}^{\circ} = \frac{141.5}{\text{sp } 60/60^{\circ}\text{F}} - 131.5$$

Where:

sp = specific gravity is the relationship or the ratio between the mass of volume of a given substance to the mass of an equal volume of water, at a given temperature.

$60/60^{\circ}\text{F}$ = standard temperature used in North America by the oil industry, which is equivalent to $15.6/15.6^{\circ}\text{C}$.

The API scale categorizes different types of oil in light crude oil, medium crude oil and heavy crude oil. Light crude oil has an API° greater than 31.1 and specific gravity less than 0.87. Medium crude oil has an API° ranging from 22.3 and 31.1 and specific gravity between 0.87 and 0.92. Heavy crude oil shows API° less than 22.3 and specific gravity higher than 0.92 (HUC, 2011).

Hence, an oil sample with high API° will yield to high value refined products, such as gasoline, jet fuel and diesel, whereas an oil sample with low API° will yield to low value products, such as heavy gas oil (DOS SANTOS, 2011). As a result of different yields, light oil is generally more expensive than heavy oil (SPEIGHT, 2011).

In regards to sulfur content, an oil sample can be defined as “sweet”, if it has less than 0.5% of sulfur in total composition, or “sour”, if sulfur content is above 0.5% (ANTUNES, 2007). Low sulfur level oil preferable as it yields to better quality refined products and is less expensive to refine than high sulfur oil (DOS SANTOS, 2001).

Table 4 illustrates the difference in output from refining different qualities of oil. Brent oil has a higher API° gravity and lower sulfur content than Ratawi oil. As a result, Brent oil yields to higher light products, such as naphtha and kerosene, which are more valuable products than gas oil and residues. On the opposite direction, Ratawi oil yields to higher heavy products, which have less market value.

Table 4 - Refining yield for different API° and sulfur oil

Source field	Brent	Bonny Lt.	Green Canyon	Ratawi
Country	Norway	Nigeria	USA	Mid East
API gravity	38.3	35.4	30.1	24.6
Specific gravity	0.8333	0.8478	0.8752	0.9065
Sulfur %	0.37	0.14	2.00	3.90
% Yields				
Light ends	2.3	1.5	1.5	1.1
Light naphtha	6.3	3.9	2.8	2.8
Medium naphtha	14.4	14.4	8.5	8.0
Heavy naphtha	9.4	9.4	5.6	5.0
Kerosene	9.9	12.5	8.5	7.4
Atmospheric gas oil	15.1	21.6	14.1	10.6
Light gas oil	17.6	20.7	18.3	17.2
Heavy gas oil	12.7	10.5	14.6	15.0
Residue	12.3	5.5	26.1	32.9
Total	100.0	100.0	100.0	100.0
Total naphthas	30.1	27.7	16.9	15.8
Total middle distillate	25.0	34.1	22.6	18.0

Source: HSU; ROBINSON, 2006.

The diesel output depends on the oil properties used as feedstock and the refining operations. In terms of quality, it is desirable a short delay between injection and ignition, which is measured by the cetane number⁷ (ONURSAL; GAUTMAN, 1997). Physical characteristics of diesel, such as viscosity, gravity and mid-boiling point, have an impact on ignition, and; therefore, will have an impact in the cetane number (RANDY, 2003).

A higher cetane number results in higher energy efficiency and power output, reduces noise and greenhouse effect emission due to improved fuel combustion. The cetane number for diesel fuel ranges from 43 to 57 and numbers below 45 increase black smoke and gas emissions (ONURSAL; GAUTMAN, 1997).

Besides from refined petroleum, diesel can be produced from coal or natural gas. The conversion of synthesis gas or syngas derived from these sources has been considered as an alternative to oil-based fuels. The processes are known as coal-to-liquids and gas-to-liquids (MOULIJN; MAKKEE; DIEPEN, 2013).

⁷ Cetane number is the percentage of cetane, which ignites easily, present in a mixture of cetane and 2-methyl naphthalene (SENAPATI, 2006).

Syngas or synthesis gas is a gas mixture of predominantly carbon monoxide (CO) and hydrogen (H₂) and carbon dioxide (CO₂) (BROWN, 2011). Syngas is produced by gasification, which is a thermal process that uses any carbonaceous fuel, such as coal, natural gas or biomass, to gas using heat (HIGMAN; BURGT, 2008).

In the case of coal, the gasification occurs with steam and oxygen (O) and steam. The gas is cleaned to extract CO₂, ash and sulphur dioxide (SO₂) as these components undermine an optimal performance of the Fischer-Tropsch process⁸. After cleaned, CO and H₂ react in the presence of an iron-based catalyst to form various hydrocarbons at 200-250°C or 320-350°C. The share of middle-distillates produced can reach 75%, with 80% diesel production and 20% kerosene production (VALLENTIN, 2008).

The Fischer-Tropsch synthesis is capable of producing synthetic products like liquid fuels, such as high cetane diesel, and petrochemical products that are free from all major contaminants as sulfur, and heavy metal, and; therefore, present very high quality (SERRANO; AGUADO, ESCOLA; 2011).

2.1.2 Consumption and Reserves

In spite of society's concerns, fossil fuels such as oil⁹, natural gas and coal should continue to be the most important energy sources in the world, although renewables' participation should increase in relative terms (Energy Information Administration - EIA, 2011).

These three sources combined are expected to supply 81% of world's energy needs in 2015 and 78% in 2035, which is illustrated in Table 5. This percentage decline in relative terms reflects the expected increase in renewable, nuclear and biofuels sources in absolute terms at a higher rate than petroleum, coal and natural gas.

⁸ The best known process to convert solid and gas into liquids is Fischer-Tropsch. German coal researchers Fischer and Tropsch discovered in 1923 that syngas could be converted catalytic into hydrocarbons. The process was extensively used before and during World War II (MOULIJN, MAKKEE, DIEPEN, 2013).

⁹ Oil includes petroleum in a broader category of liquid fuels, which includes petroleum and other liquid fuels, petroleum-derived fuels and non-petroleum-derived liquid fuels, such as ethanol and biodiesel, coal-to-liquids, and gas-to-liquids. Table 5 was adjusted to exclude biofuels from liquids (EIA, 2011).

Table 5 – Energy consumption by source in quadrillion BTU¹⁰

	2008	2015	2020	2025	2030	2035	CAGR 2008-2035
Liquids	170.0	182.4	189.8	199.4	207.8	215.8	4.9%
Coal	139.0	157.3	164.6	179.7	194.7	209.1	8.5%
Natural gas	114.3	127.3	138.0	149.4	162.3	174.7	8.9%
Renewables	51.3	68.5	82.2	91.7	100.6	109.5	16.4%
Nuclear	27.2	33.1	38.9	43.7	47.4	51.2	13.5%
Biofuels	3.0	4.8	6.0	7.6	8.8	9.4	25.5%
Total	504.8	573.5	619.5	671.5	721.6	769.7	8.8%
% of fossil fuels	84%	81%	79%	79%	78%	78%	

Compound annual growth rate (CAGR)

Source: Energy Information Administration - EIA, 2011

The landscape for transportation and for the automobile changed significantly with the development of fuel-fired internal combustion engine during the 20th Century. Steam engines were inefficient in terms of energy conversion and not portable, which made this technology unsuitable for fast transport (SOLOMON; KRISHNA, 2011).

The automotive industry also benefited from the oil availability at low prices by the early 20th Century and from a shift in the relationship between production and consumption into the age of mass production. Changes in production methods aiming to increase automobiles efficiency and affordability continue to develop until later 20th Century (SOLOMON; KRISHNA, 2011).

Automotive transportation largely developed on internal combustion engines. Gasoline spark-ignition and diesel compression-ignition engines are types of internal combustion engines largely used in converting chemical energy into mechanical energy. Diesel compression-ignition engines can develop more power in a more efficient way than gasoline, although at a higher cost (LAKSHMINARAYANAN; AGVAH, 2010).

Therefore, the development of the automotive industry and the abundance of liquid fossil fuels shifted society's organization for transports. The energy consumption in the transportation sector should continue to be significantly based on liquid fuels, which are expected to correspond to more than 95% of the total energy source deployed in the sector as Table 6 depicts.

¹⁰ British Thermal Unit (BTU) is the amount of heat necessary to raise one pound of water by one Fahrenheit degree (KIRTLEY, 2010).

Table 6 – Energy consumption in the transportation sector by source in quadrillion BTU

	2008	2015	2020	2025	2030	2035	CAGR 2008-2035
Liquids	93.5	106.8	114.6	123.9	130.7	136.1	7.8%
Natural Gas	3.6	3.7	3.8	3.9	4.2	4.6	5.0%
Coal	0.2	0.2	0.1	0.0	0.0	0.0	na
Electricity	0.9	1.2	1.2	1.3	1.5	1.4	9.2%
Renewables	0.0	0.0	0.0	0.0	0.0	0.0	na
Total	98.2	111.9	119.7	129.1	136.4	142.1	7.7%
Liquids as a % of total	95%	95%	96%	96%	96%	96%	

Source: Energy Information Administration - EIA, 2011

In terms of total liquids consumption, the transportation sector corresponds to the majority of the end-consumption for this energy type, followed by the industrial segment, as Table 7 illustrates. Five energy-intensive industries represent more than 60% of all industrial energy consumption, which includes the chemical (33% of total), iron and steel (14%), non-metallic minerals (7%), pulp and paper (4%) and nonferrous metals (3%) (EIA, 2011).

Table 7 – Liquids consumption by sector in quadrillion BTU

	2008	2015	2020	2025	2030	2035	CAGR 2008-2035
Transportation	93.5	106.8	114.6	123.9	130.7	136.1	7.8%
Industrial	55.3	57.5	59.2	61.9	65.1	68.6	4.4%
Residential	9.8	9.7	9.1	8.9	8.8	8.8	-2.1%
Electric power	9.7	9.0	8.6	8.2	7.8	7.5	-5.0%
Commercial	4.6	4.3	4.2	4.1	4.1	4.1	-2.3%
Total	173.0	187.3	195.8	207.0	216.6	225.2	5.4%
Transportation as a % of total	54%	57%	59%	60%	60%	60%	

Source: Energy Information Administration - EIA, 2011

Although petroleum, natural gas and coal are finite energy sources, the availability of reserves still remains high, with proved reserves above 50 years (BP, 2013), as illustrated on Table 8. Therefore, despite fossil fuels' non-renewable profile and geopolitical supply instability, it is the environmental concern that should stimulate the shifting towards renewable energy sources (GOLDEMBERG et al. 1998 apud BOTELHO, 2012).

Table 8 – Estimates for world reserves versus production

Source	Reserves (R) (2012)	Production (P) (2012)	R/P ratio (years)
Oil ^a	1,690	31.9	52.9
Gas ^b	187	3.4	55.7
Coal ^c	861	7.9	109.5

(a) thousand million barrels, (b) trillion of cubic feet, (c) billions of tons.

Source: BP, 2013.

In oil exploration and production, reserve and resource have a different meaning. According to SPE (Society of Petroleum Engineers, 2011), the initial efforts for a definition of reserves started in 1937 by API in the U.S. In 1946, AGA (American Gas Association) also proposed a similar definition for natural gas. In 1962, SPE (2011) was involved in additional discussions to define a methodological concept for reserves. The demand was brought by financial and insurance institutions and investors that received oil reserves as collateral for financial operations and; therefore, needed to be defined based on uniformed concepts and methodology.

As a consequence, in 1965, SPE (2011) established new criteria for the definition of oil reserves, which through the following decades converge to definitions of other important sector associations. According to SPE's (2011) last revision, the potential oil quantities of an exploration and production project could be categorized as reserves, contingent resources and prospective resources, which carry an increasing risk of exploration and production.

Oil reserves are discovered and economically feasible, which require clear evidences of oil existence by at least one drill and positive net present value (NPV) under certain assumptions. Contingent resources are discovered, but not feasible at the time of the evaluation, which means these resources could or could not be feasible in the future. Finally, prospective resources were not discovered (SPE, 2011).

Table 9 depicts that in spite of growing demand, R/P ratio increase for oil and natural gas, reflecting the escalation in reserves absolute figures over the past 20 years. Coal is an exception as global reserves depleted faster than reserve's increased. Nevertheless, coal reserves remain at the highest R/P ratio, and above 100 years, when compared to oil and coal (BP, 2013).

Table 9 – Historical perspective of total reserves and R/P ratio

Source	Reserves (R) (1992)	Reserves (R) (2012)	% Change (1992-2012)	R/P ratio (1992)	R/P ratio (2012)
Oil	1,039	1,690	63%	43.2	52.9
Gas	118	187	59%	58.3	55.7
Coal	1,273	861	-32%	230.0	109.5

Source: BP, 2013.

2.1.3 Oil Supply

In terms of fossil fuel supply, Table 10 shows that Middle East countries hold a substantial amount of reserves, which represent 48.1% of oil and 38.4% of natural gas' total available reserves, which makes political conflicts in the region potentially negative for oil supply and oil prices.

Table 10 – Breakdown existing reserves by region

Region/Source	Oil	Natural Gas	Coal
North America	13.2%	5.2%	28.5%
Central and South America	19.7%	3.6%	1.5%
Europe and Eurasia	8.5%	37.8%	35.4%
Middle East	48.1%	38.4%	0.1%
Africa	8.0%	7.0%	3.7%
Asia Pacific	2.5%	8.0%	30.9%
Total	100.0%	100.0%	100.0%

Source: BP, 2013.

Conflicts in Middle East and consequences to oil supply are well explored in the literature, from the oil discovery in Saudi Arabia, the reasons and consequences of the first and the second oil shocks (SIMMONS, 2005), the details about conflicts in the region (ŞEN; BABALI, 2007 and YERGIN, 2011) and the quantitative analysis of supply interruption on intrastate conflicts (TOFT, 2011).

Şen et al (2007) listed security elements affecting the Gulf region. According to them, international competition for oil, Arab and Israel war conflicts, Iran-Arab and Arab-Arab conflicts, US-Gulf war conflicts of Kuwait and Iraq and radicalism and terrorist attacks affected the region and world's oil supply. Based on historical disputes, Toft (2011) supports

the idea that less than 50% of intrastate conflicts in the Middle East region result in production decline in the region. Therefore, the author concludes that risk perception from financial markets, policy analysts might be anticipating unrealistic fears of a drop in production.

Abrupt changes in oil prices are referred to as oil shocks because of the quick and unforeseen nature of occurrences (FAFOLA, 2005). The first oil shock increased oil price from \$3.29 per barrel to \$11.58 per barrel in 1973 as a result of Arab members of OPEC¹¹ (Organization of Petroleum Export Countries) decision to cut supply to countries supporting Israel in their conflict with Egypt and Syria in the Yom Kippur War (ARAVOSSIS, 2006).

The second oil shock increased oil price doublet to \$31.61 per barrel from 1978 to 1979. The popular uprising in Iran has significantly reduced oil output in the country. This caused major dislocations in the country's oil industry resulting in a decline in production from 5.7 million barrels of oil per day to 0.7 million barrels of oil per day (VASSOLIYOU, 2009). Although net supply fell less than 5%, worldwide panic drove prices higher (ARAVOSSIS, 2006).

In the third oil shock price reached record \$40.42 per barrel from \$15 per barrel in 1990 on the Gulf War, following Saddam Hussein retreat from Kuwait setting oil fields on fire. Contrary to the other oil shocks, this shock last only for six months (ARAVOSSIS, 2006).

2.2 Biodiesel

2.2.1 Overview

Biofuels, such as biodiesel, are one of the several different energy sources that can be produced with biomass. Biomass is the organic matter available on renewable basis, which includes agricultural crops, wood, residues, animal wastes, municipal waste and aquatic plants (FAN, 2010). The definition of biofuels is wide and comprises liquid, gaseous and

¹¹ In 1960, countries that produced most the oil in the world formed a cartel, named OPEC. The original formation included Iran, Iraq, Kuwait, Saudi Arabia and Venezuela. By 1973, Qatar, Indonesia, Libya, the United Arab Emirates, Algeria, Nigeria, Ecuador and Gabon joined the organization. These countries combined control 75% of world's oil reserves and try to coordinate production (MANKIW, 2012).

solid fuels produced from renewable feedstock, which is the key difference when compared to fossil fuels (DEMIRBAS, 2010).

Besides biofuels, biomass can produce energy through direct combustion to generate heat or electricity. It can also be gasified to produce syngas for power generation and liquid fuel synthesis and digested anaerobically to generate biogas for heat and electricity (FAN, 2010). Please refer to Appendix A for a schematic view of biogas production.

Biomass can also be defined as material of recent biological origin, which can be divided in three categories according to the stage of production in which are generated as feedstock (SPEIGHT, 2011).

1. Primary biomass feedstock is collected from the field or forest, which includes grains and oilseed crops, as well as the residues and waste from harvesting.
2. Secondary biomass feedstock is a by-product of primary biomass processing, which includes physical and chemical breakdown, producing black liquor in paper making, cheese whey in cheese making or animal manure.
3. Tertiary biomass feedstock comprises residues and wastes from post-consumption, which includes municipal solid waste (MSW), packaging wastes, fats, greases and oils, yard trimming, among others.

The use of biomass as a fuel source dates back the 1800's. The initial development of internal combustion vehicles' industry precedes the development of oil-based fossil fuels' industry. In 1826, the first internal combustion engine was patented by Samuel Morey and used a combination of ethanol and pine tree oil as fuel in boats (TOMES; LAKSHMANAN; SONGSTAD, 2011). Eugene Langen, who owned a sugar refinery and mostly likely had association with ethanol production, funded the development of Nicholas Otto's internal combustion engine in 1860. Later, in 1900, the world's first diesel engine would be presented in Paris World's Fair in ran on peanut oil (TOMES; LAKSHMANAN; SONGSTAD, 2011).

The first automobile built by Henry Ford in 1896 was designed to run on ethanol, which later was adapted to run on ethanol, gasoline, or a combination of these fuels. Henry's Ford later

entered in a partnership with Standard Oil Company to distribute and sell corn-based fuel at service stations, which was unsuccessful due to low oil prices (PAHL, 2008). The development of new energy technologies and fuels also appear to be part of society's efforts to search for a solution to supply crisis. For example, a blend of ethanol and pine tree oil was used as a replacement for whale oil used in lamp oil in late 1830 (TOMES; LAKSHMANAN; SONGSTAD, 2011).

The boost in world's ethanol production to supply fuel needs during World War I (LIU; ROSENTRATER, 2012) and the use of direct coal-liquefaction technology to replace oil-based fuels during World War II (THE NATIONAL ACADEMY OF SCIENCES, 2009) are also examples of initiatives to develop new energy alternatives and technology in response to a supply crisis.

Liquid fuels are also called biofuels can be divided, according to their feedstock and production technology, in four generations (DERMIBAS, 2010). The most common biofuel is ethanol (SPEIGHT, 2011), which is obtained from the fermentation of starch or sugar. Together with ethanol, biodiesel based on lipids from plants are the main biofuels used in transportation (REJINDERS; HUIJBREGTS, 2009).

1. First generation biofuels are produced through well understood techniques and for mature commercial markets (IEA, 2008), which includes ethanol produced from the fermentation of crops such as sugarcane, sugar beet, wheat, potatoes or maize (SCRAGG, 2009) and biodiesel produced from the vegetable oil extracted from seeds and plants, such as rapeseed, soybean, palm and sunflower (DERMIBAS, 2010).
2. Second generation biofuels involve more sophisticated technology and comprise ethanol and biodiesel produced directly from lignocellulose, which is available in non-food crops, agricultural residues and organic waste (SCRAGG, 2009). Lignocellulose is a structural material of plants, which contains lignin, (REJINDERS; HUIJBREGTS, 2009) whose degradation is complex and requires enzymatic systems (NIGAM; PANDEY, 2009).
3. Third generation biofuels use especially designed feedstock, such as or adapted energy crops through the use of biotechnology, which include molecular genetics and

transgenic crops (IICA – *Instituto Interamericano de Cooperación para la Agricultura*, 2009). Biofuel from algae is considered a third generation biofuel (DERMIBAS, 2010).

4. Fourth generation biofuels would represent a revolutionary advance on environmental concern regarding energy production. The aim of fourth generation biofuels is to reach a negative carbon production balance, which includes generation biofuels from trees or plants with greater capacity of carbon dioxide (CO₂) storage (IICA, 2009).

From a chemical perspective, biodiesel is a monoalkyl esters of a long-chain fatty acids derived from renewable biolipids (DERMIBAS, 2010). Biodiesel could also be defined as a mixture of fatty acid esters, normally methyl esters (SCRAGG, 2009). The major fatty acids present in vegetable oils are the oleic acid (C₁₈H₃₄O₂), linoleic acid (C₁₈H₃₂O₂) and palmitic acid (C₁₆H₃₂O), which can be observed in table 11, for different vegetable oils (DERMIBAS, 2007).

Table 11 – Fatty acid % composition of vegetable oils

Fatty acid	Pamitic	Palmitoleic	Stearic	Oleic	Linoleic	Linolenic	Others
Carbon : Double bonds	16:0	16:1	18:0	18:1	18:2	18:3	-
Palm	42.6	0.3	4.4	40.5	10.1	0.2	1.9
Soybeans	11.9	0.3	4.1	23.2	54.2	6.3	0.0
Rapessed	3.8	0.0	2.0	62.2	22.0	9.0	1.0
Sunflower seed	6.4	0.1	2.9	17.7	72.9	0.0	0.0
Peanut	11.5	0.0	2.4	48.3	32.0	0.9	4.9
Cottonseed	28.7	0.0	0.9	13.0	57.4	0.0	0.0
Coconut	7.8	0.1	3.0	4.4	0.8	0.0	83.9
Olive	5.0	0.3	1.6	74.7	17.6	0.0	0.8

Source: GUPTA; DEMIRBAS, 2010.

2.2.2 Production

Liquid fuels can be produced by three main routes, according to FRN (2010), the thermochemical route, the physical-chemical route and the biochemical route, as illustrated on Appendix A. The existing technologies to produce biodiesel include the transesterification (physical-chemical), pyrolysis (thermochemical), dilution with hydrocarbons blending and

micro emulsion (ATABANI; SILITONGA; BADRUDDIN; MAHLIA; MASJUKI; MEKHILEF, 2012).

The transesterification method is the current method of choice to produce biodiesel. The advantages of this process are the low temperature and pressure of the reaction, the high conversion yield with minimal side reactions and time required, the direct conversion with no intermediate products and the simple construction of the facility (DERMIBAS, 2007). Transesterification is also regarded as the best method compared to other approaches due to its low cost and simplicity (ATABANI; SILITONGA; BADRUDDIN; MAHLIA; MASJUKI; MEKHILEF, 2012).

The typical production of biodiesel occurs in the reaction of lipids from vegetable oil crushed from oil seeds or animal fat with methanol or ethanol, in the presence of a catalyst, which yields to methyl or ethyl esters (biodiesel) and glycerin. This reaction is denominated transesterification¹² and its purpose is to reduce the viscosity of the vegetable oil or animal fat (DERMIBAS, 2010). Biodiesel's high viscosity, low volatility and polyunsaturated characteristics are the main challenges to produce a similar fuel compared to diesel (ATABANI; SILITONGA; BADRUDDIN; MAHLIA; MASJUKI; MEKHILEF, 2012). Appendix B provides a schematic view of the biodiesel production.

The generic transesterification reaction for biodiesel production, expressed as shown in the following formula, should be carried out between 50°C and 60°C at atmospheric pressure (ROMANO; SORICHETTI, 2011).

Where:

$RCOOR'$ = triglyceride

$R''OH$ = methanol¹³ or ethanol

$R'OH$ = glycerol

¹² The first patent for producing fatty acids was awarded in 1937 to powering buses in Belgium (KNOTHE et al. 2001 apud REJINDERS; HUIJBREGTS, 2009).

¹³ Methanol is preferred because of lower price compared to other alcohols (DERMIBAS, 2008).

RCOOR" = ester mixture or volatile fatty acid methyl esters (FAME), which needs to be purified to become biodiesel.

The transesterification reaction can be catalyzed by alkalis, acids or enzymes, from which, alkalis such as sodium hydroxide (NaOH), potassium hydroxide (KOH) and sodium methoxide (CH_3NaO) are the most commonly used. The increase in the amount of alkali catalyst, from the usual 0.1% to 1% of oil weight, reduces FAME yield and increases glycerol (WANG, 2009).

In terms of reaction time, the comparison of various transesterification methods using methanol as a solvent show that the reaction could take from half a minute to two hours, depending on the method and reaction temperature. In acid or alkali catalytic process, the reaction takes 60 to 360 minutes at a temperature of 30 to 35 °C. The use of the catalytic supercritical methanol method significantly reduces the reaction time to 30 seconds to 1.5 minute, but needs a higher reaction temperature of 250 to 300 °C (DERMIBAS, 2009).

The stoichiometric ratio for the transesterification reactions demands three moles of alcohol and one mole of triglyceride to form three moles of fatty acid ester (FAME) and one mole of glycerol (DERMIBAS, 2007). Glycerol is a by-product of the biodiesel production and represents 10% of the quantities of oil used (SCRAGG; 2009).

A stoichiometric material balance of the transesterification yields to the simplified equation (GRABOSKI; MCCORMIK, 1998):

One of the others method to produce biodiesel is pyrolysis. In this method, oils or fats are thermally cracked in the absence of oxygen (O) to similar fossil fuels. The process requires high maintenance costs, mostly associated to the distillation unit for various fractions separation (POGAKU; SARBATLY, 2013). The equipment for pyrolysis is expensive for modest throughputs (ABBASZAADEH; GHOBADIAN; OMIDKHAH; NAJAFI, 2012).

Pyrolysis or thermal cracking of vegetable oils can produce fuels with high cetane, low viscosity and acceptable sulfur, water and sediment contents. However, ash contents, carbon residues and pour points remain the main problem of this method (ATABANI; SILITONGA; BADRUDDIN; MAHLIA; MASJUKI; MEKHILEF, 2012).

Biodiesel production is relative concentrated in the U.S, Germany, Argentina, Brazil, France and Indonesia. These countries together corresponded to 65% of total biodiesel produced in the globe (Biodiesel Production - EIA, 2013). Biodiesel is mostly produced from edible vegetable oils corresponding to 95% of the feedstock for 95% of global production (GUI et. al 2008 apud SPEIGHT 2011). In the U.S. and Argentina biodiesel is mostly produced by using soybean as a feedstock, in Europe, Canada and Northern U.S. is rapeseed and sunflower, in Malaysia and Indonesia is oil palm and in India is jatropha (SPEIGHT, 2011).

Besides soybean, the U.S., also use canola oil, tallow animal fat and poultry fat to produce biodiesel. In 2012, 4,023 million pounds of soybean oil were consumed exclusively to produce biodiesel, 787 million pounds of canola oil, 571 million pounds of corn oil, and 382 million pounds of tallow animal fat and 170 million pounds of poultry fat (U.S. Inputs to Biodiesel Productions - EIA, 2013).

Table 12 – Biofuel production by country in thousand barrels per day

	2008	% of total	2009	% of total	2010	% of total	2011	% of total
United States	44.1	16.8%	33.6	10.9%	22.4	6.6%	63.1	15.6%
Germany	55.0	21.0%	45.0	14.6%	49.0	14.5%	52.0	12.9%
Argentina	13.9	5.3%	23.1	7.5%	36.0	10.7%	47.3	11.7%
Brazil	20.1	7.7%	27.7	9.0%	41.1	12.2%	46.1	11.4%
France	34.4	13.1%	41.0	13.3%	37.0	11.0%	34.0	8.4%
Indonesia	2.0	0.8%	6.0	1.9%	8.0	2.4%	20.0	5.0%
Spain	4.3	1.6%	14.0	4.5%	16.0	4.7%	12.0	3.0%
Italy	13.1	5.0%	15.6	5.0%	14.5	4.3%	11.2	2.8%
Thailand	7.7	2.9%	10.5	3.4%	11.0	3.3%	10.2	2.5%
World	262.1	100.0%	309.1	100.0%	337.8	100.0%	403.7	100.0%

Source: EIA, 2013.

In terms of biodiesel's global trading, Europe is the main importer of biodiesel produced in the U.S., Argentina, Asia and Canada, as illustrated in Appendix C. This suggests that the majority of biodiesel produced by Germany, France, Spain and Italy is not sufficient to match

existing demand in the region; consequently, requiring additional supply from other large producers (EDENHOFER; MADRUGA; SOKANA, 2012).

2.2.3 Fossil Fuel Comparison

According to Romano et al (2011), there are environmental, safety and healthy advantages of biodiesel use as a replacement for diesel fuel. Some of benefits are:

- Renewable source from vegetable oil or animal fats;
- Lower toxicity and reduced carcinogenic substances than diesel;
- Lower carbon monoxide (CO) emission and particulate matter;
- Degrades faster than diesel, which is positive on spills;
- No sulfur dioxide (SO₂) emissions;
- Higher flash point (100°C minimum) or less flammable than diesel.

On the other hand, for Romano et al (2011) there are also disadvantages in the use of, which are mostly related to efficiency and practical use. Some of the weaknesses are:

- Lower calorific value of biodiesel, which results in higher fuel consumption;
- Inconvenient in cold climates due to its higher freezing point;
- Long-term storage is not recommended;
- May degrade plastics and natural rubber gaskets and hoses in the engine;
- Higher nitrous oxide (NO_x) emissions;
- Dissolves sediments in the storage tank potentially damaging the injection system.

Gupta et al (2010), as depicted in Table 13, show that diesel fossil fuel has one of the highest heating values compared to biodiesel from different vegetable oil sources. In addition, diesel has a relatively high cetane number, but viscosity is much lower compared to biodiesel.

A significant disadvantage of biodiesel is the competition with food supply of vegetable oil and the used of land to produce oil seed crops. The solution apparently is to grow oil plants on land that is not being used for growing food. Another interaction between biodiesel and

fuel price is the high price of the later, reflecting the high cost of food (GUPTA; DERMIBAS, 2010).

Table 13 – Fuel properties of vegetable oils and diesel

Fuel type	Heating value (MJ/kg)	Density (kg/m ³)	Viscosity at 27°C (mm ² /s)	Cetane number
Diesel - low sulfur	43,4	815	4,3	47,0
Sunflower oil	39,5	918	58,5	37,1
Cottonseed oil	39,6	912	50,1	48,1
Soybean oil	39,6	914	65,4	38,0
Corn oil	37,8	915	46,3	37,6
Poppy oil	38,9	921	56,1	-
Rapeseed oil	37,6	914	39,2	37,6

Source: GUPTA; DEMIRBAS, 2010.

2.3 Public Policies for Biofuels

Public policies are conscious choices that result from government's decision. Public policies are composed of two interrelated elements: policy goals and policy means. Policy goals are the aims and expectations that result in a course of action or not, while policy refers to the techniques that could be used to achieve those goals (HOWLETT, 2011).

The means of techniques to achieve public policy goals could specific government tools such as regulation, information campaigns, public enterprises or government subsidies to change a behavior (HOWLETT, 2011).

Energy policy covers issues related to the production, distribution and consumption of energy, including international treaties. The manner that a government decides to address these issues could be over specific legislation, incentives to invest, guidelines for energy production and consumption, taxations, among others (GUPTA; DERMIBAS, 2010).

Further developments in biofuels production will largely continue to rely on public policy support. The limited GHG emission savings from some biofuel alternatives limits the argument for including this energy conversion method in climate mitigation policies. Nevertheless, the reduction in dependence from imported oil remains an important argument for continue policy support (EIA, 2012).

Biofuels, which includes biodiesel and ethanol, should receive \$46 billion in subsidies by 2020 and \$59 billion by 2035 versus \$24 billion received in 2011. Subsidies to biofuels are largely concentrated in the European Union, which allocated \$11 billion to biofuels in 2011, mostly in biodiesel. In the same year, the U.S. allocated \$8 billion to biofuels, mostly to ethanol (EIA, 2012).

With new standards defined in 2010, the full implementation of Renewable Fuel Standards (RFS) in the U.S. should increase annual tax credits subsidies for biofuels to \$27 billion in 2022. The total liability from 2008 through 2022 is estimated to achieve \$200 billion (SCHNEPF; YACOBUCCI, 2010).

The American Taxpayer Relief Act of 2012 defined the U.S. federal tax credits available for biofuels during the fiscal year of 2013. For biodiesel and renewable diesel the tax credit is \$1.0 per gallon. Small agri-biodiesel producer is entitling to \$0.10 per gallon for the initial 15 million gallon production with production capacity below 60 million gallons (KPMG, 2013).

The Act also extends until December 31, 2013 the \$0.5 per gallon tax credit for alternative fuels, which includes fuels derived from biomass, compressed or liquefied biogas, compressed or liquefied natural gas and liquefied petroleum gas (KPMG, 2013).

3. Municipal Solid Waste (MSW)

This chapter analyzes the issues associated with the increasing generation of municipal solid waste from social, environmental and economic perspectives. The chapter also analyses existing methods for waste management, with a particular interest in investigating most used methods and most recommended methods.

3.1 Overview

Concerns about adequate treatment and disposal of waste appeared together with the social organization in communities, which resulted in the concentration of generated waste as well. Records from ancient Greece in 500 B.C indicate waste management concerns by the issuance of a law forbidden throwing waste in streets (WILLIAMS, 2005).

The undesirable effects of waste and the relationship between contamination and personal hygiene are also not new, with Greek and Persian scholars back in 400 B.C suggesting the relationship between waste and epidemics by infectious diseases

Although definitions vary greatly in scope, MSW incorporates solid or semi-solid waste produced in population centers (PAHO et. al 2005 apud The World Bank, 2012), which is collected and treated by, or for the municipality excluding sewage, construction and demolition waste (OECD et. al 2008 apud The World Bank, 2012). Therefore, MSW could be divided in two main groups of organic matter and recyclable waste.

The disposal of MSW is one of a more serious and controversial issues facing governments around the world. Despite all the technological improvement, production decision and marketing strategies, MSW production continues to surge (CHERMISINOFF, 2003).

The World Bank (2012) expects MSW production to reach 2.2 billion tons in 2025 versus current estimate of 1.3 billion tons, which would urge for more investments especially in low income countries.

MSW generation is closely related to economic prosperity. Table 14 depicts the average amount of MSD produced per inhabitant in a single day by the world, countries grouped according to similar income (Appendix D), selected countries and cities.

The waste generation is a clearly a function of economic prosperity; therefore, a high per capita waste generation is positively correlated to improvements in the standard of life. The increase in waste generation reflects consumption behavior, which is based on the greater consumption of cheap and disposable products (CIAPPEI; RINTANEN, 2011).

Countries grouped as high-income generate 2.13 kg/capita/day and represent 47% of total generated MSW, while contain only 26% of the total urban population. In the opposite direction, the population grouped in the lower income category generates 0.60 kg/capita/day, which represents 6% of total MSW generation, but corresponds to 12% of total urban population.

Table 14 – MSW generation by group of countries

Group	Urban population (millions)	MSW (ton/day)	MSW (kg/capita/day)	MSW (lbs/capita/day)
World	2,982	3,532,256	1.18	2.61
High-Income Countries	774	1,649,547	2.13	4.70
Upper-Middle Income Countries	572	665,586	1.16	2.57
Lower-Middle Income Countries	1,293	1,012,321	0.78	1.73
Lower Income Countries	343	204,802	0.60	1.32
Country				
Brazil	145	149,096	1.03	2.27
India	322	109,589	0.34	0.75
USA	242	624,700	2.58	5.69
State/City				
Sao Paulo City	10	20,856	2.00	4.41
Delhi City	10	5,875	0.57	1.26
Greater Mumbai	12	5,390	0.45	0.99
New York State	19	36,600	1.93	4.25

Source: The World Bank, 2012, Department of Environmental Conservation, 2008 (New York State's MSW) and United States Census Bureau, 2008 (New York's State population).

In spite of lower per capita MSW generation of lower and lower-income countries, MSW collection and treatment has become one of the most serious problems facing municipal authorities in cities, regardless to city's size. The MSW issues reflect the rapid increase in population, urban density and consumption behavior in these areas (PINDERHUGHES, 2004).

In addition to MSW volume generation, the type of MSW is significantly different when groups of countries with a different income profile are compared. Table 15 shows a higher percentage of recyclable MSW to high-income countries and a higher percentage of organic matter to the lower income group.

The type and amount of MSW is determined by many factors, such as population density, economic prosperity, difference in fuel sources, difference in diets, climate conditions, and cultural practices, among others (PINDERHUGHES, 2004).

In terms of cultural aspects, lower-income individuals recycle less than high-income individuals, which appear to be the result of the lack of opportunity to recycle as differences in recycling nearly disappeared when access to recycling facilities is available to everyone (BERGER et al. 1997 apud JACKSON; ONES; DILCHERT, 2012).

However, income has a negative impact when recycling is associated to an environmental behavior that helps the individual to save money (D'MELLO; WIERNIK; ONE; DILCHERT et al. 2011 apud JACKSON; ONES; DILCHERT; 2012)

Table 15 – MSW profile by group of countries

Group	Recycleable	Paper	Glass	Metals	Plastics	Organic ^a	Others ^b	Source
World	36.0%	17.0%	5.0%	4.0%	10.0%	46.0%	18.0%	World Bank; 2012
High-Income Countries	55.0%	31.0%	7.0%	6.0%	11.0%	28.0%	17.0%	World Bank; 2012
Upper-Middle Income Countries	33.0%	14.0%	5.0%	3.0%	11.0%	54.0%	13.0%	World Bank; 2012
Lower-Middle Income Countries	26.0%	9.0%	3.0%	2.0%	12.0%	59.0%	15.0%	World Bank; 2012
Lower Income Countries	19.0%	5.0%	3.0%	3.0%	8.0%	64.0%	17.0%	World Bank; 2012
Brazil	31.9%	13.1%	2.4%	2.9%	13.5%	51.4%	16.7%	IPEA; 2010
India	2.5%	0.8%	0.4%	0.6%	0.6%	44.0%	53.5%	SINGH; 2010
USA	54.5%	28.5%	4.6%	9.0%	12.4%	33.7%	11.8%	EPA; 2010
Sao Paulo City	32.9%	12.4%	1.8%	2.2%	16.5%	59.2%	7.9%	IPEA; 2010
Delhi City	12.5%	6.0%	5.6%	0.9%	na	38.9%	48.6%	ANAND; 2010
New York State	53.0%	27.0%	3.0%	6.0%	17.0%	28.0%	19.0%	DEC; 2008

(a) Includes food waste, yard and wood wastes.

(b) Includes ceramics, textiles, leather, rubber, bones, inerts, ashes, coconut husks, bulky wastes, and household goods. Construction and demolition are not included as MSW, according to The World Bank (2012).

3.2 Waste Treatment

The classification of waste supports the implementing more cost-effective management policies and strategies. Waste groups, such as municipal, hazardous, industrial, medical, construction and demolition, radioactive, mining and agricultural are mostly managed separately and under specific federal and state legislation (PICHTEL, 2010).

Policies and legislation about MSW management evolved from cleansing and sanitation to encompass a larger global perspective of environmental protection and sustainable development (LETCHER; VALLERO, 2011).

And economical and environmental sustainable approach to MSW requires an integrated analysis of its collection, recycling, disposal and public education (KUTZ, 2009). The budget allocated to MSW treatment in bigger cities is equivalent to 5% to 10% of the total budgeted (NEERI et al. 2005 apud REDDY, 2011).

The cost of MSW management is significantly affected by the chosen waste treatment method. In low-income countries, the collection represents 80-90% of the total MSW budget, because most of the waste is sent to open dumps. On opposed direction, collection represents 10% of total MSW budget in high-income countries due to the higher costs associate to more sophisticated MSW management techniques, which include sanitary landfill and incineration (MALIK; GROHMANN, 2012).

In absolute terms, the \$ per capita/year spent in MSW's management is higher in high-income countries than in low-income countries. In high-income cities the "per capita/year cost" could be higher than \$45, for example in New York is \$106/capita and in London is \$46/capita. In low income countries the per capita/year cost could be less than \$10/capita, for example, \$7 in Caracas and \$0.7 in Accra (MACFRALANE et al. 1998 apud RAV, 2012).

Although landfill continues to be the most used treatment method for MSW, other waste diversion methods and initiatives provide a better alternative to landfill. Initiatives on waste reduction, recycling, and recovery methods such as aerobic composting and anaerobic digestions are; therefore, better alternatives than landfill, incineration or controlled dumping (The World Bank, 2012).

The waste reduction method seeks the re-design of products, production and consumption to reduce the quantity of waste. The reduction of waste also reduces greenhouse gas emissions and energy consumption in the production phase, in the logistics and in the collections of the waste (The World Bank, 2012).

With the same purpose of reducing greenhouse gas emissions and energy, recycling and reuse also represent a preferable alternative, because less energy is required and less greenhouse gas are produced, compared to the production of a new product using raw materials (The World Bank, 2012).

The source-separated collection is a key element in MSW management. The separation of waste begins at the source where MSW is generated and involves the whole process of collecting, transporting, disposal and recycling (TAI; ZHANG; CHE; FENG, 2011).

3.2.1 Landfills

The majority of world's MSW or 43.2% representing 339.4 million tons/year of total disposal is deposited in landfills, as illustrated in Table 16. In the landfill treatment method, waste is discarded at the specific disposal site and the material is consistently pushed, compacted and covered with soil or other cover material (LI; CHEN; TANG; TANG, 2008)

Table 16 provides a breakdown by group of countries regarding MSW destination, which could be to dumps, landfill, composting, recycling or incineration.

Table 16 – MSW destination by group of countries

	Dumps	Landfills	Compost	Recycled	Incineration	Other
World	9.2%	43.2%	8.7%	17.1%	15.6%	6.2%
High-Income Countries	0.0%	42.5%	11.2%	21.9%	20.7%	3.6%
Upper-Middle Income Countries	32.4%	58.9%	1.0%	1.4%	0.1%	6.2%
Lower-Middle Income Countries	48.8%	11.0%	2.2%	5.2%	0.2%	32.5%
Lower Income Countries	12.5%	58.5%	1.3%	0.5%	1.3%	25.8%

Source: The World Bank, 2012.

The landfill method is very important in MSW strategic management because it is the most cost-effective method of disposing waste. However, engineering techniques are required to control or minimize leachate¹⁴ and gas emissions to the environment, which include a landfill cap to reduce the infiltration and protect groundwater and a gas recovery system to protect air quality (KUTZ, 2009).

The inadequate MSW management strategies persisted until relatively recent period. In the USA, for example, until 1960s most of MSW was burned in open dumps to reduce volume. As a result, these dumps produced clouds of smoke without air pollution controls. It was not until 1970s, with public objection against this practice and air pollution laws that dumps were converted into landfills (NEBEL; WRIGHT, 1993).

The cost of landfill disposal varies from \$10/ton to \$30/ton in lower-income countries and from \$40/ton to \$100/ton in high-income countries, as illustrates Table 17. The difference in cost is associated to the more advanced engineering profile of landfills in high-income countries compared to low-income countries, among others (The World Bank, 2012)

¹⁴ Leachate is the contaminated liquid that results from water infiltration of water through a landfill (RHYNER, 1995). Leachate is difficult to characterize because composition depends on waste characteristics, temperature and waste's age (VELINNI, 2007).

Table 17 – Estimated MSW management cost by income country in \$/ton

	Lower	Lower-Middle	Upper-Middle	High
Collection	20-50	30-75	40-90	85-250
Sanitary landfill	10-30	15-40	25-65	40-100
Open dumping	2-8	3-10	na	na
Composting	5-30	10-40	20-75	35-90
Incineration	na	40-100	60-150	70-200

Source: The World Bank, 2012.

Landfill progresses from semi-controlled waste dump to controlled landfill and to sanitary landfill. The controlled landfill contains some level of leachate treatment and manages gas emission by flaring or passive ventilation. A sanitary landfill is a more advanced controlled landfill, with biological and chemical treatment of leachate. In this facility, gas emissions are controlled by flaring with or without thermal energy recovery (The World Bank, 2012).

The decomposed MSW in landfill generates essentially methane and carbon dioxide in a proportion to 50% to 56% of methane, depending on MSW's composition, as illustrates the following equation. Despite the lack of uniformity in MSW composition, most of food and plant components are carbon, hydrogen and oxygen in the ratio of 1:2:1 (BLIGNAUT; WIT, 2004).

Blignaut and Wit (2004) calculated the potential for electricity production by using methane from MSW in landfills. The estimates are that one ton of biodegradable MSW yields to 417m³ of methane and 15,012MJ of electricity.

3.2.2. Recycling

Recycling corresponds to 17.1% of the total world's disposals, as illustrated in Table 16, with clear indication that high-income countries have significantly higher recycling rates than low-income countries.

According to Pichtel (2010), terms regarding MSW recycling must be clarified to avoid confusion. Recycling is the use of a material in a form similar to the primary original use, such as newspapers recycled into cardboard or newspapers again or aluminum window frames recycled into beverage cans or plastic used to manufacture fabric, for example.

The main advantages of recycling are the reduction in the volume of the waste produced and the energy feedstock saved, although it may or may not save process energy. Recycling generally demands less energy than production from raw primary materials. This is the case for iron, aluminum, copper, zinc, glass, plastics and paper products (DARYL; HARVEY, 2010).

Steel is the most recycled material in the world, with a total amount higher than aluminum, glass and plastic combined. For every ton of steel that is recycled, 3.6 barrels of oil and 1.49 tons of iron ore are saved, which eliminates 50-70% of pollution associated in manufacturing steel from raw feedstock (HOWE; GERRAD, 2010).

Existing literature has other examples of energy saving and emission associate to recycling. For every ton of paper that is recycled, more than 30,000 liter of water, 3,000 to 4,000 kWh electricity and 95% of all pollution can be spared. In the case of glass, after accounting for transport and processing needs, 315 kilograms of carbon dioxide are saved per ton of recycled glass (MULVANEY; 2011).

The global value for paper, cardboard and scrap metal recyclables has a global value of at least \$30 billion, with estimated post-consumer scrap metal of 400 million tons/year and paper, cardboard of 175 million tons/year (The World Bank, 2012).

3.2.3 Incineration

The incineration method could be defined as the controlled burning of solid, liquid or gaseous wastes, which has the primarily purpose of reducing volume waste by 50% to 60% in order to extend the lifetime of land disposal facility. The key component in this definition is the need of a controlled environment rather than the simple open burning dump (PICHTEL, 2010).

Incineration method can also generate energy, which could partially offset capital and operating costs. However, this method is only cost-effective if landfill space is scarce, as a result of high urbanization and environmental constraints (JOSEPH, 2009).

Incineration is the most expensive waste management method and is largely used by high-income countries, as shown on tables 17 and 16.

In developing countries the challenges to implement incineration are the high capital and operating costs to safely burn waste, high moisture waste content and low energy value, lack of trained personnel and adequate infrastructure (JOSEPH, 2009). In developed countries, the moisture levels is typically around 50%, which is higher than the 20% to 30% range in the US and some countries in Europe (KARAGIANNIDIS, 2012).

The modern advanced incinerators combusts waste in a cleaner and efficient manner compared to previous technologies. The emission control systems used in this method employs emission control systems similar to the systems used in modern thermal power plants. The energy flow consists basically of heat transferred to steam, which is connected to electrical generators. Besides energy, another output is ash, which should be disposed in landfills (BOYE; ARCAND, 2012).

The energy recovery in an incineration facility that recovers energy can reach 35MW from 420,000 tons of MSW. The incineration occurs at 850°C in and the ideal emission to air should not contain carbon particles or carbon monoxide, which would indicate incomplete combustion. Therefore, the outcome from incineration should be carefully controlled to minimize harmful conditions and comply with tight regulatory standards (KIRWAN, 2012).

The heat value for the most common materials in MSW composition show that the heat value for plastics are the highest because of the high carbon content of the combustible fraction, low ash content and relatively low moisture content in the material. On the opposite direction, yard waste, food residues and diapers have high moisture content; therefore, heat value is low (LIU; LIPTAK, 1997).

Table 18 – Material profile by higher heating value¹⁵ (HVV)

Waste	As-Received (Btu/lb)	Dry-Basis (Btu/lb)	Moisture Content %
HDPE bottles	17,504	18,828	7.0%
Polystyrene	15,144	16,973	10.8%
Polyethylene bags	13,835	17,102	19.1%
PET bottles	13,261	13,761	3.6%
PVC bottles	9,838	10,160	3.2%
Textile, rubber	8,733	9,975	12.4%
Wood	7,186	8,430	14.8%
Corrugated & kraft	6,435	8,168	21.2%
High-grade	5,944	6,550	9.3%
Newspaper	5,767	7,733	23.2%
Magazines	5,326	5,826	8.6%
Leaves	4,499	8,030	44.0%
Fines	4,114	6,978	41.1%
Yard waste	3,565	7,731	53.9%
Disposable diapers	3,222	9,721	66.9%
Food waste	3,108	8,993	65.4%
Grass clippings	2,782	7,703	63.9%

Source: LIU; LIPTAK, 1997.

3.2.4 Dumping

The fourth largest MSW destination is dump, with 72.3 million tons/year or 9.2% of world's total MSW. The operation on a dump is the less sophisticated option for MSW treatment. The dump methodology fairly simple and involves the discard of MSW in land and often used fire to reduce volume (VESILIND; DISTEFANO, 2006).

Dump is the cheapest waste destination alternative, which makes a viable alternative for lower-income countries. Nevertheless, with the direct contact of waste with the underlying soil, or rock strata, the groundwater pollution is almost inevitable. In fact, the difference to a dump to a landfill is that the landfill method attempts to isolate waste contact directly to underlying soil or rock strata (LETCHER, VALLERO, 2011).

In the US, by the turn of 20th century several different waste disposal practices were adopted, which included ocean and underlying soil dump, incineration and reduction. From 1880's to

¹⁵ In HHV measurements, the energy required to drive off the moisture formed during combustion is not deducted LIU; LIPTAK, 1997.

1930s, land dumping remained the most common method for waste disposal, although by the 1890's sanitary engineers raised serious concerns about the method (PICHTEL, 2010).

There is basically one distinction between dumps. In semi-controlled dumps, waste has few controls and is simply placed in the underlying soil. In controlled dumps, waste is compacted and surface water is monitored. In all dumps, there are unrestricted contaminants released by gas and leachate (The World Bank, 2012).

3.2.5 Composting

Composting systems promote the biodegradation of materials through microorganisms, which after partially mineralized, yield in a combination of water, carbon dioxide and a residue humus-type material used as fertilizer depending on the MSW composition (BOYE; ARCAND, 2012).

The easily decomposable organic material is digested in an aerobic process to form carbon dioxide instead of methane in the landfills (DARYL; HARVEY, 2010).

The biodegradation concept for composting should take into account the timeframe that is necessary for it to occur. For example, paper and plastic are biodegradable, however, it could take decades or centuries, which makes misleading to categorize as biodegradable (BOYE; ARCAND, 2012).

The composting technique applied in MSW is the same applied to sludge composting, which is windrow, aerated static pile and in vessel systems. In spite of public concerns and risks associated to every MSW management method, composting is often perceived as a safer alternative to landfill and incineration (LIU; LIPTAK, 1997).

3.3 Environmental issues

MSW could have damaging consequences to public health and environment, if not properly treated. Among the potential negative effects are (LIU; LIPTAK, 1997):

- Proliferation and support of microorganisms that are unsafe and cause diseases;
- Attraction and promotion of rodent and insects that are disease vectors;
- Generation of toxic odors;
- Degradation of environmental esthetic;
- General pollution of the environment;
- Occupation of valuable space.

GHG emissions from MSW account for almost 5% of total global emissions, with methane from landfills representing an important source of pollution. Methane from landfill accounts for 12% of total methane emissions and almost 50% of total methane emissions associated to MSW. The reduction in methane production from MSW is possible with its combustion to generate electricity or as a process energy resource (The World Bank, 2012).

In spite GHG methane and carbon dioxide contribute to 81% of global warming effect, with 18% and 63% respectively; methane can cause twenty five times¹⁶ more damage as one molecule of carbon dioxide (LETCHER, 2009). Besides MSW treatment, methane also is produced in coal formations, livestock digestive processes and wetland rice cultivation (TAMMINEN, 2011).

Finkbeiner (2011) concluded, using the life cycle assessment (LCA) for MSW treatment in Delhi, that recycling has the least environmental impact, when compared to composting, landfill and incineration. Another conclusion is that landfills produce less environmental impact than incinerators during the initial years of operation, but over the years landfill becomes less attractive than incineration because of the waste accumulated in landfill.

Cherubini et al (2009) explained, through LCA of MSW treatment in Rome, that landfill treatment with or without biogas utilization is the worst waste management alternative when compared to direct incineration of waste and to a sorting plant splitting the inorganic waste fraction to produce electricity from the organic part to produce biogas, which is the best option.

¹⁶ GWP (Global Warming Potential) informs how important one molecule of pollutant x is to global warming compared to one molecule of CO₂. The GWP for CH₄ is 25 (LETCHER, 2009).

Mendes et al (2004) concluded, also using LCA of MSW in Sao Paulo, that incineration with energy recovery is the most adequate alternative, when compared to landfill. Landfill represents, according to the authors, the highest environmental cost.

Clearly (2009) concluded that publications about LCA for MSW do not ensure a clear methodological view for the reader, which makes results difficult to interpret results and comparisons. However, the author also concludes that the results from comparing landfilling and thermal treatment for MSW are more reliable because of the less-wide ranging profiles observed.

4. Conversion of Organic Matter to Biodiesel

This chapter investigates existing literature about: (i) the chemical conversion of organic solid waste in volatile fatty acids and (ii) the conversion of volatile fatty acids in fatty acids methyl ester, which later is converted in biodiesel. This main objective of this chapter is to analyze production and extraction methods in previous research to produce volatile fatty acids and fatty acids methyl ester.

4.1 Overview

D'Addario et al (1993) concluded that the use of the organic fraction of municipal solid waste (OFMSW) to produce methyl esters was technologically feasible. The main objective of the author's research was to evaluate an integrated biological process capable of addressing the detrimental effects associated with waste management technologies, namely incineration and landfill disposal.

Sans et al (1995) suggested that OFMSW could be chemically processed as a substrate in three different ways to produce either energy or chemicals, including biodiesel. According to the authors, OFMSW could be used to produce methane, which is also defined as biogas, and methyl or ethyl esters. In the biogas and in the methyl or ethyl esters productions, the outlet sludge from the anaerobic digestion is composted.

The methyl or ethyl production was possible due to further biotechnological developments that allow the possibility of terminating and controlling the anaerobic fermentation at the *acidogenic* phase. The VFA could be extracted from this liquid stage and could be converted in methyl or ethyl esters for commercial purposes (SANS; ALVAREZ; CHECCI; PAVAN; BASSETTI, 1995).

The anaerobic digestion used to breakdown easily biodegradable components of the municipal solid waste OFMSW in VFA produces mostly short-chain acids. Such acids have

low molecular value, with maximum six carbon units (GERARDI, 2003): acetate, propionate, butyrate and isobutyrate. Furthermore, diesel fuel and biodiesel have longer carbon chains compared to VFA, ranging from 10-16 (WEINER, 2000) and 16-18 (DERMIBAS, 2010), respectively. Therefore, VFA cannot be used as a fuel source for internal combustion engines before being converted into more complex chemical structures, such as lipids, for biodiesel production.

VFA is could be used as a carbon source for lipid accumulation within oleaginous microorganisms, with the aim of producing biodiesel. Most studies focused on lipid production used high-cost glucose as the carbon source, which represent 80% of the total cost. The high cost of glucose has facilitated research efforts that targeted the reduction of the carbon source cost by investigating alternative feedstock to replace glucose. In this context, research efforts focused on waste, glycerol, pectin and lactose, ethanol and starch seek as alternative. However, in most cases, the corresponding yields are too low to reduce lipid production costs (FEI; CHANG; SHANG; CHOI; KIM; KANG, 2011).

4.2 Municipal Solid Waste to Volatile Fatty Acids

The aspect of this section is to investigate the MSW conversion to VFA by using MSW's organic fraction (OFMSW), which can be easily converted to VFA by anaerobic digestion¹⁷ (*acidogenesis*) and in the absence of the use of cellulolytic enzymes.

Not all organic components of the MSW have the potential to produce biodiesel. Existing literature has designed clearly defined terminologies that refer to different components of MSW. Total solids (TS) are any dry organic substrate¹⁸. TS contain biodegradable volatile solids (BVS), refractory volatile solids (RVS) and ash. Only the biodegradable fraction (BVS) has the potential to yield biodiesel. Although BVS are easy for anaerobic bacteria to degrade, RVS are not (BROWN; TCHOBANOGLOUS; KAYHANIAN, 2007). The main component of RVS is lignin, a complex to degrade organic material associated with cellulose and thermoplastic materials. Carbons in sugar, lipids and proteins are more easy to degrade

¹⁷ Anaerobic digestion is a biotechnological process that degrades organic matter, be it organic waste, wastewater, purposely grown energy crops, in the absence of oxygen (INSAM; FRANK-WHITTLE; GOBERNA, 2010).

¹⁸ Total solids refer to the residue left after the evaporation of liquid at 103°C to 105°C (SPELLMAN, 2008).

compared to lignin. Interestingly, the main sources of carbohydrates are putrescible and yard wastes (DAVEN; KLEIN, 2008).

Total volatile solids (TVS) can be used as a crude estimate of the amount of organic matter existing in TS. TVS represent the fraction of volatile solids in TS lost on ignition¹⁹ at a higher temperature than that used to estimate TS (U.S. Environmental Protection Agency – EPA, 2001).

Anaerobic digestion is one of the methods to easily break down easily biodegradable material in the absence of oxygen, which occurs by several processes that involve multiple microorganisms (NAYONO, 2010). The anaerobic digestion of MSW is an environmental technology that reduces the harmful effects of waste, such as increasing volume, toxicity and GHG emissions. In addition, anaerobic digestion of MSW allows energy recovery and generates an end-product suitable for soil conditioning (MALIK; GROHMANN; ALVES, 2013).

The process of anaerobic digestion may be divided into several interrelated and sequential chemical reactions, including hydrolysis, fermentation or *acidogenesis*, β -oxidation or *acetogenesis* and *methanogenesis* (NAYONO, 2010).

Hydrolysis and *acidogenesis* (or *acidogenesis*) only have been described as the main processes to produce VFA from complex organics and from waste sludge. VFA is produced through the *acidogenesis* process of complex organics by a group of facultative or obligate anaerobes commonly named acid formers (PAUL; LIU, 2012).

During *hydrolysis*, polysaccharides, proteins and lipids or fat and grease, which are complex organic matters, are hydrolyzed through a rather slow and energy-consuming process by extra-cellular enzymes (NAYONO, 2010). Hydrolysis is often used to pretreat lignocellulose-based feedstock and break down components into simple sugars (DEMIRBAS, 2010).

The *hydrolysis* of cellulose through anaerobic digestion releases molecules of glucose, as shown in the following equation, in which the bacteria *cellulomonas* is able to breakdown the

¹⁹ The weight loss after ignition at 550°C (SPELLMAN, 2008).

mers of glucose. In *hydrolysis*, complex carbohydrates, complex lipids, and complex proteins are converted into simple sugars, fatty acids and amino acids, respectively (GERARDI, 2003).

In *acidogenesis* and *acetogenesis* bacteria biodegrade soluble organic compounds and breakdown products to acetic acid (CH_3COOH), hydrogen, carbon dioxide and other lower weight, simple volatile organic acids like propionic acid and butyric acid, which are converted into acetic acid. The products formed during *acidogenesis* are a result of different microbes that decompose propionate (CH_3CH_2COOH), butyrate ($H_3CH_2CH_2COOH$), ethanol (C_2H_5OH), and lactate ($CH_3CHOHCOOH$) which reactions are represented below (DERMIBAS, 2009).

In regards to OFMSW's fermentation, during *acidogenesis* the organic matter generates a mixture of VFA that includes acetate, propionate, butyrate and isobutyrate. The organic composition, the available species in the composition and the operating parameters of the reactor will determine VFA's composition (WANG; IVANOV; TAY, 2010). Sans et al (1995) have produced VFA from organic MSW under different temperatures and retention days and reported high levels of acetic acid, followed by butyric and propionic acids.

Microorganisms from the major trophic groups, working in combined and coordinated metabolic activity, in anaerobic digestion, degrade complex organic waste. For methane recovery, the anaerobic bacteria are generally grouped in four clusters (HOLLAND; KNAPP et. al 1987 apud BROWN; TCHOBANOGLOUS; KAYHANIAN, 2007).

- 1) Hydrolytic bacteria catabolize²⁰ saccharides, protein, lipids, and minor chemical constituents of biomass.
- 2) Hydrogen-producing acetogenic bacteria catabolize fatty acids and neutral end products.
- 3) Homoacetogenic bacteria catabolize unicarbon compounds or hydrolyze multi-carbon compounds to acetic acid.
- 4) Methanogenic bacteria catabolize acetate and one carbon compound to methane.

There are two main steps in the anaerobic digestion: the biodegradation of organic matter into carbon dioxide, hydrogen and volatile fatty acids and the conversion of VFA is transformed into methane (WUKASCH, 1994).

Putrescible organic waste materials with high nitrogen and moisture²¹ could be easily metabolized or biodegrade, by microorganisms, compared to other organic waste materials. Materials that can be easily used in *acidogenesis* are food waste, grass clippings, and other green pulpy yard waste. Disposable diapers, cotton and wools textiles are also largely biodegradable (LIU; LIPTAK, 1997).

Table 19 – Ultimate composition of dry MSW and moisture content

Waste category/Composition	Carbon (%)	Hydrogen (%)	Nitrogen (%)	Chlorine (%)	Sulfur (%)	Oxygen (%)	Ash (%)	Moisture (%)
Disposable diapers	48.4	7.6	0.5	0.2	0.4	38.8	4.1	66.9
Food waste	45.4	6.9	3.3	0.7	0.3	32.3	11.0	65.4
Grass clippings	43.3	5.9	2.6	0.6	0.3	37.6	9.7	63.9
Other yard waste	40.7	5.0	1.3	0.3	0.1	40.0	12.6	50.1
Leaves	50.0	5.7	0.8	0.1	0.1	36.0	7.3	44.0
Fines	37.3	5.3	1.6	0.5	0.5	29.5	25.3	41.1

Source: LIU; LIPTAK, 1997.

A more detailed analysis has shown that food waste and specific residues of yard waste are largely biodegrade (LIU; LIPTAK, 1997). Food waste, textiles/rubber/leather, grass clipping, other organic, fines and other yard waste maintain the highest concentration of nitrogen (Table 20).

²⁰ Catabolism is a process in which the cell is able to degrade substances into smaller and simpler constituents (LIM, 1998).

²¹ Moisture is defined as the ratio of the fluid's weight retained by solids to the weight of the wet material (CHEREMISSINOFF, 2003).

Table 20 – MSW sorted by high nitrogen content

Waste category/Composition	Carbon (%)	Hydrogen (%)	Nitrogen (%)	Chlorine (%)	Sulfur (%)	Oxygen (%)	Moisture (%)
Disposable diapers	48.4	7.6	0.5	0.2	0.4	38.8	66.9
Food waste	45.4	6.9	3.3	0.7	0.3	32.3	65.4
Grass clippings	43.3	5.9	2.6	0.6	0.3	37.6	63.9
Other yard waste	40.7	5.0	1.3	0.3	0.1	40.0	50.1
Leaves	50.0	5.7	0.8	0.1	0.1	36.0	44.0
Fines	37.3	5.3	1.6	0.5	0.5	29.5	41.1

Source: LIU; LIPTAK, 1997.

Disposable diapers, food waste, grass clipping, other yard waste and leaves contain the highest moisture content (Table 21).

Table 21 – MSW sorted by high moisture content

Waste category/Composition	Carbon (%)	Hydrogen (%)	Nitrogen (%)	Chlorine (%)	Sulfur (%)	Oxygen (%)	Moisture (%)
Disposable diapers	48.4	7.6	0.5	0.2	0.4	38.8	66.9
Food waste	45.4	6.9	3.3	0.7	0.3	32.3	65.4
Grass clippings	43.3	5.9	2.6	0.6	0.3	37.6	63.9
Other yard waste	40.7	5.0	1.3	0.3	0.1	40.0	50.1
Leaves	50.0	5.7	0.8	0.1	0.1	36.0	44.0
Fines	37.3	5.3	1.6	0.5	0.5	29.5	41.1

Source: LIU; LIPTAK, 1997.

Pichtel (2005) and Brown et al (2007) concluded that food and yard wastes are the organic substrates with the highest biodegradable fraction (BF) to volatile solids (VS, which is BVS and RVS), which is consistent to the conclusions attained by Lui et al (1997).

Table 22 – Biodegradable fraction as % of volatile solids

Organic substrate	Methods	
	Long-term batch ^a	Lignin content ^b
Office paper	83%	82%
Food waste	83%	82%
Yard waste	72%	72%
Mix blend	70%	na
Newspaper	24%	22%

Source: (a) TCHOBANOGLOUS et al 1995 apud PICHTEL, 2005 and (b) BROWN; TCHOBANOGLOUS; KAYHANIAN, 2007.

In *acidogenesis* or fermentation, the bacterial culture determines the productivity, yield and purity of the feedstock to VFA (YANG, 2007). Table 23 shows different experiments to convert MSW to VFA. The highest absolute VFA generation was reported by Sans et al (1995) using *mesophilic*²² conditions to reach 23.1 g/g. However, in terms of productivity another experiment reported by the same group of researchers, but under *thermophilic* conditions produced 6.7 g/g per day.

Table 23 – VFA yields from MSW experiments

Feedstock Condition	VFA/TVS (%)	VFA/TC (%)	Retention (days)	VFA production (g/g)	VFA production (g/g per day)	Source
MSW thermophilic	14.3%	23.7%	2	13.4	6.7	SANS; 1995
MSW mesophilic	10.8%	21.5%	4	18.3	4.6	SANS; 1995
MSW thermophilic	15.1%	23.1%	4	17.0	4.3	SANS; 1995
MSW mesophilic	10.0%	17.2%	6	23.1	3.9	SANS; 1995
MSW thermophilic	14.6%	20.9%	6	19.6	3.3	SANS; 1995
MSW	7.5%	na	8	12.5	1.6	ANTONPOULOS; 1998
MSW	20.0%	na	12	15.0	1.3	D'ADDARIO; 1992
MSW thermophilic	4.6%	8.1%	6	8.3	1.4	SANS; 1995

Total TC considers the average TC content for the two samples of MSW used by Sans (2005) of 22.05% of San Giorgi di Nogaro sample and Treviso sample in Italy.

The experiments described in Table 23 used substrate based on a TS content of around 25% in order to simulate the organic fraction of refuse produced in western cities (SANS; ALVAREZ; CHECCI; PAVAN; BASSETTI, 1995). The percentage is consistent with the 28% organic fraction of MSW presented in Table 15, which also indicates a higher fraction of organic matter in the MSW from upper-middle income to low-income countries ranging from 54% to 64% (The World Bank; 2012).

²² There are three temperature ranges under which bacteria activity peaks. Below 15°C is called psychrophilic, between 15°C and 45°C is mesophilic and between 45°C and 60°C is thermophilic (NIJAGUNA, 2002).

Table 24 – Detailed VFA yields

Experiment		2	3	4.1	4.2	1.1	1.2	2	3
Conditions		mesophilic	mesophilic	mesophilic	mesophilic	thermophilic	thermophilic	thermophilic	thermophilic
Organic loading rate (TVS)	kg/m ³ /day	85.2	42.3	33.9	38.5	30.1	22.4	28.2	46.8
Retention time	days	2	4	6	6	6	6	4	2
Total VFA production	g/l	11.8	18.3	13.0	23.1	8.3	19.6	17.0	13.4
VFA / Retention time	g/l/day	5.9	4.6	2.2	3.9	1.4	3.3	4.3	6.7
Total solids (TS)	%	24.8%	24.5%	28.6%	28.6%	27.1%	28.8%	22.5%	23.1%
TVS/TS	%	64.0%	65.0%	54.5%	56.2%	58.0%	46.8%	49.8%	54.1%
Total Carbon (TC)/TS	%	32.6%	32.6%	32.6%	32.6%	32.6%	32.6%	32.6%	32.6%
TC	kg/m ³	86.8	84.9	121.9	134.2	101.6	93.7	73.9	56.4
TVS	kg/m ³	170.4	169.2	203.4	231.0	180.6	134.4	112.8	93.6
TS	kg/m ³	266.1	260.3	373.5	411.2	311.3	287.3	226.4	173.0
MSW	kg/m ³	1,071.7	1,062.8	1,306.4	1,440.1	1,147.4	997.8	1,005.3	749.4
VFA/MSW yield	%	1.1%	1.7%	1.0%	1.6%	0.7%	2.0%	1.7%	1.8%
VFA/TS yield	%	4.4%	7.0%	3.5%	5.6%	2.7%	6.8%	7.5%	7.7%
VFA/TVS yield	%	6.9%	10.8%	6.4%	10.0%	4.6%	14.6%	15.1%	14.3%
VFA/TC yield	%	13.6%	21.5%	10.7%	17.2%	8.1%	20.9%	23.1%	23.7%

Source: SANS; ALVAREZ; CHECCI; PAVAN; BASSETTI; 1995.

VFA, carbon dioxide, hydrogen and water are among the chemical elements that are produced in the *acidogenesis* phase (DERMIBAS, 2009). Yet, other components of the organic waste, such as nitrogen, chlorine, sulfur and ash are not degradable by the same anaerobic digestion process, as depicted in Table 19. According to Sans et al (1995), the screwed sludge that remains after VFA is extracted from the liquid phase could proceed directly to a composting process. In fact, it may be possible to recover part of the organic fraction still remaining in the residue.

According to Alkaya et al (2009), the liquid-liquid extraction technique to recovery VFA from fermentation broths is one of the most efficient, economical and environmental method for the separation of carboxylic acids. There are other techniques to recover acids from anaerobic digestion, which include *electrodialysis*, ion-exchange and adsorption.

Alkaya et al (2009) reported experiment results using dissolved trioctyl-phosphine oxide (TOPO) in kerosene with different ratios of 5%, 10% and 20%. The conclusion is that a higher recovery rate at higher concentrations of TOPO in kerosene. At 20% TOPO concentration and pH 2.5, VFA recoveries ranged from 61% to 98%. Under the same concentration, but pH of 5.5, VFA recoveries ranged from 23% to 73%. Mostafa (1999) also concluded that the optimum VFA extraction occurs at 20% TOPO concentration in kerosene at 30°C, with recovery ratios ranging from 75% to almost 80%.

Kim et al (2005) published research about the filtration performance of ceramic membranes to recovery VFA from sludge in a working system with capacity of 76 liters, which included an anaerobic fermenter, a micro-ceramic filtration module, a sludge container and a VFA container. The authors concluded that the optimal membrane size should be around $1\ \mu\text{m}^{23}$ to allow 80% recovery of the VFA.

Nordin et al (2010) affirms that ceramic membranes resist to pH, chemicals and extreme temperatures, which makes this alternative more efficient than polymeric membranes. However, ceramic membranes are generally more expensive than polymeric. When comparing the financial feasibility of different ultrafiltration systems for a pulp and paper mill, the authors concluded that the most competitive alternative was the parallel configuration with polymeric membrane.

However, Ramaswamy et al (2013) explained that the lifetime of a ceramic membrane in a pulp and paper facility is much longer than that of polymeric. In a pulp and paper facility, for example, the lifetime of a polymeric membrane is estimated in 18 months and the ceramic membrane in six years. According to the authors, the lifetime of the membrane, in both cases, is affected by the operating conditions. Extreme pH, high temperatures tend to shorten the membrane's lifetime.

4.3 Volatile Fatty Acids to Fatty Acid Methyl Ester

Oleaginous microorganisms have the ability to accumulate lipids that are of the same type found in plants and animal oils and fats. Interestingly, only microorganisms that can accumulate lipids above 20% of the dry cell biomass are termed oleaginous, which mostly includes yeast and fungi (SHETTY; PALIYATH; POMETTO; LEVIN, 2006).

These microorganisms have been reported to accumulate maximum intracellular triglycerides or lipids, the fuel precursor that are converted into FAME, of up to 50% to 70%. The efforts to use oleaginous fungi for oil production on a cheap feedstock of carbon, such as molasses,

²³ Microfiltration is the denomination of the process that separates microorganisms, inorganic particles, oil and colloids. In microfiltration the size of the retentate components ranges from $0.1\ \mu\text{m}$ to $10\ \mu\text{m}$ (WANG; IVANOV, TAY, HUNG, 2010)

sludge sewage, credo glycerol and agricultural bioproducts increase the competitiveness of the production system compared to other feedstock (SATYANARAYANA; JOHRI; PRAKASH, 2012).

In addition to the cost benefits from using less expensive carbon feedstock, as opposed to those from vegetable oil crops, microbial oils are not affected by seasonal and climatic conditions. Another advantage is the minimization of the controversial debate of using edible carbons to produce biodiesel as opposed to food, as well as the need for the agricultural land (SATYANARAYANA; JOHRI; PRAKASH, 2012).

Table 25 summarizes the yield for lipid production by using different carbon sources and strains. According to existing literature, the highest yield using exclusive VFA is 0.167 g/g or 16.7% y l/s (yield lipid to substrate) with the use of *C. albidus* as strain for a four-day reaction.

Table 25 – Lipid yields

Strain	Carbon Source	Time of reaction days	Lipid content (w/w %)	Yield l/s (g/g)	Source
<i>Y. lipolytica</i>	Glucose and VFAs	2.5	40.2%	0.200	FONTANILLE; 2012
<i>Y. lipolytica</i>	Glucose + propionic acid	2.5	38.1%	0.200	FONTANILLE; 2012
<i>C. albidus</i>	VFAs	4.0	27.8%	0.167	FEI; 2011
<i>Y. lipolytica</i>	Glycerol and VFAs	2.5	34.6%	0.160	FONTANILLE; 2012
<i>M. isabellina</i>	Pectin	na	25.0%	0.110	apud FEI 2011
<i>C. albidus</i>	Starch	na	33.0%	0.100	apud FEI 2011
<i>R. glutinis</i>	Wastewater	na	19.0%	0.095	apud FEI 2011
<i>M. isabellina</i>	Sweet Sorghum	na	30.0%	0.090	apud FEI 2011
<i>C. echinulata</i>	Xylose	na	19.5%	0.062	apud FEI 2011
<i>C. echinulata</i>	Tomato Hydrolysate	na	13.5%	0.060	apud FEI 2011
<i>M. isabellina</i>	Glycerol	na	18.8%	0.048	apud FEI 2011

Source: The author.

Fei et al (2011) used ammonia chloride as a nitrogen source for the yeast under 25°C, pH of 6.0 culture for 96 hours, and VFA as the carbon source to reach a 0.167 g/g. The nitrogen source was fully consumed during the harvesting of the biomass, with an initial concentration of 0.02 mol/liter. Pamitic, oleic and linoleic acids were the main VFAs produced under this experiment, which correspond to those of other vegetable oils used as a feedstock to produce biodiesel. The highest lipid accumulation by *C. albidus* was observed when pH ranged from 5.5 to 7.0.

Fontanille et al (2012) reported a conversion yield of 0.20 g/g when adding glucose to VFA with the use of another *Y. lipolytica* as the oleaginous microorganism. The experiments were conducted under 30°C, pH of 5.6 for 60 hours, with ammonia chloride used as the nitrogen source. Under this experiment, oleic and linoleic acids were the main VFAs produced, which is in line with the main VFAs reported by Fei et al (2010).

In terms of extraction methods, Jin et al (2012) concluded that the downstream process to recovery lipids is considered a major barrier for large-scale production and proposed an innovative process that could reduce significantly costs and the energy consumption of the process. The authors suggested an enzyme-assisted lipid extraction method from *R. toruloides*, with ethyl-acetate and pre-treated biomass, where 96.6% of lipids were covered at room temperature.

Cescut el al (2011) reported lipid recoveries above 98% when applying the pressurized liquid extraction method. A cycle-time of 15 minutes and 100°C degree with 144% use of dispersant Hydromatrix® resulted in the best combination to extract lipids within the cells. The authors concluded that this recovery method has major cost advantages, given that time was reduced by a factor of 10. In addition to time saving, the method also requires 70% less solvents compared with traditional extraction methods, which may reduce operating costs.

Amanor-Boadu et al (2013) emphasized the significant debate about the quantity of lipids that may be extracted from algae when discussing the modeling assumptions for the economic feasibility analysis for an algal biodiesel plant with a total capacity of 50 million of gallons per year. The authors used a hexane solvent extraction technology for oil recovery, based in the premise that the same technical complexity of other oleaginous grains may be applied to algae. However, the authors acknowledged that the assumption of a 99% oil recovery is debatable and should be considered a “best case” assumption.

5. Project Appraisal

The main objective of this chapter is to calculate the selling price per liter of the biodiesel produced from the organic component of the municipal solid waste. This chapter is divided in two main parts. The first part analyzes the most common financial methods to evaluate a project from a financial perspective. The second part defines the assumptions used as inputs in the financial feasibility analysis, which are related to production yields, investments, operating costs and financial costs.

5.1 Financial Methods

This section investigates and analyses the most commonly used financial methods to evaluate projects, which are the net present value and the internal rate of return. Other methods, such as the real option, were also analyzed.

5.1.1 Net Present Value and Internal Rate of Return

There are many capital budgeting²⁴ methods to evaluate a project, but the net present value (NPV) method, which provides a direct monetary measure, is the single best measure of profitability (EHRHARDT; BRIGHAM, 2009).

Together with the NPV method, the internal rate of return (IRR) method is widely used in investments' decisions as a measure of profitability expressed as percentage rate of return (EHRHARDT; BRIGHAM, 2009). NPV and IRR are consistent with a company's goal of maximize shareholder's wealth; therefore most firms largely use these methods (BESLEY; BRIGHAM, 2009).

²⁴ Capital budgeting is the process of identifying and selecting long-lived assets that will generate benefits over more than one year (PETERSON; FABOZZI, 2002).

Graham and Harvey (2001) survey 392 CFOs (Chief Financial Officers) about the preferred methods used to evaluate projects or acquisitions. The conclusion is that the vast majority of executives use NPV or IRR. In this study, 75.61% said to always or almost always to use the IRR method and 74.93% said to always or almost always to use the NPV method.

Both IRR and NPV methods incorporate the concept of the time value of money, which has been integrated in business analysis for a long time. In 1202, Italian scholar Fibonacci developed detailed mathematical tools for finance by calculating present value, compounding interest, pricing goods, among others. Fibonacci's work was written at a time of unprecedented economic vitality from commercial interactions between the East and the West, which triggered the development of finance methods to evaluate these transactions (GOETZMANN; ROUWENHORST, 2005).

Keynes (1936) explained that Fisher's "rate of return over cost" concept, published in 1930 was identical to his definition of "marginal efficiency of capital", which is the rate employed in compounding the present worth of costs and returns, making these two equal. In 1960, Bierman and Smidt (2007) explained that several terms are used to define IRR, including "marginal efficiency of capital" coined by Keynes.

According to Damodaran (2011) the NPV method is one of the foundations in corporate finance, which reflects the sum of present value of expected cash flows on a project, minus all investment needs²⁵, as illustrates formula. Koller, Goedhart and Wessels (2010) define free cash flow as the cash flow generated by operations, deducted from investments made in the business.

The NPV of a project could be expressed represented in the following formula. If the NPV of a project is positive, it generates value for the firm, whereas if NPV is negative, the project destroys value for the firm (DAMORADAN, 2006).

$$\text{NPV of project} = \sum_{t=1}^{t=n} \frac{CF_t}{(1+r)^t}$$

²⁵ It is common in finance practice to speak of firm's free cash flow and a project's cash flow or net cash flow, but these concepts are identical (BRIGHAM; EHRHARDT, 2013).

Where

CF_t = cash flow in period t

r = discount rate

n = life of the project

The free cash flow could be calculated by two different methods, depending on the scope of the analysis, which are the free cash flow to firm (FCFF) or enterprise cash flow and the free cash flow to equity (FCFE). The FCFF is based on cash available to all investors holding claims against the company, whereas the FCFE refers to common equity holders (DEPAMPHILIS, 2012).

The FCFF and FCFE calculation could be summarized according to the following formulas (BRIGHAM; EHRHARDT, 2013 and DEPAMPHILIS, 2012).

$$FCFF = NOPAT^{26} + D\&A^{27} - \Delta \text{ working capital} - CAPEX^{28}$$

$$NOPAT^{29} = EBIT \times (1 - \text{tax rate})$$

$$FCFE = \text{net income} + D\&A - \Delta \text{ working capital} - CAPEX + \Delta \text{ debt}$$

Alternately (PINTO; HENRY; ROBINSON; STOWE, 2010):

$$FCFE = FCFF - \text{interest expense} (1 - \text{tax}) + \Delta \text{ debt}$$

The discount rate (r) represents the cost of capital or the expected return to investors, which is the price charged by investors for the risk that expected cash flows could be different from what anticipated (KOLLER; GOEDHART; WESSSELS, 2010).

In order to be successfully implemented, the cost of capital assumption should be consistent to the scope of the free cash flow calculation. For the FCFE the appropriate discount rate is

²⁶ Earnings Before Interest and Taxes (BRIGHAM; EHRHARDT, 2013).

²⁷ Depreciation and Amortization. Ibid.

²⁸ Capital expenditures. Ibid.

²⁹ Net Operating Profit After Tax. Ibid.

the cost of equity, whereas for FCFF, the discount rate is the weighted average cost of capital (WACC) (LAOPODIS, 2013).

The CAPM (Capital Asset Pricing Model) calculates the cost of capital by defining the opportunity cost of equity, which is the return foregone by investing in a project rather than investing in available securities (BREALEY; MYERS, 2003). Therefore, if equity is invested in one project, it cannot be invested elsewhere to earn return (DRURY, 2006).

The CAPM is represented by the following formula (COPELAND; KOLLER; MURRIN, 1994).

$$K_s = R_f + \beta_i [E(R_m) - R_f]$$

Where:

R_f = the risk-free rate of return. The risk free concept is based on a hypothetical security with zero default risk and unrelated to market returns. The most reasonable alternative is to use government securities, from which the ten-year US Treasury-bond rate is the most appropriated (COPELAND; KOLLER; MURRIN, 1994).

The suitability of the ten-year Treasury bond relies in the similar duration of the cash flow and the duration of the stock market index portfolio, which also consistent to β calculation (COPELAND; KOLLER; MURRIN, 1994).

When valuing European companies, the ten-year German bonds are a suitable reference due to higher liquidity and lower credit risk, compared to other European countries (KOLLER; GOEDHART; WESSSELS, 2010).

The unbiased estimate in risk-free estimate is to use yields of the government bonds, which for example reflect markets expectations on inflation, as opposed to initial total return (KASPER, 1997).

$E(R_m) - R_f$ = the market risk premium is the difference between expected return and risk-free rate of return (COPELAND; KOLLER; MURRIN, 1994).

The suggested market risk premium ranges from 5% to 6% for US based companies, which reflect the geometrical long-term average risk for S&P 500³⁰ return over long-term government securities from 1926 to 1992.

Depending on the holding period, from 1900-2009 the market risk premium from US stocks to US government bond ranged from 5.4% to 6.1% (KOLLER; GOEDHART; WESSSELS, 2010).

$E(R_m)$ = the expected rate of return on the overall market portfolio (COPELAND; KOLLER; MURRIN, 1994).

β = the systematic³¹ risk of the equity (COPELAND; KOLLER; MURRIN, 1994).

The β for a company is not a stand-alone risk measure, given that it represents the risk of investing in a certain company relative to the market risk as a whole (CRUNDWELL, 2008).

Therefore, the use of β depends on whether the company has shares traded in the stock market or not (COPELAND; KOLLER; MURRIN, 1994).

Although β calculation could be obtained from a robust estimation process, judgment is still required to consider industry developments with the economy. The following formula represents the variables involved in the β calculation (KOLLER; GOEDHART; WESSSELS, 2010).

$$\beta_i = \frac{\text{COV}(R_i, R_m)}{\sigma_m}$$

³⁰ The S&P 500 includes 500 companies of US equities corresponding to approximately 80% coverage of available market cap (S&P Dow Jones Indices LLC, 2013).

³¹ The risk of an event that triggers a loss of economic value or confidence in a substantial part of the financial system with significant negative effects to the real economy (Group of Ten et 2001 apud NICOLO; KWAST, 2002).

Where:

COV = covariance

R_m = return of the market index

R_i = return of security i

σ_m = Variance of the market returns

The WACC, which is the appropriate discount rate for FCFF, is the weighted average of the after-tax cost of debt and the cost of equity, as described in the following formula (KOLLER; GOEDHART; WESSSELS, 2010).

$$WACC = \frac{D}{V} K_d (1-T_m) + \frac{E}{V} K_e$$

$$V = D + E$$

Where:

D/V = target level of debt to enterprise value.

E/V = target level of equity to enterprise value,

V = enterprise value

The use of a target debt and equity level is addresses two main points; first, the company's current capital structure³² may not reflect the long-term expected structure and second, a target structure solves the circularity problem involved in calculating WACC (COPELAND; KOLLER; MURRIN, 1994).

Three approaches could be used to develop a target structure for a company, which include the market value based capital, review comparable companies and review managements financing strategies and implications for the target capital structure (COPELAND; KOLLER; MURRIN, 1994).

³² Capital structure is the proportion of debt and equity on a firm's balance sheet. The optimum capital structure provides the minimum cost of capital and maximizes value (KHAN, 2004).

The market value of a company is primarily debt and equity or the market value of all claims against the enterprise. There are two approaches to calculate market's debt market value; the first is to use the market value of debt if available and the second is to value debt by discounting promised cash flows at the appropriate yield of maturity³³ (KOLLER; GOEDHART; WESSSELS, 2010).

K_d = cost of debt, which could be the yield to maturity of the company's long-term bond for investment grade³⁴ companies.

For companies below investment grade, yield to maturity should not be used because probability of default and recovery rate after default will not reflect an adequate proxy for the company's cost of debt. Instead, for non-investment grade companies or below, using the adjusted present value (APV) is recommended and not WACC (KOLLER; GOEDHART; WESSSELS, 2010).

K_e = cost of equity or K_s (COPELAND; KOLLER; MURRIN, 1994).

T_m = marginal income tax rate of the entity being valued, which is K_d reduced by the marginal tax rate (KOLLER; GOEDHART; WESSSELS, 2010).

In regards to the time horizon for the projection of cash flows, it is possible to focus on key value drivers, such as operating margins and capital efficiency for a five to ten-year period. After that, projecting even the key drivers becomes meaningless and the continuing-value³⁵ should be estimated (KOLLER; GOEDHART; WESSSELS, 2010).

The continuing-value is the present value of cash flow after the explicit forecast period, which combined will represent the total value. The continuing-value could be expressed according to the following equation, for cash flow growth at a constant rate, or return on investment

³³ The yield to maturity of a bond is the discount rate that equals the NPV of interest and principal payments with the present price of the bond (MOYER; MCGUIGAN; KRETLOW, 2009).

³⁴ Credit rating agencies rate company's debt offering as investment-grade or non-investment grade. Investment grade suggests a stronger balance sheet and low credit risk while non-investment grade have relatively higher credit risk (STOWELL, 2010).

³⁵ The cash flow generated during a stable growth period is caked terminal, sustainable, horizon or continuing growth value (DEPAMPHILIS, 2012).

(ROIC) equation that expresses value in terms of ROIC and growth. These approaches would have the same result (COPELAND; KOLLER; MURRIN, 1994).

$$\text{Continuing value} = \frac{\text{FCF}_{t+1}}{\text{WACC} - g}$$

$$\text{Continuing value} = \frac{\text{NOPLAT}_{t+1} (1 - \frac{g}{\text{ROIC}})}{\text{WACC} - g}$$

$$\text{ROIC} = \frac{\text{NOPLAT}}{\text{Invested Capital}}$$

Where:

g = the expected growth rate in free cash flow in perpetuity.

NOPLAT = net operating profit less adjusted taxes in the first year after explicit forecast.

ROIC = expected rate of return on new investment.

Invested capital = operating working capital + net fixed assets + other assets

The continuing-value could also be calculated for FCFE at constant growth rate (DEPAMPHILIS, 2012) and expressing value in terms of return on equity (ROE) and growth, as illustrates the following formulas (KOLLER; GOEDHART; WESSSELS, 2010).

$$\text{Continuing value} = \frac{\text{FCE}_{t+1}}{K_e - g}$$

$$\text{Continuing value} = \frac{\text{Net income}_{t+1} (1 - \frac{g}{\text{ROE}})}{K_e - g}$$

Based on the definition of IRR provided by Brigham and Houston (2012) that the IRR rate is the discount rate that makes a project's NPV to be equal to zero, the IRR would be expressed as illustrated in the next formula, which is the NPV formula adjusted to NPV zero.

$$\text{NPV of project} = 0 = \sum_{t=1}^{t=n} \frac{CF_t}{(1+IRR)^t}$$

In the same way that net cash flow can be calculated to the firm and to the equity holders, IRR can also be calculated both ways. The IRR based on the free cash flow to the firm should consider the total investment and has to be compared to the cost of capital. The IRR based on the free cash flow to equity should account for the equity investment and has to be compared to the cost of equity (DAMODARAN, 2011).

Once the NPV is computed, the project is acceptable if $NPV > 0$ and rejected if $NPV < 0$. The same concept applies to IRR analysis. A project with $NPV > 0$ implies a return above the hurdle rate, which is the cost of equity for FCFE and the weighted-average cost of capital for FCFF (DAMODARAN, 2011).

Once the IRR is computed, the project is acceptable if $IRR > \text{cost of capital}$ and rejected if $IRR < \text{cost of capital}$. The same methodology is used for comparing IRR to cost of equity for FCFE and to the weighted-average cost of capital for FCFF is valid to allow comparison (DAMODARAN, 2011).

When analyzing mutually exclusive independent projects (P1 and P2, for example) there is the possibility that NPV and IRR calculation provide conflicting results. The conflict relies on different relative magnitudes for NPV and IRR, which are $NPV P1 > NPV P2$ and $IRR P1 < IRR P2$. In this situation, the NPV method should be used because this decision is more consistent to the goal of maximizing value of the firm (BESLEY; BRIGHAM, 2009).

5.1.2 Real Options

Options can be categorized in financial options and real options. Financial options are derived from financial assets, which could be stocks or bonds generally traded in the stock market. Real options derive from real assets, such as real estate property, projects or intellectual property, which are not negotiated in the stock market (KODUKULA; PAPUDESU, 2006).

Real option valuation derives from financial option valuation techniques introduced by Black, Scholes and Merton in 1973, which awarded the 1997 Nobel Prize in economy for their contributions in the field of derivative valuation (SCHWARTZ; TRIGEORGIS, 2004).

The holder of an option has the right, but not the obligation, to exercise the right or to abandon the right, which in regards to real options is equivalent to abandon the investment or postpone it for a more appropriate time (KODUKULA; PAPUDESU, 2006).

Therefore, the opportunity to invest in a certain project is like an option for a corporation, as it provides the right to invest, but not the commitment to invest (LUEHRMAN, 1998)

The Black-Scholes formula for a European call³⁶ on non-dividend paying stocks could be defined as (KANG; 2009):

$$C = S N(d_1) - K (e^{-rt}) N(d_2)$$

$$d_1 = \frac{\ln(S/K) + (r + \sigma^2/2) T}{\sigma\sqrt{T}}$$

$$d_2 = d_1 - \sigma\sqrt{T}$$

³⁶ An option that could be exercised by the holder at the time of expiration is a European option. An option that could be exercised at any moment by the holder until expiration is an American option. Under the same conditions, the price of an American option should be higher than or equal to the European option (JIANG, 2005).

Where

C = value of call

S = current value of the underlying asset

K = exercise price of the option

T = life of expiration of the option

r = risk-free interest rate during the life of the option

σ^2 = variance in the value of the underlying asset

$N(d_1)$, $N(d_2)$ = cumulative normal distribution functions

According to Trigeorgis (1995), an option-based valuation approach can be useful in defining the value associated to the flexibility of a project, which include the option to defer and investment, expand or contract the scale of operations, temporarily shut down, switch use and abandon the project.

The value of a project, under the real option approach, consider the static NPV, which assumes managerial decisions are limited to the initial project, and the option premium, which is the value of the flexibility (TRIGEORGIS; 1995).

The main differences in the parameters for the value of a financial option and a real option are illustrated in Table 26.

Table 26 – Parameters for financial and real options value

Financial option	Real option	Variable
Exercise price	Cost to acquire asset	K
Stock price	NPV	S
Time to expiration	Time of availability	t
Variance of stock returns	Variance of scenarios	σ^2
Risk-free rate of return	Risk-free rate of return	r

Source: BRACH, 2003.

According to LUEHRMAN (1998) the valuation of a project can be calculated by the use of a valuation matrix, which requires the following inputs:

- the net present value of all future cash flows associate to the project, deducted from investments;
- the risk measure that quantifies the uncertainty related to the project, adjusted by the option to postpone the project ($\sigma\sqrt{t}$);
- the ratio expressing the relationship between the net present value of the project divided by the net present value of the investments associated to the project.

The use of the Black & Scholes model is controversial, with empirical evidences that managers prefer other methods when considering capital budget allocation decisions. Graham and Harvey (2001) survey 392 CFOs regarding the methods used to evaluate projects or acquisitions and concluded that only 26.59% always or almost always incorporate real option methods.

Copeland and Tufano (2004) describe the results of another survey by Bain & Company with 451 senior executive, in which one third of participants who tried to incorporate real option to management tools gave-up using the tool after one year of use. The authors suggest that managers could adopt more use-friendly real option methodologies, such as binomial methods and should improve company's ability to monitor the conditions for timely exercise project's options.

5.2 Assumptions and Results

The chemical engineering design is responsible for the conception and specifications of a plant that could result in further financial forecasts to verify the economic feasibility of an engineering process. The financial input estimates resulting from the engineering design could be mostly divided in capital cost, production cost and revenues (TOWLER; SINNOT, 2013).

The capital cost refers to fixed capital investments and working capital. The fixed capital investment includes the costs to design, construct, and installing the facility, which can be categorized in the inside battery limits (ISBL) or the cost of the plant itself, the offsite battery

limits (OSBL) or the infrastructure, the engineering and construction costs and finally, the contingency charges (TOWLER; SINNOT, 2013).

Capital costs can be categorized in five segments depending on the accuracy and purpose of the estimate. The Association for the Advancement of Cost Estimating International (AACE International) classifies these categories, which vary from ballpark estimates to as-bid estimates. The “Class 5” estimate’s accuracy is $\pm 30\%$ to 50% of the costs of similar processes and is used for initial studies for screening purposes. On the other hand, the “Class 1” estimate’s accuracy is $\pm 5\%$ to 10% and is based on concluded negotiations on procurement (TOWLER; SINNOT, 2013).

OSBL are typically estimated as a percentage of ISBL, which could range from 10% to 100% of ISBL costs, depending on the project’s facility. In chemical processes, OSBL ranges from 20% to 50% of ISBL with 40% mostly used as an initial detail when no details of the site are known (TOWLER; SINNOT, 2013).

The cost to design is part of engineering costs, which besides the detailed design of the facility, also includes the procurement of plant items, construction supervision and service charges and contractor’s profit. This cost represent 30% of ISBL and OSBL combined, but could be as low as 10% for smaller scale plants (TOWLER; SINNOT, 2013).

The contingent charges represent extra costs to the project’s budget and include changes in prices of items, currency fluctuations, labor disputes, adjustments to project’s scope and other unexpected problems. A minimum 10% of ISBL and OSBL costs should be considered as a contingent cost. However, if technology is uncertain, a higher contingent charge of 50% should be used (TOWLER; SINNOT, 2013).

Production cost could be divided into fixed costs and variable costs. Variable costs are proportional to output and include raw material, utilities, chemical consumables, effluent disposal and packaging or shipping. Fixed costs mostly refer to labor, maintenance, taxes, insurance, rent of land, environmental changers and royalty payments (TOWLER; SINNOT, 2013).

Rent of land and buildings are assumed to be rented in most of projects rather than acquired. This cost represents 1% or 2% of ISBL and OSBL. However, if land and building are acquired, the cost of the investment needs to be added to the fixed capital investment (TOWLER; SINNOT, 2013).

We assume that the process to produce biodiesel from organic MSW will be based on the same process used for biogas production, which instead should be interrupted at the *acidogenesis* when VFA is generated (WANG; IVANOV; TAY, 2010).

The following production steps consider an additional reactor to convert VFA into FAME by using microorganisms in aerobic digestion and the typical transesterification used in the conversion of lipids into biodiesel, which yields to methyl or ethyl esters (biodiesel) and glycerin (DERMIBAS, 2010).

5.2.1 Yields

For the OFMSW to VFA conversion, the model assumes results reported by Sans et al (1995) under *thermophilic* conditions. Under this experiment, a 13.4 g/g yield was obtained, with retention period of two days, as depicted on Table 23. This experiment also reported the highest absolute VFA production to total carbon (TC) of 23.7%, among other selected experiments, and also has the highest productivity of 6.7 g/g per day, as detailed on Table 24. This is equivalent to a 4.42% yield of VFA to OFMSW.

The use of VFA as a percentage of TC or TVS allows for the incorporation of different MSW profiles, as long as the TC or TVS contents are known. Sans, Alvarez, Checci, Pavan and Bassetti (1995) experiments do not provide a detailed composition of MSW used in their experiments; therefore, VFA yield based on TC may be an alternative solution. The primary input considers that only the organic MSW is used as substrate; therefore, recyclable matter is not used as substrate, although some papers are easily degradable (TCHOBANOGLIOUS et al 1995 apud PICHTEL, 2010).

According to Alkaya et al (2009), the liquid-liquid extraction technique to recovery VFA from fermentation broths is one of the most efficient, economical and environmental method

for the separation of carboxylic acids, with recovery ratios reaching up to 98%. Kim et al (2005) published research about the filtration performance of ceramic membranes to recovery VFA from sludge and concluded that the optimal membrane size should be around 1 μm to allow 80% recovery of the VFA. This dissertation estimates a recovery ratio of 85% by using ceramic membranes for microfiltration.

For the VFA to FAME conversion, the model assumes a 0.167 l/s yield, use of *C. albidus* as strains with a retention period of four days (FEI; CHANG; SHANG; CHOI; KIM; KANG, 2011). Although other studies have reported higher yields, these experiments combined other feedstock to VFA in order to increase yield (FONTANILLE; KUMAR; CHRISTOPHE; NOUAILLE; LARROCHE, 2012), which is not the scope of this dissertation.

For VFA extraction, Amanor-Boadu et al (2013) analyzed the used a hexane solvent extraction technology for oil recovery, based in the premise that the same technical complexity of other oleaginous grains may be applied to algae. The authors considered a 99% oil recovery as the best case assumption, which is incorporated as the VFA recovery ratio.

For the biodiesel production from lipids, the dissertation assumes the transesterification method, which is the best method available due to its low cost and simplicity (ATABANI; SILITONGA; BADRUDDIN; MAHLIA; MASJUKI; MEKHILEF, 2012). The recovery ratio of 94% and the glycerol generated as a by-product of biodiesel production is 10% (SCRAGG, 2009), which is incorporated in this analysis.

Figure 1 – Schematic production and extraction yields

Source: The author.

5.2.2 Capital Costs

The capital cost estimated for the MSW to FAME conversion was divided in three different groups, the *acidogenesis* production facility or VFA production, the VFA to lipids conversion and finally the transesterification process or biodiesel production.

The VFA production's capital costs are based on biogas plants literature for Germany's biogas producers (FRN, 2010), which indicates gains of scale for plant sizes greater than 3,000 m³ of digester capacity.

Over the number of different examples provided by FRN (2010), as depicted on Table 27, example VII uses biowaste as the main source of feedstock. Biowaste includes food waste and grease, whereas the other examples use grain crops, silage and slurry as the main feedstock, which are not in the scope of this dissertation.

Table 27 – Capital cost references for anaerobic fermentation phase

	unit	I	II	III	IV	V	VI	VII	VIII
Substrate storage and loading (A)	\$	148,073	242,993	385,815	391,918	260,282	485,142	230,062	854,760
Digester (B)	\$	95,590	143,410	314,575	343,476	359,980	410,599	364,793	787,027
Digester capacity	m ³	620	1,200	2,800	3,000	3,400	4,000	3,400	7,400
Digester cost per volume	\$/m ³	154	120	112	114	106	103	107	106
Digested storage (C)	\$	106,719	155,725	259,034	236,632	259,149	279,832	736,408	492,464
Storage capacity	m ³	1,100	2,000	4,100	2,800	4,100	3,800	11,400	6,800
Storage cost per volume	\$/m ³	97	78	63	85	63	74	65	72
Total capital cost (A+B+C)	\$	350,383	542,128	959,424	972,025	879,411	1,175,573	1,331,263	2,134,252

\$/EUR currency conversion of 1.3256 (Bloomberg, August 14, 2013) from original reference.

Source: FRN, 2010

Therefore, the assumption incorporated in this dissertation was biogas' plant example VII, as illustrates Table 27. The capital cost for biogas' plant example VII is \$1,331,263 for each 3,400 m³ of fermenter capacity, which includes (FRN; 2010):

- Substrate store and loading: silo slabs of concrete, with concrete walls and steel tank for intermediate storage for substrates delivered in liquid form.
- Receiving tank: concrete tank, with pumping equipment, substrate pipes, level measuring and leaking detection systems.
- Fermenter: above ground insulated concrete container with agitator equipment, gas-tight cover, instrumentation for control and safety and leak detection system, among others.
- Digestate storage: concrete tank with agitator equipment, substrate pipes, unloading equipment, leak detection system, instrumentation and control equipment, among others.

With a retention period of two days and in order to maximize capital cost utilization, two digesters are necessary. The two days for the reaction are based on the Sans (1995), for MSW conversion to VFA under *thermophilic* conditions for a 23.7% yield of VFA to TC. The VFA production requires another fermenter, but for aerobic digestion and not anaerobic digestion as the previous chemical process requires. The assumption for the fermenter is also based on FRN (2010) estimates. However, due to the yield conversion, the VFA volume generated would be lower than the organic MSW input.

Therefore, a digester with a lower 3,400 m³ of digester capacity is required, as a significant part of the organic MSW will not be converted in VFA, which will later be pumped to the 11,400 m³ digested storage tank as suggested by FRN (2010). With a retention period of four days (FEI, 2011) and in order to maximize capital cost utilization, four digesters of 620m³ are necessary or 18% of initial organic MSW input. The digesters used in the VFA production phase could be even smaller, given that the VFA to organic MSW yield is estimated at 4.4%. However, the dissertation assumes the smallest digester size available at FRN (2010) studies in order to maintain consistency among cost references. The capital cost of this digester is based on the example I of \$95,590 per each unit (FRN, 2010).

For the VFA extraction, Arora et al (2011) estimated capital and operating costs for the evaporation and filtration of a thin stillage from a 40 million gallons per year ethanol plant at \$274,340. However, the authors have allocated capital and operating costs into a single calculation of an estimated total operating cost per year. As a result, the assumption in this dissertation incorporates the entire amount in the income statement as an expense, with no equivalent investment, which is detailed in the following section.

Amanor-Boadu et al (2013) estimated an oil extraction cost of \$81 million for an algal biodiesel plant with a total capacity of 50 million of gallons per year. The authors used a hexane solvent extraction technology for oil recovery. Assuming that the gains of scale will be the same for the OFMSW to biodiesel production, the capital investment needed for the extraction of 1,127,560 gallons of oil corresponds to \$1,838,373.

Graboski et al (1998) use as a reference for capital cost \$2.0/gallon of biodiesel produced per year as a reference for a 10 million gallon per year plant processing vegetable oil. Based on this study, Tomes, Lakshmanan and Songstad (2010) concluded that the transesterification requires relatively low capital investments compared to the \$2.15/gallon of biodiesel production cost. The authors also referred a project comparison for ethanol and biodiesel production, in which is calculated that a 45 million gallons of production per year soybean biodiesel facility requires a total investment of \$0.52/gallon.

Haas et al (2006) estimated the \$11,348,000 capital investments for a moderately sized 10 million gallons of production per year with soybean oil as feedstock, which is \$1.13/gallon. Vecchio et al. (2006) apud Marques (2006) estimated a \$0.49 per gallon for an annual

production of 112.8 million liters of biodiesel in a facility located in Sao Paulo state in Brazil. This is based on a density 0.8771 g/cm^3 (MARQUES, 2006).

Shumaker (2007), in a study on the feasibility of biodiesel production in the state of Georgia, United States provided capital cost references for different plant sizes using vegetable oil as feedstock, based on annual production capacity. The capital costs are \$1.90/gallon for 500 thousand gallons of biodiesel annual production, \$1.13/gallon for a 3 million production, \$0.64/gallon for a 9.6 million gallon production and \$0.50/gallon for a 15 million gallon production.

Collins (2006) explains that the general rule of thumb for the cost of building a biodiesel plant is \$1.0/gallon of annual capacity. However, according to the author, the economies of scale the “per gallon cost” of building a plant begins to decrease as the plant size exceeds 5 million gallons per year of capacity. Based on the different scale-based references for biodiesel production and on a biodiesel production capacity of around 650 thousand gallons per year, the capital cost would range from \$2.0/gallon of annual capacity to \$1.9/gallon.

The dissertation assumes the average range of reference of \$1.95/gallon for 1,127,560 gallons of annual production, which implies a total capital cost of \$2,198,741 for the transesterification process only. In acid or alkali catalytic process, the reaction takes 60 to 360 minutes at a temperature of 30 to 35 °C (DERMIBAS, 2007), which implies that one tank is sufficient to process the FAME production from VFA.

Based on the capital costs for VFA production, FAME production and transesterification, the total capital cost IBSL is \$7,082,000. From the ISBL estimate, 40% is OSBL capital costs (TOWLER; SINNOTT, 2013), which is equivalent to \$2,832,800.

The design and construction, and the contingent capital costs are each 10% of total IBSL and OSBL (TOWLER; SINNOTT, 2013). This represents additional capital costs of \$1,982,960 and a total capital cost for the facility of \$11,897,760, which is detailed on Table 28.

Table 28 – Estimated capital costs

	Phase	Capacity m ³	Investment \$/m ³	Investment \$
Digester 1	OMSW - VFA	3,400	392	1,331,263
Digester 2	OMSW - VFA	3,400	392	1,331,263
Fermenter 3	VFA - FAME	620	154	95,590
Fermenter 4	VFA - FAME	620	154	95,590
Fermenter 5	VFA - FAME	620	154	95,590
Fermenter 6	VFA - FAME	620	154	95,590
Lipid extraction	VFA - FAME			1,838,373
Transesterification	FAME			2,198,741
Total (ISBL)				7,082,000
OSBL				2,832,800
Design and construction				991,480
Contingent				991,480
Total investment				11,897,760

Source: The author.

The construction period for a biodiesel plant varies from 12 months to 18 months (PAHL; 2008), whereas to build and commission a biogas plant could take 9 months to 15 months (Biomass Energy, 2013). The dissertation bases the construction period in 15 months, which is the average construction period for a biodiesel plant. As a consequence, the capital cost expenditure was proportionally adjusted for 80% in the first 12 months of construction and the remaining 20% for the last three months of construction in the subsequent year.

5.2.3 Financial Costs and Leverage

The life cycle of financing sources in a project could have different phases. The initial venture financed is mostly with equity. From equity, financing evolves to debt financing structures of bank debt, bond and syndicated loans and potentially an initial public offering when the venture becomes institutionalized and risk diminishes (QUIRY; FUR; SALVI; DALLOCHIO; VERNIMMEN, 2011).

In venture capital deals, debt-financing instruments could correspond to 6.5% up to 38.7% of total investments (BETTIGNIES; 2008 apud CUMMING, 2010). Venture capital is mostly

associated with equity financing, but debt financing is not uncommon to companies in the early stage of development.

On the other extreme, project finance provides a higher debt financing. According to Finnerty (2007), the initial leverage mean and the median for project finance projects in the petrochemical industry was 78% and 78% and in the oil & gas industry was 76% and 77%. The reference is based on above \$1 billion of investments financed by project finance transactions from 2002 to 2012 around the globe.

In terms of debt mean and median maturity for project finance, bank loans mature in 9.4 years and 8.0 years and bonds in 13.6 years and 13.3 years. The most significant concentration of bank loan's maturities is in the range of 5 years to 9.9 years, with 47% of the bank loan deals and 10 years to 14.9 years for bonds (FINNERTY, 2007).

The leverage assumption for the scope of this dissertation is the average percentage of debt in venture capital deals of 23% and the average for project finance deals of 77%, which is 50% leverage. In terms of maturity, the assumption is 10 years, which is the average between the lower point of the range of bank debt and the highest point of the range, but in year six of the projections net debt to EBITDA reaches 2.0x and remains unchanged.

In terms of financial interest cost, Salmon et al (2011) provided an estimate for geothermal power plants in the US ranging from 10-year US treasury plus 325 bps to 375 bps with signed purchase power agreements (PPA) contract with a creditworthy counterpart and engineering procurement contract (EPC). Based on the 10-year US treasury³⁷ the total cost of debt would range from 6.06% to 6.56% per year.

The U.S. Department of Energy (2011) in a report recommending different cost structures for fossil-fuel energy based projects indicates the cost for some energy related project finance deals in 2009-2010 ranging from 300 bps to 400 bps plus LIBOR³⁸ for 5 years to 10 years of tenor. Based on the 1-year LIBOR the total cost of debt would be 3.72% and 4.72%.

³⁷ U.S. treasury yield of 2.81% (Bloomberg August 26, 2013). <http://www.bloomberg.com/markets/rates-bonds/government-bonds/us/>

³⁸ London Interbank Offered Rate (LIBOR) is the benchmark interest rate provided by British Bank Association (BBA), the leading association for the United Kingdom's banking and financial sector <http://www.bbalibor.com/>

In the same report, the U.S. Department of Energy (2011) provides parameters of the financial cost for different risks associates to energy generation. For high risk fuels projects the nominal dollar cost is LIBOR plus 6.5% and for high risk independent power producers the cost is LIBOR +5%. Based on the 1-year LIBOR the total cost of debt would be 7.22% and 5.72%.

Although there is discrepancy between the interest rate references, the dissertation incorporates the highest cost of debt of 7.22% per year in real terms. Given that the reference for cost is in nominal terms and the projections are in real terms, the interest rate must be converted to real terms. According to Fisher's equation³⁹ and based on expected inflation, the real interest rate is 5.12%.

5.2.4 Revenues and Operating Costs

The costs of production could be divided into variable costs, those proportional to the plant output, and variable costs, which are incurred regardless of the plant's output. The variable costs include raw material, utilities, consumables, effluent disposal and packaging and shipping. Fixed costs include operating labor, maintenance, insurance, rent of land, environmental charges, running licenses, royalties in some cases and capital charges (TOWLER; SINNOT, 2013).

In order to estimate the feedstock cost, the calculation considered the initial digester capacity of 3,400 m³ as the maximum nominal capacity, a 771.5 kg/m³ density for food waste, a 336 kg/m³ for yard trimming and 675 kg/m³ for trees, which is based on the average of medium and compacted densities for each waste materials (Environmental Protection Agency - EPA Victoria, 2013). The average density was calculated in 579.8 kg/m³. There are significant variations within density references in the existing literature due to different compacted levels of waste. For example, 290 kg/m³ for food waste (PICHTEL; 2005) and 104 kg/m³ for yard waste (RHYNER; 1995) when not compacted.

³⁹ The mathematical formula to adjust the real rate of interest for the inflation is $1 + \text{nominal rate} = (1 + \text{real rate}) \times (1 + \text{expected annualized inflation})$ (MOLES; PARRINO; KIDWELL, 2011). Unadjusted 12-month inflation of 1.8% ended in June 2013 (The United States Department of Labor, 2013) and 2014 inflation is expected to be at 2.0% (Congressional Budget Office, 2013).

In terms of organic MSW component, the proportions used are 41.2% for food scraps, 39.8% for yard trimmings and 19.0% for wood (United States Environmental Protection Agency – EPA, 2010). The capacity of the digester of 3,400 m³ divided by the average substrate or feedstock density of 579.8 kg/ m³ provides the equivalent maximum kilograms or tons that could be loaded in a total amount of 1,971,361 kilograms or 1,971 tons.

According to FRN (2010), the cost of catering food waste is €5.0/ton or \$6.63/ton converting to \$/€ provided by Bloomberg (2013). This cost is the market prices of the feedstock delivered to the biogas plant and properly treated as required by hygiene legislation in Germany. FRN (2010) also provides a reference cost for biowaste or private household waste of €0.0/ton, delivered under the same conditions of catering food waste. Although household waste includes food waste and yard waste, the dissertation assumes the average cost of catering waste and household of \$3.3/ton as the feedstock cost for the VFA production.

The cost of VFA extraction is based on continuous ceramic microfiltration system published by Arora et al (2011) for a 40 million gallon per year ethanol plant. In this reference, capital costs and operating costs are reported together and are \$274,340 per year, mostly on power \$146,916 and depreciation \$44,517, which should correspond to capital costs. Assuming gains of scale will be maintained, which is conservative as the filtration system in the VFA generation would have to process more than double the volume, total annual expenses are estimated in \$672,506 or \$0.002 per gallon filtered.

The cost of production for the transesterification is based on Balat (2011) for a biodiesel plant with capacity of 6,000 liters of annual capacity. The total cost of production is \$0.85/liter for a vegetable oil processing facility, which includes \$0.40/liter for feedstock, \$0.33/liter for capital costs, \$0.05/liter for methanol catalyst, \$0.11/liter for other costs, \$0.08/liter for distribution and blending and a \$0.12/liter credit for glycerol sold.

Based on the fact that the biodiesel production described in the scope of this dissertation uses organic MSW, and not vegetable oils, as feedstock the total cost of production of \$0.85/liter should be deducted from \$0.40/liter for feedstock. In addition, the \$0.33/l capital cost was replaced by Collins (2006) estimates as an investment and not as a cost, as described previously. The \$0.05/liter for methanol was allocated to consumable costs, as part of the total consumable costs, and the glycerol credit as a revenue. Therefore, reallocating these expenses and investments, and assuming that the \$0.08/liter cost of blending the biodiesel

with regular diesel and the distribution may be incurred by the buyer of the biodiesel, the transesterification cost is estimated at \$0.11/liter. The total cost of transesterification was calculated at \$506,796 per year.

Glycerol's increasing production, as a result of expanding biodiesel production, has created an excess of supply that dropped prices from \$0.25 per pound to \$0.05 per pound or \$0.11 per kilogram (YANG; ENSHASY; THONGCHUL, 2013). As a result, the glycerol revenue is estimated at \$46,225 per year for 420,225 kilograms produced per year.

The definition of a chemical process's utilities cost, including fuel, steam, water, heating or cooling, electricity and others, is far more complex than defining the cost of the feedstock. (TOWLER; SINNOT, 2013). Consumables expenses, which include electricity, ignition oil, lubricating oil and other expenses, are based on plant reference VII (FRN; 2010) of \$76,227 for each anaerobic digester or \$152,455 for the fermentation process in two digesters. In addition, consumables expenses also consider additional \$0.05/liter of FAME production for methanol used as the catalyst in the transesterification (BALAT, 2011). As a result, total consumables expenses are estimated in \$382,817.

Land and buildings rented are estimate at 1.5% per year of IBSL and OSBL based on the average cost of 1% or 2% of ISBL and OSBL (TOWLER; SINNOTT, 2013), which represents a total annual cost of \$148,722 per year. Repair and maintenance costs are estimated to be 1% to 2% of total capital costs per year (FRN, 2010), which assuming the 1.0% represents a total annual cost of \$99,148 per year. Repair and maintenance costs could be considered investments for tax accounting reasons, but the dissertation follows the FRN's (2010) classification. Insurance costs are estimated to correspond to 0.5% of total capital costs (FRN, 2010), which represents a total annual cost of \$49,574 per year.

According to FRN (2010), the labor cost associated to biogas production represents less than 10% of total costs, which accounts for annual expenses of \$555,690. The required working time for supervision of the biogas plants is 13 hours per week, which are divided in 4.4 hours per week for routine inspection, 3.2 hours per week for maintenance, 2.7 hours per week for data collection and other 2.7 hours per week for fault rectification (FRN, 2010). This number was used as a parameter for the conversion of organic MSW to biodiesel.

The required time for operating a biogas plant essentially involve the time for substrate procession and loading and is highly dependent on the type of the substrate, for liquid substrates the required operating working hours is low and involves occasional adjustments, which are covered by the supervisory maintenance hours (FRN, 2010).

For solid substrates, the working estimate is 1.25 minute of work to 8.06 minutes per ton for front loader tractor, 2.03 minutes to 6.02 minutes per ton for wheel loader and 1.5 minute to 3.83 minutes per ton for telescopic loader (FRN, 2010). An Archimedean screw could be used to move concentrated organic MSW during the VFA production process (SANS; ALVAREZ; CHECCI; PAVAN; BASSETTI, 1995). This dissertation assumes that an Archimedean screw could feed the first two digesters with the same efficiency of a loader tractor or a wheel loader (FRN, 2010).

There is conflicting information about the average depreciation for a chemical facility. FRN (2010) suggests a 6.6% average depreciation for plant VII, which refers to biowaste feedstock and is the base of this dissertation. However, other sources assume that the depreciation rate of a chemical plant is on average 10 year, which yields to a depreciation rate of 10% per year (SINNOTT; 2005). For chemical plants the salvage value is often zero, because plants usually remain operating many years after the end of the depreciable life (TOWLER; SINNOT, 2013).

The average global corporate tax is 24.08% (KPMG; 2013) over taxable income, which was used to calculate the net income.

There is limited consensus in the required IRR to equity in real terms for a project and terminology is imprecise in detailing real or nominal return. Birgisson (2011) defined a required real IRR to equity of 15% when calculating the feasibility of producing biodiesel from rapessed. The author has also mentioned another 15% required IRR to equity for biodiesel production in the U.S. (PAULSON; GINDER et al. 2007 apud. BIRGISSON, 2011).

Pandey et al (2011) also describe another example of economic feasibility studies for ethanol plant suggesting an IRR of 15%. Schmidt (2012) also suggests, in another microalgae-biofuel project, that the IRR has to be above 15% for the investment to be profitable.

Stephens et al (2010) also assumed a minimum IRR of 12% to indicate the potential for economic viability in micro algal biofuels. Therefore, this dissertation assumes a 15% real IRR to equity as a minimum level to defined the feasibility of the study.

In terms of revenues, from the total input of 1.971 tons, the dry TC content is 45.4% for food waste and 45.0% for yard waste (LIU; LIPTAK, 2000), which yield to an average dry TC content of 45.1%. TC is referred in existing literature on a dry basis, which excludes moisture content⁴⁰; therefore, TC content for the total feedstock should be adjusted. In order to calculate the TC content, including the dry and moisture content, the food waste moisture of 65.4% and the yard waste moisture of 53.9% (LIU; LIPTAK, 2000) were deducted from 100% multiplied by the dry TC percentages. This is equivalent to affirm that from the total OFMSW, 18.7% is represented by TC. Table 29 provides additional details for the inputs used to calculate TC and the main components of the organic MSW assumed for the calculations in this dissertation.

Table 29 – Organic MSW composition

Feedstock	Moisture % total	Dry Matter % total	Carbon % dry	Hydrogen % dry	Nitrogen % dry	Chroline % dry	Sulfur % dry	Oxygen % dry	Ash % dry
Food waste	65.4%	34.6%	45.4%	6.9%	3.3%	0.7%	0.3%	32.3%	11.0%
Yard waste	53.9%	46.1%	45.0%	5.6%	1.5%	0.3%	0.2%	37.7%	9.6%
Average	58.6%	41.4%	45.1%	6.0%	2.1%	0.5%	0.2%	35.9%	10.1%

Source: LIU; LIPTAK, 2000.

As described later, the VFA yield to TC is 23.7% results in 87.2 tons of VFA from 368.1 tons of TC from 1,971 tons of OFMSW or 18.7% TC content in the OFMSW. This dissertation assumes VFA production from TC yield, but most of the existing literature also refers to TVS or TS yields. In order to verify the consistency of the method, VFA production was also calculated using TVS or TS yields, which resulted in a total VFA production of 87.4 tons and 63.0 tons respectively.

Based on the VS average of 31.0% for the OFMSW, which is calculate as the dry VS of food waste of 79% and yard waste of 73% (LIU; LIPTAK) adjusted by the moisture content from Table 29, results in a total VS content of 612.1 tons from 1,971 tons of OFMSW. Under the

⁴⁰ The fraction of a substance that is in the water or the weight loss of a material that is dried (LEE, 2005).

same results reported by Sans et al (1995) under *thermophilic* conditions on Table 24, taking the VFA yield to VS of 14.3%, the VFA production would be 87.4 tons, which is in line to the 87.2 tons calculated using TC.

Based on TS content, which is OFMSW of 1,971 multiplied the 34.1% average dry mater content, total TS is 815.4 tons. TS multiplied by the VFA yield to TS of 7.73% reported by Sans et al (1995) under *thermophilic* conditions on Table 24 results in a total VFA of 63.0 tons, which is below the VFA calculated over TC and TVS yields. Stofella and Kahn (2000) reported several experiments, in which food waste TVS ranged from 84.0% to 96.8% for example, this may explain the difference in the results.

Table 30 – Feedstock main characteristics

	unit	TC	TVS	TS
Capacity	m ³	3,400	3,400	3,400
Input	ton	1,971	1,971	1,971
VS	ton	na	612.1	na
TS	ton	na	na	815.4
TC	ton	368.1	na	na
VFA production	ton	87.2	87.4	63.0
VFA extraction	ton	74.1	74.3	53.6
Lipid production	ton	12.4	12.4	8.9
Lipid extraction	ton	12.2	12.3	8.9
VFA/Input	%	4.42%	4.43%	3.20%
Lipid/Input	%	0.62%	0.62%	0.45%

Source: The author.

The average transesterification yield for using methanol for several inputs is 94%, which results in 11.5 tons of total lipids (ATABANI; SILITONGA; BADRUDDIN; MAHLIA; MASJUKI; MEKHILEF, 2012). Based on an average biodiesel density of 0.885 g/ cm³ from several sources of waste oil range from 0.881 to 0.890 g/ cm³ (SPEIGHT, 2011) and the biodiesel generation yield of 90% (SCRAGG; 2009), total production is 11,702 liters per day or more than 1.1 million per year. Based glycerol's diesel of 1.25 g/ cm³ (KLYOSOV, 2007) and 10% yield (SCRAGG; 2009), the glycerol production is 921 liters per day or 1.2 ton per day.

5.2.5 Results

As a result of incorporating the revenue and cost structures, yields and required return of 15% in real terms, the implicit biodiesel selling is equal to \$1.47 per liter. The income statement per liter of biodiesel sold for the first ten years of operations are detailed in Table 31. Please refer to Appendix E for the detailed financial model and results.

Table 31 – Income statement divided per liter of biodiesel sold

Income Statement \$/l	1	2	3	4	5	6	7	8	9	10
Revenues	1.48	1.48	1.48	1.48	1.48	1.48	1.48	1.48	1.48	1.48
Biodiesel	1.47	1.47	1.47	1.47	1.47	1.47	1.47	1.47	1.47	1.47
Glycerol	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Variable costs	(0.92)	(0.92)	(0.92)	(0.92)	(0.92)	(0.92)	(0.92)	(0.92)	(0.92)	(0.92)
Substrate cost	(0.56)	(0.56)	(0.56)	(0.56)	(0.56)	(0.56)	(0.56)	(0.56)	(0.56)	(0.56)
Extraction	(0.16)	(0.16)	(0.16)	(0.16)	(0.16)	(0.16)	(0.16)	(0.16)	(0.16)	(0.16)
Transesterification	(0.12)	(0.12)	(0.12)	(0.12)	(0.12)	(0.12)	(0.12)	(0.12)	(0.12)	(0.12)
Consumables	(0.09)	(0.09)	(0.09)	(0.09)	(0.09)	(0.09)	(0.09)	(0.09)	(0.09)	(0.09)
Fixed costs	(0.37)	(0.38)	(0.38)	(0.38)	(0.38)	(0.38)	(0.38)	(0.38)	(0.38)	(0.38)
Land	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)
Depreciation	(0.17)	(0.18)	(0.18)	(0.18)	(0.18)	(0.18)	(0.18)	(0.18)	(0.18)	(0.18)
Labor	(0.13)	(0.13)	(0.13)	(0.13)	(0.13)	(0.13)	(0.13)	(0.13)	(0.13)	(0.13)
Insurance	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Maintenance	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
Costs and expenses	(1.29)	(1.31)	(1.31)	(1.31)	(1.31)	(1.31)	(1.31)	(1.31)	(1.31)	(1.31)
Operating Income	0.19	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
EBITDA	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36
Financial result	(0.09)	(0.07)	(0.06)	(0.05)	(0.05)	(0.04)	(0.04)	(0.04)	(0.04)	(0.04)
EBT	0.11	0.11	0.11	0.12	0.13	0.13	0.14	0.14	0.14	0.14
Corporate Tax	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)
Net Income	0.08	0.08	0.09	0.09	0.10	0.10	0.10	0.10	0.10	0.10

Source: The author.

5.3 Sensitivity Analysis

5.3.1. Monte Carlo Simulation

The use of simulation analysis in investments was first suggested by David Hertz in 1964, who advocated that using probability distributions for input variables provide more informative outputs, rather than single-best estimates (DAMODARAN, 2006). In this sense, Monte Carlo⁴¹ simulation produces useful outputs for financial analysis using a stochastic⁴²

⁴¹ Monte Carlo was a code word for work that von Neumann and Ulam were doing during World War II for the atom bomb, where it was used to integrate otherwise intractable mathematical functions (VOSE, 2008).

⁴² A family of random variables defined on a probability space. If family members can be counted, then the stochastic process is said to be discrete in time, otherwise, the process is said to be continuous (VASSILIOU, 2010).

model. A family of independent and equally distributed random variables leads to the classic limited law of large numbers and the central limit theorem (KIJIMA, 2013).

As computers availability widespread, the use of Monte Carlos simulations to analyze uncertainty became more popular. In the recent years, a number of software has become available, including @RISK and Crystal Ball for Microsoft Excel use, which make Monte Carlo application computationally practical. Such programs are designed to work on an existing Excel model by allowing the user to select random inputs, the respective distribution and the target output. This process is repeated multiple times and the results recorded in an observed distribution (FERSON, 2000).

Commonly used distributions for inputs are the uniform, triangular and normal. The uniform distribution assumes that random values are equally distributed between the lower and the upper boundary, the triangular distribution needs an estimate of the mode and the normal distribution assumes the lower and the upper points are on a certain percentage of the normal curve (BOREK; PARLIKAD; WEBB; WOODALL, 2013).

The simulation presented in this dissertation used @RISK software and considered as independent variable inputs the biodiesel selling prices, capital investments, substrate cost and lipid production yield. The definition of these independent variables is based on their relevance for the cash flow to equity calculation. For example, biodiesel revenues accounts for 99% of total revenues and substrate cost is the largest components of the entire cost structure representing 45% of the total cost. The lipid production yield is also a relevant independent variable to define the productivity of the system.

The initial aim was to assume IRR as the output, in order calculate the number of scenarios yielding to an IRR greater or equal than 15%. Nevertheless, IRR calculation showed significant errors corresponding to 9.1% of total output values. The key explanation for errors relies on the limitations of the excel model to calculate IRRs⁴³ on a negative sequence of cash flows. Thus, such negative IRRs calculated as errors would underestimate the number of IRRs below 15%, impairing the analysis of the results. In order to eliminate errors from the

⁴³ Microsoft Excel uses an iterative technique for calculating IRR. After 20 tries, if IRR cannot be found, the #NUM error value is returned. <http://office.microsoft.com/en-us/excel-help/irr-HP005209146.aspx>.

sample analysis, the simulation considered absolute numbers for NPV, rather than IRR figures. Therefore, NPVs equal or greater than zero represent equal or higher than 15% IRRs.

5.3.2 Assumptions

For biodiesel selling price the sensitivity analysis assume a uniform distribution of biodiesel prices from \$1.47 per liter, the minimum price for the 15% IRR, to \$1.71 per liter, the highest selling price in Germany. The uniform distribution considers equal weights for biodiesel prices ranging from \$1.47 per liter to \$1.71 per liter. The dissertation will not incorporate in the sensitivity analysis a lower than \$1.47 per liter selling price of biodiesel, given that for any price below this level would also result in an IRR below 15%.

Table 32 – Biodiesel and diesel price references

Reference	\$/liter	Type
Biodiesel Germany ^a	1.71	Biodiesel DIN 14214
Biodiesel US Gulf ^b	1.33	Soy Methyl Ester (SME)
Biodiesel Northwest Europe ^c	1.18	Used Cooking Oil Methyl Esters (UCOME)
Biodiesel Northwest Europe ^c	1.02	Rapeseed Methyl Ester (RME)
Biodiesel Brazil ^d	0.83	Biodiesel ANP 14
Biodiesel South East Asia ^e	0.80	Palm Methyl Ester (PME)
Diesel Rotterdam	0.79	Fossil Fuel
Diesel ULSD Fuel USA ^f	0.78	Fossil Fuel
Diesel ULSD Italy	0.78	Fossil Fuel
Diesel ULSD Northwest Europe	0.78	Fossil Fuel
Diesel Northwest Europe	0.78	Fossil Fuel
Biodiesel Argentina ^g	0.74	Soy Methyl Ester (SME)

Source: The author, LexisNexis Academic, 2013

(a) Spot price as of June 22, 2013 for pure biodiesel (B100) under *Deutsches Institut für Normung* (DIN) European standards 14214 (LexisNexis Academic, 2013).

(b) National weekly average price as of June 19, 2013 for B100 biodiesel reference Iowa (United States Department of Agriculture – USDA, 2013).

(c) Spot price as of June 22, 2013 for biodiesel traded on a FOB basis Rotterdam (LexisNexis Academic, 2013).

(d) Average price of 31st public selling biodiesel auction on June 07, 2013 for product delivered at production unit including federal sales tax (*Agência Nacional do Petróleo, Gás Natural e Biocombustíveis* - ANP, 2013). BRL/\$ conversion at 2.1316 (Bloomberg).

(e) Spot price as of June 22, 2013 for biodiesel traded on a FOB basis at typical loading ports in Singapore, Malaysia and Indonesia.

(f) ULSD (Ultra-Low-Sulfur) No. 2 diesel fuel, which is a gasoil type distillate for use in high speed diesel engines generally operated under uniform speed and load conditions. Ultra-low sulfur level diesel has less than or equal to 15 ppm (parts per million) (EIA, 2013). The viscosity of the biodiesel produced from vegetable oils is slightly higher than No. 2 Diesel Fuel (PANDEY, 2009).

(g) Price as of June 22, 2013 for biodiesel FOB basis Rosario (LexisNexis Academic, 2013). The Argentinean government, through the *Secretaría de Energía*, sets biodiesel prices and current effective export tax is 20.67% (USDA, 2013).

The sensitivity to substrate cost and lipid production yield assume a normal distribution curve with σ equals to 0.1 and μ equals to 1, which correspond to a range of 83.5% to 116.4% of the basic assumption when calculation the \$1.47 per liter for the 15% IRR previously detailed. For the capital investment the sensitivity assumes an uniform distribution ranging from -30% to +30% of the base case assumption, which is the minimum dispersion for “Class 5” accuracy standards (TOWLER; SINNOT, 2013). The @RISK software ran 10,000 interactions of possible scenarios combining these independent variable inputs.

5.3.3 Results

Results obtained using @RISK software indicate that in 86.4% of the 10,000 simulations the NPV is greater than zero and IRR is greater than 15%. The maximum observed value was \$19,017,796 and the minimum was -\$9,480,517 with a mean of \$4,023,887 and a standard deviation of \$3,662,247.

The most relevant effect on the output mean NPV was caused by the changes in the lipid production yield. The variation on lipid production yield caused NPV to range from negative \$199,339 to positive \$8,181,653. The second most relevant effect came from the variation of biodiesel selling price, which ranged from \$474,909 to \$7,784,862. The other two independent variables “capital investment” and “substrate cost” ranged from \$2,140,689 to \$5,922,988 and from \$2,145,240 to 5,736,985 respectively. Please refer to Appendix F and G for the outputs and to Appendix H for more details regarding the independent variable inputs.

6. Final Remarks

The first chapter of this dissertation introduced the general theme, with considerations about municipal solid waste and energy, and narrowed the scope of the research to biodiesel production. The primary objective of this dissertation was to evaluate the financial feasibility of producing biodiesel from organic municipal solid waste.

The second part presented an overview of fuel energy, with particular focus on the supply-demand characteristics and the production of diesel and biodiesel. The main conclusions are: (i) fossil fuels, such as diesel, should continue to be a relevant energy source for transportation, (ii) political instability in major oil production regions and environmental concerns are likely to advance the development of renewable sources.

The third chapter analyzed municipal solid waste from a feedstock perspective to biodiesel production. The main conclusions are: (i) environmental concerns should trigger the adoption of more sophisticated and expensive waste management methods and (ii) the development of efficient technologies to use abundantly available municipal solid waste as a feedstock to produce energy could be an alternative to reduce such costs.

The fourth chapter discussed existing literature about the production and extraction of volatile fatty acids and fatty acid methyl esters to produce biodiesel. The conclusions are: (i) the productivity is relatively low compared to conventional biodiesel production and (ii) there is a dismal number of research integrating the entire process of converting municipal solid waste into biodiesel.

The fifth part addresses the primary objective of this dissertation, which was to evaluate the financial feasibility of producing biodiesel from organic municipal solid waste. We concluded that the biodiesel selling price of \$1.47 per liter is not competitive with diesel, based on selected parameters evaluated in this dissertation, for a 15% internal rate of return. Diesel fuel prices of \$0.78 to \$0.79 per liter result in a price advantage for the fossil fuel, as depicted

Table 32. These results contradict our original hypothesis that the MSW-VFA technology would be competitive at oil prices above \$100 per barrel, which is reflected in diesel prices.

Notably, when compared to the price of biodiesel derived from vegetable oil, OFMSW-based biodiesel is competitive with Germany and the U.S. Gulf Coast, yet not competitive with biodiesel produced in Northwest Europe, South Asia, Argentina and Brazil. Consequently, our results partially confirm the hypothesis that MSW-VFA may be financially feasible when compared to existing sources of biodiesel produced from vegetable oils.

In spite of existing subsidies for biodiesel production, the selling price of \$1.47 per liter that we use to evaluate the OFMSW-VFA technology does not account for any government grant. Therefore, if we incorporate in our assumptions any form of subsidy, the OFMSW-VFA technology may become more competitive, which could reduce the selling price or increase the IRR. The OFMSW-based biodiesel is only competitive to the U.S. Gulf Coast, for example, if the \$0.13 per liter subsidy is incorporated in the selling price of \$1.47 per liter. Further investigation on the precise direct and indirect subsidies to biodiesel, and the potential application to MSW feedstock, are essential and would allow for the incorporation of such benefits in future studies.

Thus, the competitiveness of the biodiesel produced from OFMSW is highly dependent on subsidies granted to biodiesel produced from vegetable oils. In addition, a significant portion of these biodiesel costs are impacted by agricultural commodity prices, such as soybean, rapeseed, sunflower and palm oil, which have a meaningful impact on biodiesel prices from vegetable oils.

The effective development and implementation of OFMSW-VFA technology is possible when assuming a continuous and homogenous feedstock supply over the existence of the project. The existence of heavy metals, pesticide residues, antibiotics and others may increase operating costs, capital costs and reduces productivity, which will reduce the IRR of the project or require a higher selling price for the biodiesel. Therefore, waste source segregation and feedstock control is an important variable in using the OFMSW-VFA technology.

There is significant discrepancy between source segregation and waste collection practices around the globe and the appropriate waste separation could significantly reduce waste

management costs. Waste collection public policies could improve, thus allowing the use of MSW as a sustainable feedstock stream. The proper separation and collection of the waste by categories such as recyclables, organic, toxic or contaminants is critical to sustainable biodiesel production.

In the context of a reliable feedstock stream, OFMSW-VFA technology could be investigated in other industrial activities that generate waste or liabilities, such as animal slurry from poultry, beef and dairy farms, where animals are confined, carbons from food production and processing, and from sewage. The integration of other feedstock sources are essential to implement the project in a large scale because of the significant amount of organic MSW needed to benefit from the gains of scale related to capital investments. We estimated a total daily input of 1,971 tons per day of organic waste for the facility, which is equivalent to the daily organic waste produced by almost 3.7 million people, based on the global average organic waste generation of 0.54 kg per inhabitant per day (The World Bank, 2012).

There is limited literature about the physical, economic, logistics, cost and chemical composition of organic waste; therefore, further investigation could increase the quality of research related to the production of energy from MSW. The absence of extensive literature about the integrated chemical engineering process required to produce of biodiesel from organic MSW also represents an interesting potential for further research. Additional experiments considering the entire production process, from VFA and lipids generation and production, could improve further feasibility research in the biodiesel production field.

The demand for biodiesel at competitive prices seems to be less of a challenge since the infrastructure to utilize such product is similar to the existing infrastructure used in the diesel distribution and consumption. Biodiesel may be mixed with diesel with minimum, if any, changes to existing distribution channels and internal combustion engines source (The World Bank, 2007). However, in spite of the existing infrastructure utilization, the production of high value-added chemicals from MSW could prove more profitable than biodiesel. Thus, further investigations should be conducted to analyze the potential uses of MSW feedstock to increase the profitability of the MSW-VFA technology.

Future research could explore the financial feasibility of producing biodiesel from other sources combined with VFA, such as glucose and glycerol. Fontanille et al (2012) and Fei et

al (2010) reported experiments using a combination of feedstock with VFA as the carbon source. The use of glycerol as a feedstock could be particularly interesting because it is generated as a byproduct in the transesterification processes to extract biodiesel from lipids (ROMANO; SORICHETTI, 2011) and glycerol's market price has significantly dropped as biodiesel production increased (YANG; ENSHASY; THONGCHUL, 2013).

Based on the productivity yields, this technology may have a greater economic impact as a waste management solution rather than an alternative to produce biodiesel. This technological contribution seems to be an alternative solution to landfills and incineration. With existing waste management solutions' costs ranging from \$10 to \$200 per ton (The World Bank, 2012), the MSW-VFA technology could reduce waste management costs, and at the same time, produce value-added biodiesel. Thus, transforming a liability, such as the waste treatment, to a feedstock may lead to a substantial increase in the IRR. Our financial model estimates a cost for the feedstock using the MSW-VFA, but municipalities currently pay for waste treatment solutions.

In terms of relevance, compared to existing MSW generation and biodiesel production, the MSW-VFA modeled in this dissertation is capable of processing a feedstock that is equivalent to 0.12% of the total organic waste generated in the world, as depicted in Tables 14 and 15. These results are based on a plant design that assumes the biodiesel facility is expected to process 1,978 tons of MSW per day, which is equivalent to the total waste produced by 1.2 million people.

When compared to the biodiesel output, our facility is expected to produce 98 barrels per day or 11,702 liters per day, which is equivalent to 0.024% of the world's biofuel production, as depicted in Table 12. As a consequence, the MSW-VFA is a more efficient waste management solution than a renewable biofuel alternative. These results encourage research aims to examine this technology from an integrated MSW-lipid production and at a larger scale.

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APPENDIX A – Schematic example of a biogas production plant

Source: Endress+Hauser

<http://www.endress.com/eh/home.nsf/#page/~biogas-process>

APPENDIX A – Biomass and potential uses for energy

Source: FRN; 2010

APPENDIX B – Schematic example of a biodiesel production plant

Biodiesel Production

Source: Endress and Hauser

<http://www.endress.com/eh/home.nsf/#page/~biodiesel-process>

APPENDIX C – Global biofuels production and main trade

Source: EDENHOFER; MADRUGA; SOKANA, 2012.

APPENDIX D – Country ordering according to income

Lower income	Lower middle income	Upper middle income	High income
Chad	Bulgaria	Colombia	Barbados
Comoros	Cameroon	Costa Rica	Belgium
Congo, Dem. Rep.	Cape Verde	Cuba	Brunei Darussalam
Eritrea	China	Dominica	Canada
Ethiopia	Congo, Rep.	Dominican Republic	Croatia
Gambia	Cote d'Ivoire	Fiji	Cyprus
Ghana	Ecuador	Gabon	Czech Republic
Guinea	Egypt, Arab Rep.	Georgia	Denmark
Haiti	El Salvador	Grenada	Estonia
Kenya	Guatemala	Jamaica	Finland
Lao PDR	Guyana	Latvia	France
Liberia	Honduras	Lebanon	Germany
Madagascar	India	Lithuania	Greece
Malawi	Indonesia	Malaysia	Hong Kong, China
Mali	Iran, Islamic Rep.	Mauritius	Hungary
Mauritania	Iraq	Mexico	Iceland
Mongolia	Jordan	Myanmar	Ireland
Mozambique	Lesotho	Namibia	Israel
Nepal	Macedonia, FYR	Panama	Italy
Niger	Maldives	Peru	Japan
Rwanda	Marshall Islands	Poland	Korea, South
Senegal	Marocco	Romania	Kuwait
Sierre Leone	Nicaragua	Russian Federation	Luxembourg
Tanzania	Nigeria	Seychelles	Macao, China
Togo	Pakistan	South Africa	Malta
Uganda	Paraguay	St. Kitts and Nevis	Monaco
Vanuatu	Philippines	St. Lucia	Netherlands
Vietnam	Sao Tome and Principe	St. Vincent and the Grenadines	New Zealand
Zambia	Solomon Islands	Suriname	Norway
Zimbabwe	Sri Lanka	Tajikistan	Oman
	Sudan	Uruguay	Portugal
	Swaziland	Venezuela, RB	Qatar
	Syrian Arab Rep.		Saudi Arabia
	Thailand		Singapore
	Tonga		Slovak Republic
	Tunisia		Slovenia
	Turkey		Spain
	Turkmenistan		Sweden
	West Bank and Gaza		Switzerland
			Trinidad and Tobago
			United Arab Emirates
			United Kingdom
			United States

Source: The World Bank, 2012.

APPENDIX F – Detailed simulation results

Relatório Output do @RISK para S NPV

Data: quarta-feira, 22 de janeiro de 2014 16:53:28

Resumo de informação da simulação	
Nome da planilha	Biodiesel Model Test MC No Perp.
Número de Simulações	1
Número de Iterações	10000
Número de Inputs	4
Número de Outputs	1
Tipo de Amostragem	Hipercubo Latino
Tempo de início da simulação	22/01/14 17:38
Duração da Simulação	00:00:34
Gerador de Aleatório	Mersenne Twister
Semente aleatória	490859950

Sumário Estatístico para S NPV	
Estatísticas	Percentil
Mínimo	5% (1.706.685,0)
Máximo	10% (601.688,9)
Média	15% 249.468,5
Desv Pad	20% 863.649,1
Variância	25% 1.443.770,0
Assimetria	30% 2.001.317,4
Curtose	35% 2.500.960,7
Mediana	40% 2.996.497,2
Moda	45% 3.477.554,5
X Esquerda	50% 3.940.367,6
P Esquerda	55% 4.374.797,3
X Direita	60% 4.853.495,5
P Direita	65% 5.311.453,9
Dif X	70% 5.868.304,8
Dif P	75% 6.449.925,7
Erros	80% 7.112.105,2
Filtrar Min	85% 7.829.444,1
Filtrar Max	90% 8.812.473,3
Filtrados	95% 10.262.539,2

Mudança na estatística de output de S NPV			
Posto	Nome	Inferior	Superior
1	Lipid production	(199.339,9)	8.181.653,1
2	Biodiesel price	474.909,4	7.784.861,9
3	Capex	2.140.638,9	5.922.988,4
4	Substrate cost	2.145.240,0	5.736.985,0

APPENDIX G – Simulation results

APPENDIX H – Independent variables

Resultados de inputs do @RISK								
Data: quarta-feira, 22 de janeiro de 2014 16:53:32								
Nome	Célula	Gráfico	Min	Média	Max	5%	95%	Erros
Capex	B2		70%	100%	130%	73%	127%	0
Biodiesel price	B3		1,47	1,69	1,91	1,49	1,89	0
Substrate cost	B4		62%	100%	139%	84%	116%	0
Lipid production	B5		60%	100%	139%	84%	116%	0