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Article

Economic Analysis of Thermal Catalytic Process of Palm Oil (*Elaeis Guineesensis,* Jacq) and Palm Oil Neutralizing Sludge

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Abstract: Palm oil (dendê) is, from an economic, environmental, and social point of view, the vegetable oil with great potential, where the Pará state in Brazil is one of the world´s great producers. During your refining, according the type of processing, is produced a residue (neutralizing sludge). Studies of economic analysis using these materials are accomplished in this work considering the thermos-catalytic cracking process the palm oil (Elaeis guineensis, Jacq) and palm oil neutralizing sludge. The thermo-catalytic processes were carried out in pilot scale (THERMTEK/LEQ/UFPA/IME/RJ), and their economic feasibility analyzed. The yields of biofuels produced by fractional distillation were also studied. The physicochemical characteristics of the raw materials, the organic liquid product (bio-oil) and the chemical composition of kerosene, light-diesel and heavy-diesel from the palm oil (Elaeis guineensis, Jacq), as well as those of biogasoline and biokerosene from the palm oil neutralizing sludge were also determined. The economic indicators for the evaluation of the most viable cracking (pyrolysis) and distillation process of bio-oils were analized. The analysis of the indicators showed the economic viability of crude palm oil (*Elaeis guineensis*, Jacq) and *unfeasibility* for the palm oil neutralization sludge (also high yield of bio-oil has been obtained, the main negative aspect it was the distillation yield of 20%). The minimum fuel selling price (MFSP) obtained is this work for the biofuels was of 1.34 US$/L) and the breakeven point obtained was of 1.30 US$/L. *The sensibility analysis demonstrated that the pyrolysis and distillation yields are the most important variables to affect the minimum fuel selling price (MFSP).*

Keywords: Palm oil; Neutralizing sludge, Thermal processing; Biofuels; Economic analysis; Technical feasibility.

1. Introduction

We need energy, for example, to run industries, for domestic consumption in homes, for transportation, and for various other purposes. This energy, which comes from different sources, together form a system that is referred to as energy matrix. In other words, it represents all the sources available in a country, state, or in the world, to supply the need (demand) for energy.

The world's energy matrix is mainly composed of non-renewable sources, such as coal, oil, and natural gas. Figure 1 shows the world energy matrix in 2018 (EPE, 2021) Renewable sources such as solar, wind, and geothermal energy, together account for only 2% of the world energy matrix (marked as "Others" in the graph). Combined with hydraulic energy and biomass, only about 14% of the global energy sources are renewable.

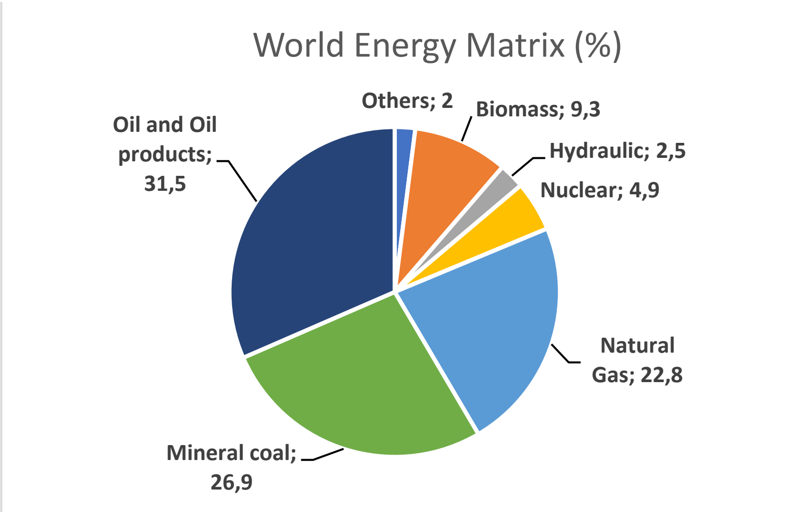

Figure 1. World Energy Matrix 2018 (EPE, 2021).

Brazil's energy matrix is very different from that of the rest of the world. In Brazil, although energy consumption from non-renewable sources exceeds that from renewable sources, it uses more renewable energy than the rest of the world. Firewood and charcoal, hydraulics, cane derivatives, and other forms of renewable energy, together account for 46.2%, or almost half of Brazil's energy matrix (Figure 2).

This characteristic of Brazil's energy matrix is important. Non-renewable energy sources are mainly responsible for the emission of greenhouse gases emissions (GHGs). Given that Brazil consumes more energy from renewable sources than other countries, it emits less GHG per inhabitant than most other countries (EPE, 2021).

The oil crisis that has taken place in recent decades, coupled with the increased demand for fuels and the growing concern for the environment, advocates the search for alternative sources in the production of energy (SUAREZ et al., 2009). Alternative sources of renewable energy, such as biomass, are favored over the use of petroleum products because they can reduce the emission of gases that cause the greenhouse gas emissions effect.

Among the alternative renewable energy sources that are mature enough to be used commercially, only biomass has been identified with high technological efficiency (CORTEZ et al., 2011). Biomass has the flexibility to generate both electric energy and transportation fuels (CORTEZ et al., 20

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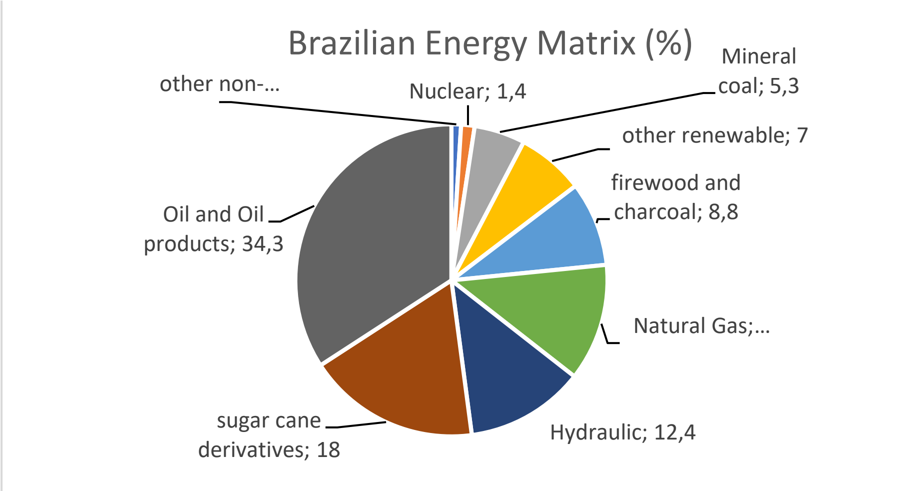

Figure 2. Brazilian energy matrix 2019 (EPE, 2021).

Brazil's consumption of renewable energy is higher than the rest of the world's renewable energy consumption (Figure 3).

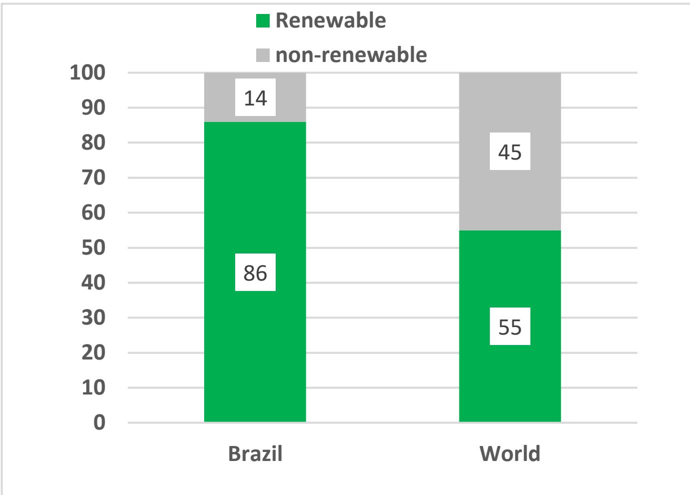

Figure 3. Percentage of renewable and non-renewable sources in Brazil and in the world (EPE, 2021).

WRIGHT et al., (2010) presented a techno-economic study which examined fast pyrolysis (cracking) of corn stover to bio-oil with subsequent upgrading of the bio-oil to naphtha and diesel range fuels. Two 2000 dry tonne per day scenarios are developed onsite for fuel upgrading, while the second scenario relies on merchant hydrogen. Fuel product value estimates are \$3.09 and \$2.11 per gallon of gasoline equivalent (\$0.82 and \$0.56 per liter).

TRIPPE et al., (2010) investigates the decentralized fast pyrolysis process step which converts biomass into a so-called biosyncrude consisting of pyrolysis and char. The biosyncrude can be further processed to synthetic fuels via pressurized entrained flow gasification, gas cleaning and synthesis in biomass-to-liquid production concepts such as the considered bioliq concept. The techno-economic analysis of the decentralized pyrolysis plant with a capacity of 100 MW thermal energy input concludes that at a present, it is

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possible to produce the biosyncrude in Germany at costs of about 35€/MWh compared to 22€/MWh for natural gas or 15€/MWh for coal which are inputs for coal-to-liquid and gas-to-liquid process.

According BROWN et al., (2013) a previous Iowa State University (ISU) analysis published in 2010 investigated the technical and economic feasibility of the fast pyrolysis and hydroprocessing of biomass, and concluded that the pathway could produce cellulosic biofuels for a minimum fuel selling price (MFSP) of $2.11/gal (US$ 0.56 / L). In 2013 a new study was presented, the MFSP for a 2000 MTPD facility employing fast pyrolysis and hydroprocessing to convert corn stover gasoline and diesel fuel is calculated to quantify the economic feasibility of the pathway. The present analysis determines the MFSP of gasoline and diesel fuel produced via fast pyrolysis and hydroprocessing to be $2.57/gal (US$ 0.68 / L).

ZHANG et al., (2013) presented the economic feasibility of a facility producing monosaccharides, hydrogen and transportation fuels (gasoline and diesel) via fast pyrolysis and upgrading pathway was evaluated by modeling a 2000 dry metric ton biomass/day facility using Aspen Plus. A facility internal rate of return (IRR) of 11.4% based on market prices of $3.33/kg hydrogen, $2.92/gal (US$ 0.77 / L) gasoline and diesel, $0.64/kg was calculated.

Several studies have reported yields of 50-75 % bio-oil (although yields above or below this range are not uncommon, depending on the kind of feedstock, reactor and operational conditions employed (BROWN et al., 2013)), 15-25 % char, and 10-20 % gas (GREGOIRE and BAIN, 1994; MULLANEY and FARAG, 2002).

MOTA (2013) studied the production of biofuels from the cracking process at different scales of production. Part of the product obtained was distilled batch scale with a column of type vigreux and pilot scale with a column of type packaging. In these reactions of thermal cracking and catalytic cracking, was verified the efficiency of the use of catalysts, was also evaluated different types of catalysts and catalytic potential of waste materials, as well as different types of raw materials. It was obtained results of yields of Bio-oil of 63.6%, coke of 8% and Biogas 28.4%.

According THILAKARATNE et al., (2014) a techno-economic analysis of mild catalytic pyrolysis (CP) of woody biomass followed by upgrading of the partially deoxygenated pyrolysis liquid is performed to assess this pathway's economic feasibility for the production of hydrocarbon-based biofuels. A minimum fuel selling price (MFSP) of $3.69 per gal (0.98 US$ / L) is estimated assuming 10% internal rate of return. The process gives a product fuel yield of 58.6 gal per MT of biomass which is equivalent to a mass conversion rate of 17.7 wt %.

SANTOS (2015) presented studies of the soap phase residue derived from refining vegetable oils, which are agro-industrial residues obtained after the neutralization stage of vegetable oils, which are aggregate low-value material, in addition to being an environmental liability for agribusiness thus is becoming increasingly attractive the use of these residues as raw material for generation bio-fuels. This work studied the neutralization sludge of palm oil as an alternative raw material, from the point of view, economic and environmental to the process of catalytic and thermocatalytic cracking. It was obtained results of yields of Bio-oil of 71.37%, coke of 23.55% and Biogas 0.48%.

CASTRO (2019) presented the work which it was investigated the production of biofuels via pyrolysis, in laboratory scale, Semi-pilot and pilot, of açaí seeds (Euterpe oleracea) in Natura (SAIN) and impregnated with aqueous solution of sodium hydroxide (NaOH) 2 mol. L^{-1} (SANAOH). The experiments were carried out at 350, 400 and 450 °C, at 1.0 atm. It was obtained results of yields of Bio-oil of 11.03%, coke of 39.84% and Biogas 31.62%.

With growing concerns about our use of fossil-based fuels and associated greenhouse gas emissions, utilization of biomass for alternative fuel sources is on the rise. Biomass is defined as organic matter that is renewable and bio-degradable (BADGER et al., 2011).

Biomass can be converted to the either ethanol or bio-oil. Pyrolysis is the chemical composition organic materials by heat (around 500 ºC) in the absence of oxygen (BRIDWATER et al., 1999). After cooling and condensation, a dark brown liquid (bio-oil) is formed. The pyrolysis process produces three main products: a liquid organic (bio-oil), coke, and gases (MOTA, 2013; SANTOS, 2015; CASTRO, 2019). Bio-oil from fast pyrolysis of biomass has great potential to be one of the main renewable energy sources (JAROENKHSEMMESUK and TIPPA VAWONG, 2015).

For nearly a decade techno-economic analysis have been performed for pyrolysis oil production (GREGOIRE and BAIN, 1994; MULLANEY and FARAG, 2002; RINGER et al., 2006). Large-scale plant systems tend to generate lower production costs (BADGER et al., 2011).

This study focuses on the economic evaluation of the production of catalytic pyrolysis bio-oil, coke and methane gas from processing biomass on bath reactor. The incentives for producing with thermocatalytic pyrolysis technology are (LAPPAS, 2022; LAPPAS, 2012). (1) better quality oil with a high energy content (28-30 MJ / Kg) compared with 16-18 MJ / Kg for bio-oil from thermal pyrolysis (BRIDGWATER et al., 1999; RINGER et al., 2006), (2) higher stability in storage and transportation, and (3) lower acidity and as a result less corrosive. For these reasons, it is important to estimate the cost of producing bio-oil and, therefore, be in a better position to consider its further use in commercial applications for either transportation fuels or chemicals. The economic analysis is accomplished based on pilot plant data with commercially available catalyst (Na_2CO_3) in all experiments evaluate in this work.

Energy from biomass is extracted through the thermocatalytic cracking (pyrolysis) and distillation process (MOTA, 2013). Pyrolysis of biomass, such as palm oil (Elaeis guineensis, Jacq), can produce biofuels. After distillation, these organic liquid products (Biofuels) are similar to gasoline, kerosene, and diesel of fossil origin – (ONG and BHATIA, 2009).

Economic feasibility of two raw materials (biomass), crude palm oil (*Elaeis guineensis*, Jacq) and palm oil neutralization sludge, has been studied to evaluate the best investment alternative. The economic feasibility analysis of these raw materials was based on the following economic indicators: simple payback criterion, discounted payback, net present value (NPV), internal rate of return (IRR), and index of profitability (IP).

Figure 4 presents the scheme used in the process by MOTA (2013) to convert the palm oil (*Elaeis guineensis*, Jacq) in organic liquid product (bio-oil), coke and methane gas though pyrolysis process using sodium carbonate as a catalyst at 450ºC, followed distillation to obtain biofuels (biogasoline, biokerosene, green diesel).

Figure 5 presents the scheme used in the process by SANTOS (2015) to convert the palm oil neutralizing sludge in organic liquid product (bio-oil), coke and methane gas though pyrolysis process using sodium carbonate as a catalyst at 440ºC, followed distillation to obtain biofuels (biogasoline, biokerosene).

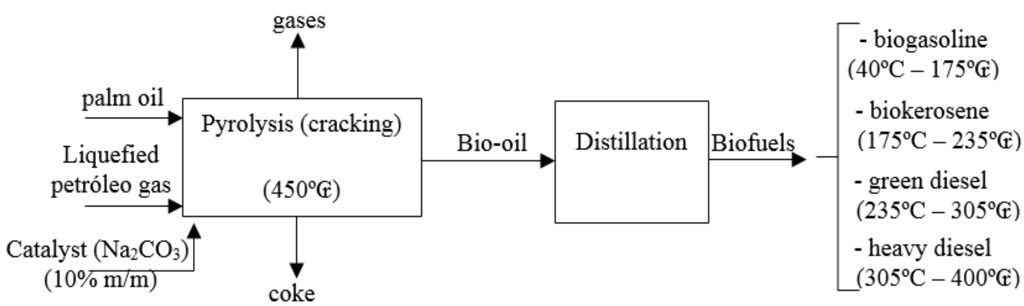

Figure 4. Scheme of convertion of palm oil (*Elaeis guineensis*, Jacq) in biofuels.

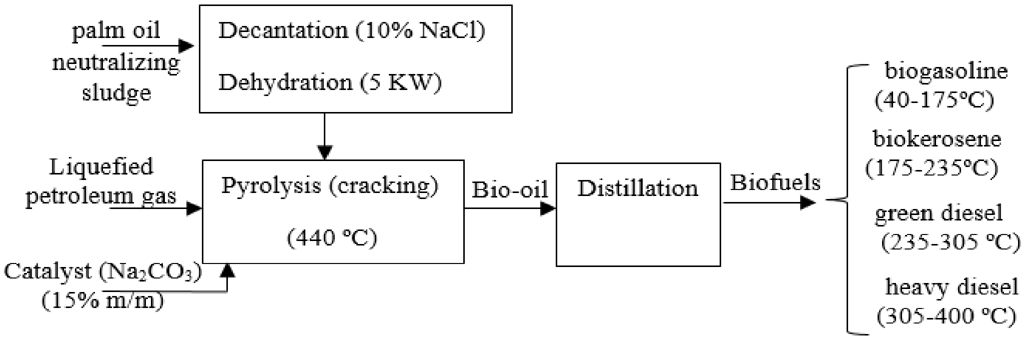

Figure 5. Scheme of convertion of palm oil neutralizing sludge in biofuels.

2. Materials and Methods

2.1. Materials

2.1.1. Palm oil (Elaeis guineensis, Jacq)

Palm oil (dendê) is, from an economic, environmental, and social point of view, the vegetable oil with great potential. Palm and palm kernel oils have low concentrations of polyunsaturated carboxylic acids, such as linolenic acid, and therefore have minimal problems with flavor reversal. Palm oil contains approximately equal amounts of saturated and unsaturated fatty acids. Unsaturated fatty acids include 39% oleic acid, while the saturated fatty acids include 44% palmitic acid, and 5% stearic acid. In comparison, palm kernel oil is 54–70% unsaturated, and includes a large amount of lauric acid, similar to coconut oil (MOTA, 2013). Table 1 shows the chemical composition in terms of fatty acids of the palm oil and of the kernel palm oil, according (BARNWAL and SHARMA, 2005).

Table 1. Chemical composition of common fat acids of the palm oil and of the palm kernel.

Fat acids	Representation	Palm oil	Oleina of Palm oil	Stearin of palm oil	Palm kernel
Lauric	C 12:0	< 0.4	0.1 – 0.4	0.1 – 0.4	41.0 – 55.0
Myristic	C 14:0	0.5 – 2.0	0.5 – 1.0	1.1 – 1.8	14.0 – 16.0
Palmitisc	C 16:0	41.0 – 47.0	34.0 – 39.0	48.4 – 73.8	6.5 – 10.0
Palmitoleic	C 16:1	< 0.6	< 0.5	0.05 – 2.0	-
Stearic	C 18:0	3.5 – 6.0	2.0 - 30	3.9 – 5.6	1.3 – 3.0
Oleic	C 18:1	36.0 – 44.0	43.0 – 50.0	15.6 – 36.0	12.0 – 19.0
Linoléico	C 18:2	6.5 – 12.0	9.0- 13.0	3.2 – 9.8	1.0 – 3.5
Linoleic	C 18:3	< 0.5	< 0.1	0.1 – 0.6	-
Arachid	C 20:1	< 1.0	-	0.3 – 0.6	

Source: BARWAL e SHARMA (2005).

Palm oil can be broken down into two components, after refining: an olein (60%) and stearin (40%). Olein is a liquid oil, intended for cooking and stearin can be used as fat in the cake and biscuit industry, serving also as a raw material for the manufacture of margarine, mayonnaise and ice cream. In addition, it can replace tallow in the production of soaps (NATALI, 1996). Table 2 shows the physicochemical characteristics of the crude palm oil and its reference (Table 3) obtained by MOTA (2013).

Table 2. Result of the physicochemical characterization of crude palm oil used in the cracking process on a pilot scale.

Properties	Crude palm oil
Density (g/cm^3)	0.9
Kinematic viscosity (cSt)	48.05
Acidity Index (mg KOH/g)	4.80
Saponification Index (mg KOH/g)	179.40
Ester index (mg KOH/g)	174.60
Refractive index	1.46
Free fatty acids – FFA (%)	2.41

Source: MOTA (2013).

Table 3. References of physicochemical caracteristics of the palm oil.

References	Units	Values
Especific mass (50ºꞒ / 20 ºC)	g/cm^3	0.891 – 0.899
Refractive index	-	1.454 – 1.456
Iodine index	G I_2 / 100g	50 - 60
Saponification index	mg KOH / g	190 - 209
Melting point	°Ꞓ	33 - 40
Free fat acids for the virgin palm oil	mg KOH / g	10.0

Source: RDC Nº 270, de 22/09/2005, of the National Health Surveillance Agency.

2.1.2. Palm neutralizing sludge

Palm oil neutralization sludge is an aqueous alkaline lipid emulsion that contains approximately 50% water, with free fatty acids, phosphatides, triglycerides, pigments, and other non-polar compounds (SANTOS, 2015). Neutralization sludge is generated at a rate of approximately 6% of the refining volume of the crude palm oil (HAAS, 2005). The low added cost of the neutralization sludge, and the environmental characteristics of its waste make the sludge a technically alternative viable for the production of biofuels. The cracking process, allows the sludge to transform into hydrocarbon mixtures (SANTOS, 2015).

Table 4 presents the results of physicochemical analysis of the palm oil neutralizing sludge after the dehydration process accomplished in the agitated tank reactor, as well as the water percentage obtained in the pyrolysis process up to the 100 ºC.

Table 4. Physicochemical characterization of the palm oil neutralizing sludge used as raw material in the pyrolysis pilot plant.

Characteristics	Values
Acidity index (mg NaOH / g)	6.64
Saponification index (mg KOH / g)	56.32
PH	7.16
Water content Exp. 5 (%)	32.8

Source: SANTOS (2015).

2.2. Thermal-cracking, thermal-catalytic cracking and distillation process

The pyrolysis, thermal-catalytic cracking and distillation processes of the raw palm oil (*Elaeis guineensis*, Jacq) and palm oil neutralization sludge, described by MOTA (2013), SANTOS (2015), respectively were studied. Two separate processes, for each raw material, were carried out in a pilot cracking unit (THERMTEK/IME/UFPA).

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2.3. Project evaluation criteria

2.3.1. Simple Payback

Simple payback is the time required for the investment made in the project to be fully recovered. The investor establishes the maximum term as a criterion to consider the feasibility of the project. Simple payback has the following characteristics :

- *It does not consider the value of money over time, which is contrary to the basic principle that a currency unit today is worth more than the same currency unit tomorrow.*
- *The project's cash flow, the amounts recorded, are considered historical (fixed).*
- *All amounts indicated in the cash flow that are positioned after the simple payback are not considered in the judgment analysis (comparison between the time defined by the investor for the return on investment and the return time obtained in the payback study).*

2.3.2. Discount Payback

The discounted payback method is similar to the simple payback, except that it considers the attractiveness or discount rate. It considers the value of money over time by adding the company's cost of capital to the simple payback. All cash flow elements are discounted at the defined rate, which is usually the current value on the zero date (RÊGO *et al.*, 2010). The discounted payback period is the investment recovery time at a chosen interest rate. This method is close to the criterion of Net Present Value (NPV).

Simple payback and discounted payback can be used to break similar NPV situations where faster cash recovery becomes relevant. They can also be used as a secondary analysis filter as a measure of liquidity risk or they can be generalized as a degree of project risk. Over time, the uncertainties associated with the project, such as revenue forecasts and corresponding costs, tend to increase, and with them, the associated risk. Finally, they assist in the analysis of projects without major financial significance for investors.

2.3.3. Net Present Value (NPV)

This criterion considers the value of money over time. It consists of two basic principles:

1. *A currency unit today is worth more than a currency unit tomorrow,*
2. *A secure currency is better than an uncertain currency.*

NPV is a criterion that works with the entire cash flow over a period of time. The values pertaining to cash flow are: 1. fixed investment; 2. investment in working capital; 3. gross operating revenue; 4. total operating cost; 5. project lifetime.

Together they are referred to as endogenous values. The equations below are used to prepare cash flow using the NPV criterion:

$$\text{Total Revenue} = \text{Sales Price} \times \text{Quantity} \tag{1}$$

$$\text{Total Cost} = \text{Total Unit Cost} \times \text{Quantity} \tag{2}$$

$$\text{Total Unit Cost} = \text{Unit Fixed Cost} + \text{Unit Variable Cost} \tag{3}$$

A variable effective interest rate is used in the NPV as an exogenous measure because it is a variable obtained from the financial market. Its value includes the premium for the decision to implement a project in the chemical industry that comes with risk.

By definition, NPV is the difference between the present value of cash flow ($PV_{C.F}$) and the value of investment (INV) made in the project, according to equation (4):

$$NPV = INV + PV_{C.F} \tag{4}$$

The present value of the cash flow ($PV_{C.F}$) is the result of moving all the values recorded in each period, at a certain minimum attractiveness rate [10].

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NPV criteria decision rules

The project is considered viable if the NPV is greater than zero, because this guarantees that the present value of the cash flow ($PV_{C.F}$) is greater than the value of the investment; therefore, it can be defined as follows:

a) recovers the full value of the investment;

b) a value is added to the company's equity, equivalent to the result obtained from the NPV.

If the NPV is equal to zero, then the company is in an uncertain situation and may or may not invest in the project. The final decision depends on other considerations.

If the NPV is negative, then the investment should not be made because the investment value will be higher than the present value of the cash flow ($PV_{C.F}$). In such situations the investment is not entirely recoverable.

The NPV criterion works with discounted cash flow, which means that future cash flow values when transported to point to suffer a loss in value due to the application of the interest rate.

2.3.4. Internal Rate of Return (IRR)

The Internal Rate of Return (IRR) criterion represents the value of a rate that belongs to the project itself. This means that the criterion is an endogenous measure because there is no need, as is the case with the NPV criterion, to use an attractive rate to move future values to the zero point.

This criterion is widely used because its result, which is given in the form of quantified percentage values, is easy to understand and interpret. This criterion works with the entire cash flow and considers the value of money over time. The IRR is specific to each project and its definition is as follows: “It is a rate that makes the NPV equal to zero”. The point at which the NPV becomes zero corresponds to the IRR (RÊGO *et al.*, 2010).

IRR decision-making criteria

The IRR decision-making process can then be summarized as follows:

a) cost of capital < IRR, project must be accepted (NPV > 0);

b) cost of capital = IRR it can be accepted or not (NPV = 0).

c) cost of capital > IRR, project must be rejected (NPV < 0).

2.3.5. Index of Profitability (IP)

This criterion involves characteristics similar to the previous criteria, as it also considers the value of money over time and uses all cash flow. This criterion is close to the NPV criterion, as it is defined as follows:

The index of profitability is the ratio of the NPV plus the investment divided by the entire investment (INV), according to equation (5), as follows:

$$IP = \frac{NPV + INV}{INV} \tag{5}$$

Index of Profitability (IP)

The index of profitability is the ratio of the NPV plus the investment divided by the entire investment (INV), according to equation (5), as follows:

Index of Profitability (IP) decision criteria

A project will be viable if the value of IP is greater than one, which means that the INV has been recovered and something has been added to the company's equity.

If the IP is equal to one, the decision will depend on other aspects, because in such a case, only the recovery of the investment is guaranteed.

For results in which the IP is less than 1, the project is not viable, because the investment is not fully recoverable.

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2.4. Calculation Methodology

The calculations, from item 2.4.1 Feed rate up to item 2.4.12 total profit per day, are applied to the Tables 8 (Revenues and expenses using crude palm oil (*Elaeis guineensis*, Jacq) as raw material.) and Table 16 (Revenues and expenses using palm oil neutralizing sludge as raw material). Table 5 are presented the parameters used in the equations below.

Table 5. Process parameters used in the equations.

Process parameters	Value	Unit
M is the mass of palm oil	145.5	Kg
M is the mass of palm oil neutralizing sludge	145.5	Kg
N_{sh} is the number of shifts per day	3	-
N_{bat} is the number of batchs per shift using palm oil considering the feed rate	2	-
N_{bat} is the number of batchs per shift using palm oil neutralizing sludge considering the feed rate	1	-
d is the density of the palm oil	$0.97 . 10^{-3}$	kg/L
d is the density of the palm oil neutralizing sludge	$0.97 . 10^{-3}$	kg/L
Y_{oil} is the pyrolysis process yield of the bio-oil from the palm oil	63.6	%
Y_{oil} is the pyrolysis process yield of the bio-oil from the palm oil neutralizing sludge	71.37	%
Y_{coke} is the pyrolysis process yield of coke from the palm oil	8	%
Y_{coke} is the pyrolysis process yield of coke from palm oil neutralizing sludge	23.55	%
P_{coke} is the price of coke	0.30	US$/kg
d_{coke} is the coke density	1.10^{-3}	kg/L
Y_{gas} is the pyrolysis process yield of methane gas from the palm oil	28.4	%
Y_{gas} is the pyrolysis process yield of methane gas from the palm oil neutralizing sludge	0.48	%
P_{LPG} is the price of liquefied petroleum gas	0.503	US$/L
d_{gas} is the methane gas density	$0.72 . 10^{-3}$	kg/L
Y_{bio} is the distillated process yield of palm oil	60	%
Y_{bio} is the distillated process yield of neutralizing sludge	20	%
P_{RM} is the price of raw material of palm oil	0.23	US$/kg
P_{RM} is the price of raw material of the palm oil neutralizing sludge (it was considered 15% of the palm oil price)	0.0345	US$/kg
P_{cat} is the price of catalyst	0.52	US$/kg
C_m is the cost of manpower in thirty days	1562.5	US$/month
N_{bat} is the number of batchs per day to palm oil considering the distillation	5	-
N_{bat} is the number of batchs per day to palm oil neutralizing sludge considering the distil-lation	3	-
P_{KW} is the power of the distillation colum	5	KW
t is the distillation operation time during one day	24	h
P_{KWh} is the price of the KWh	0.2186	KWh
SP_{bio} is the sale price to the biofuels produced with palm oil or palm oil neutralizing sludge	1.34	US$/L
$\%NaCl$ is the percentage of sodium chloride in m/m	10	%
P_{NaCl} is the price of sodium chloride	0.005	US$/L
P_{deh} is the power of the dehydration equipment	5	KW
t_{deh} is the time of dehydration	1	h

2.4.1. Feed rate

$$Q = \frac{M \,.\, N_{sh} \,.\, N_{bat}}{d} \quad (6)$$

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Where Q is the volumetric flow rate of palm oil or palm oil neutralizing sludge [L/day], M the mass of palm oil or palm oil neutralizing sludge in [kg] per shift;

N_{sh} = number of shifts per day [-]; N_{bat} = number of batchs per shift using palm oil or palm oil neutralizing sludge [-]; d = density of the lipid material or açaí seed palm oil or palm oil neutralizing sludge in [kg/L].

2.4.2. Flow of Organic liquid product (OLP)

$$Q_{bio} = (\,Y_{oil}\ .\ Q\,)/100 \tag{7}$$

Q_{bio}= flow of liquid product organic (bio-oil) [L/day]; Y_{oil} = pyrolysis process yield of the bio-oil from the palm oil or palm oil neutralizing sludge in [%]; Q = flow of palm oil or palm oil neutralizing sludge [L/day].

2.4.3. Flow of Solid product (coke)

$$m_{coke} = \frac{(Y_{coke}\ .\ Q\ .\ P_{coke})}{100\ .\ d_{coke}} \tag{8}$$

m_{coke} = flow of coke [US$/day]; Y_{coke} = pyrolysis process yield of coke from the palm oil or palm oil neutralizing sludge in [%]; Q = flow of palm oil or palm oil neutralizing sludge in [L/day]; P_{coke} = price of coke [US$/kg]; d_{coke} = coke density [kg/L].

2.4.4. Flow of Gaseous product (Biogas)

$$m_{gas} = \frac{(Y_{gas}\ .\ Q\ .\ f2\ .\ P_{LPG}\ .\ f1)}{100\ .\ d_{gas}} \tag{9}$$

m_{gas} = flow of methane gas [R$/day]; Y_{gas} = pyrolysis process yield of methane gas from the palm oil or palm oil neutralizing sludge in [%]; Q = flow of palm oil or palm oil neutralizing sludge in [L/day]; P_{LPG} = price of liquefied petroleum gas [US$/L]; $f1$ = it was considered that the methane gas flow it is 10% of the Y_{gas} pyrolysis process yield of methane gas; $f2$ = it was considered that the price of the methane gas is 50% of the liquefied petroleum gas (L.P.G) [-]; d_{gas} = methane gas density [kg/L].

2.4.5. Flow of Distilled biofuel

$$D_{bio} = (\,Y_{bio}.\,Q_{bio})\ /\ 100 \tag{10}$$

D_{bio} = distillated biofuel [L/day]; Y_{bio} = distillated process yield palm oil or palm oil neutralizing sludge in [%]; Q_{bio} = flow of organic liquid product (bio-oil) [L/day].

2.4.6. Cost of Raw Material

$$C_{RM} = \frac{P_{RM}\ .\ Q}{d_{RM}\ .\ (D_{bio} + m_{coke} + m_{gas})} \tag{11}$$

C_{RM} = cost of raw material of palm oil or palm oil neutralizing sludge [R$/L]; P_{RM} = price of raw material of palm oil or palm oil neutralizing sludge (it was considered 15% of the palm oil price) in [US$/kg]; Q = flow of palm oil or palm oil neutralizing sludge in [L/day]; d_{RM} = density of the palm oil or palm oil neutralizing sludge in [kg/L].

2.4.7. Cost of Catalyst

$$C_{cat} = \frac{Q\ .\ d\ .\ P_{cat}\ .\ m_{cat}}{100\ .\ (D_{bio} + m_{coke} + m_{gas})} \tag{12}$$

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C_{cat} = cost of catalyst Na_2CO_3 in [R$/L]; P_{cat} = price of catalyst (0.52) [US$ / Kg]; m_{cat} = percent of catalyst in relation the feed rate (10% to palm oil and 15% to palm oil neutralizing sludge) in [%].

2.4.8. Cost of Liquefied petroleum gas (LPG)

$$C_{LPG} = \frac{Q\ .\ P_{LPG}\ .m_{LPG}}{(D_{bio}\ +\ m_{coke}\ +\ m_{gas})} \quad (13)$$

C_{LPG} = cost of liquefied petroleum gas in [US$/L];$P_{LPG}$ = price of liquefied petroleum gas (0.503) [US$/L]; m_{LPG} = percent of liquefied petroleum gas in relation the feed rate (10) for all raw materials [%].

2.4.9. Cost of Manpower

$$C_{MP} = \frac{C_m}{30\ .\ (D_{bio}\ +\ m_{coke}\ +\ m_{gas})} \quad (14)$$

C_{MP} = cost of manpower [US$/L]; C_m = cost of manpower in thirty days [US$/month].

2.4.10. Cost of Distillation (Heating)

The number of distillation columns depending the bio-oil produced in each pyrolysis process. It was considered 120 Kg per unit of distillation to the palm oil or palm oil neutralizing sludge.

$$D_c = \frac{N_{bat}\ .\ P_{KW}\ .\ t\ .\ P_{KWh}}{(D_{bio}\ +\ m_{coke}\ +\ m_{gas})} \quad (15)$$

D_c = distillation cost in [US$/L]; N_{bat} = number of batchs per day to palm oil or palm oil neutralizing sludge in [-]; P_{KW} = power of the distillation colum in [KW]; t = distillation operation time during one day in [h]; P_{KWh} = price of the KWh in [US$/KWh].

2.4.11. Tax

$$T = \frac{\%T\ .\ SP_{bio}}{100} \quad (16)$$

T = tax in [US$/L]; $\%T$ = percentage of tax in [%]; SP_{bio} = sale price to the biofuels produced with lipid material and açaí seed [US$/L];

2.4.12. Total profit per day

$$TP = D_{bio}\ .\ (SP_{biol} - TE)\ +\ m_{coke}\ +\ m_{gas} \quad (17)$$

TP = total profit per day [US$/day]; D_{bio} = distillated biofuel [L/day]; SP_{biol} = sale price of biofuel [US$/L]; TE = total expenses [US$/L];

2.4.13. Cost of Decant (NaCl_10%)

This calculation is applied only to the Table 5.16 (Revenues and expenses using palm oil neutralizing sludge as raw material).

$$C_{NaCl} = \frac{\%NaCl\ .\ Q\ .\ P_{NaCl}}{(D_{bio} + m_{coke} + m_{gas})} \quad (19)$$

C_{NaCl} = cost of sodium chloride [US$ / L]; $\%NaCl$ = percentage of sodium chloride (10) in m/m [%]; P_{NaCl} = price of sodium chloride (0.005) [US$ / L].

2.4.14. Dehydration

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This calculation is applied to the Table 5.9 (Revenues and expenses using palm oil neutralizing sludge).

$$C_{deh} = \frac{P_{deh} \cdot f_{KWh} \cdot t_{deh} \cdot N_{deh} \cdot P_{kwh}}{(D_{bio} + m_{coke} + m_{gas})} \quad (2018)$$

C_{deh} = cost of dehydration [US$/L]; P_{deh} = power of the boiler in [cal]; f_{KWh} = factor of conversion from calories (cal) to KWh in [KWh/cal]; t_{deh} = time of dehydration per batch [h]; N_{deh} = number of dehydration batch per day [-]; P_{KWh} = price of the KWh in [US$/KWh].

3. Results

3.1. Palm oil (Elaeis guineensis, Jacq)

The results presented is this work were the pyrolysis of the crude palm oil with 10% of catalyst (Na_2CO_3) accomplished in pilot unit. The results presented by MOTA (2013) on yields related to pyrolysis and distillation, are shown in Table 6. An important point to note is that only an estimated value of the distillation yield is shared due to problems encountered during the pilot unit distillation experiments (the results of yield distillation used was around 65% to the stand experiments according MOTA (2013).

Table 6. Yields results of the pyrolysis and distillation process using crude palm oil (*Elaeis guineensis*, Jacq) MOTA (2019).

Availability pyrolysis	75%
Organic Liquid Product / Bio-oil	63.6%
Solid product (coke)	8%
Gaseous product (Biogas)	28.4%
Distillation yield	60%

Table 7 presents the results of the crude palm oil characterization used as raw material in the pyrolysis pilot unit. The results indicate a suitable product.

Table 7. Results of the physicochemical characterization of the crude palm oil used as raw material.

Properties	Crude palm oil Na_2CO_3 (10%)
Density [g/cm³]	0.95
Kinematic viscosity [cSt]	2.90
Acidity index [mg KOH / g]	8.98
Saponification index [mg KOH / g]	9.19
Ester index [mg KOH / g]	0.21
Free fatty acids – AFF [%]	4.51
Refractive index	1.45
Melting point [ºC]	19.10
Corrosiveness	1A
Water and Sediment [%]	*
Carbon residue [%]	0.73

Source: MOTA (2013).

Regarding the biofuels products from the distillation, it has been determined quantitatively the compounds contents of the fraction similar of the biogasoline (fraction

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40ºC – 175ºC). Table 8 presents the mains substances existing in the gasoline product, which are the hydrocarbons and oxygenated. Among the identified and quantified hydrocarbons are normal paraffinic, branched paraffinic, naphthenic, aromatics and olefins, which are the main components also present in distillation fractions of petroleum according to SZKLO & ULLER (2008) and FARAH (2012). Table 8 shows that the hydrocarbons correspond to 52.76 % and the oxygenated compounds correspond to 47.24 %. These results are in agreement with SZKLO & ULLER (2008).

Table 8. Chemical compositional analysis of the fraction of 40ºC - 175ºC (biogasoline) regarding the content of oxygenated and hydrocarbons.

Compounds	**Content [%]**
Hydrocarbons	**52.76**
Normal paraffins	15.78
Branched paraffins	0
Naphthenico	3.50
Aromatics	1.94
Olefíns	31.54
Oxigenated compounds	47.24
Others	47.24

Source: MOTA (2013).

Table 9 presents the chemical compositional analysis of the fraction of 175ºC - 235ºC (biokerosene) regarding the content of oxygenates and hydrocarbons. It is possible to affirm that the biokerosene it is composed by the presence of hydrocarbons aromatics, normal paraffinic, naphthenic and mainly olefins, besides these there are oxygenated compounds, which the percentage of hydrocarbons and of oxygenated correspond to 86.37 % and 13.63 %, respectively.

Table 9. Chemical compositional analysis of the fraction of 175ºC - 235ºC (biokerosene) regarding the content of oxygenated and hydrocarbons.

Compounds	**Content [%]**
Hydrocarbons	**86.37**
Normal paraffins	19.48
Branched paraffins	0
Naphthenico	19.63
Aromatics	7.04
Olefíns	40.22
Oxygenated compounds	**13.63**
Others	13,63

Source: MOTA (2013).

Table 10 presents the results related with the distillation fraction from 235ºC - 305ºC which corresponds to green diesel. It has been identified a mixture rich in hydrocarbons as mainly normal paraffins and olefins. The total percentage of hydrocarbons correspond to 91.38 % and oxygenated 8.62 %.

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Table 10. Chemical compositional analysis of the fraction of 175ºC - 235ºC (green diesel) regarding the content of oxygenated and hydrocarbons.

Compounds	**Content [%]**
Hydrocarbons	**91.38**
Normal paraffins	31.27
Branched paraffins	0
Naphthenico	5.67
Aromatics	0
Olefíns	54.44
Oxygenated compounds	**8.62**
Others	8.62

Source: MOTA (2013).

Table 11 presents the results related with the distillation fraction from 305ºC - 400ºC which corresponds to heavy diesel. It has been identified a mixture rich in hydrocarbons as mainly normal paraffins and olefins. The total percentage of hydrocarbons correspond to 70.78 % and oxygenated 29.22 %. These results are in agreement with FARAH (2012).

Table 11. Chemical compositional analysis of the fraction of 305ºC - 400ºC (heavy diesel) regarding the content of oxygenated and hydrocarbons.

Compounds	**Content [%]**
Hydrocarbons	**70.78**
Normal paraffins	25.30
Branched paraffins	0
Naphthenico	9.64
Aromatics	0
Olefíns	35.84
Oxygenated compounds	**29.22**
Others	29.22

Source: MOTA (2013).

- Results of the economic feasibility analysis of the palm oil (*Elaeis guineensis*, Jacq) used as raw material

Table 12 presents the economic parameters for discounted cash flow analysis. The total project investment is US$ 79.791,36 (seventy-nine thousand seven hundred and ninety- one dollars and thirty six cents) and corresponds to the initial investment of the cash flow.

Table 12. Economic Parameters for Discounted Cash Flow Analysis.

Plant life	5	years
Plant size / biomass feed rate (palm oil, neutraling sludge) respectively.	900; 450	L/day
Discount rate	10	% per year
Financing	100	% equity
Plant recovery period	5	years
Federal tax rate	10	%
Feedstock cost (palm oil, neutraling sludge) respectively.	0.23; 0.034	US$ / L

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Availability (palm oil, neutraling sludge)	75; 56.25	%
On stream time	6.570; 4860	h
Reference year	2021	
Electricity price	0.2186	US$ / KWh
Total purchased equipment costs (TPEC)	26.901,37	US$
Direct costs (including equip installation, instruments and controls, piping electrical and misc. buildings)	16.409,83	US$ (61% TPEC)
Total installed equipment cost (TIEC)	43.311,20	US$ (61% TPEC + TPEC)
Warehouse	649,67	US$ (1,5% TIEC)
Site development	1.949,00	US$ (4,5% TIEC)
Total installed cost (TIC)	45.909,87	US$ (TIEC + warehouse + site development)
Indirect Field Costs (IFC)		
- field expenses	9.181,97	US$ (20% TIC)
- home office & construction fee	11.477,47	US$ (25% TIC)
- Project contingency	1.377,30	US$ (3% TIC)
- prorateable costs	4.590,99	US$ (10%TIC)
Total capital investment (TCI)	72.537,60	US$ (TIC + IFC)
Other costs (startup, permits, etc.)	7.253,76	US$ (10% TCI)
Total Project Investment (TPI)	79.791,36	US$ (TCI+ Other costs)

Note: This is the same base of SPATH AND SAYTON (2003).

Table 13 presents the total revenue, total expense and the annual profit of US$ 25.172,0 (twenty-five thousand one hundred and seventy-two dollars) per year. The minimum fuel selling price (MFSP) obtained is this work for the biofuels was 1.34 US$ / L (this is currently practiced in Brazil). The literature mentioned in this work presents values of 0.68 up to 0.98 US$ / L.

Table 13. Revenues and expenses of using crude palm oil (*Elaeis guineensis*, Jacq) as raw material.

Revenue		
Feed rate_75% (Availability)_Cracking	900.00	L/day_d = 0,97 kg/m³
Organic Liquid Product / Bio-oil_63,6% (1)	572.40	L/day (feed distilled)
Solid product (coke)_8% (2)	21.80	US$/day
Gaseous product (Biogas)_28,4% (3)	8.93	US$/day
Distilled biofuel_60% (4)	343.4	L/day
Sale price of biofuel (5)	**1.340**	US$/L
Total expenses (6) = (7)+(8)+(9)+(10)+(11)+(12)	1.23	US$/L
Raw material (palm oil) (7)	0.470	US$/L
Catalyst_ 10% (8)	0.104	US$/L
Liquefied petroleum gas (LPG)_10% (9)	0.103	US$/L
Manpower (10)	0.12	US$/L
Distillation (Heating)_5 KW (11)	0.297	US$/L
Federal tax rate 10% (12)	0.134	US$/L
Profit margin (13) = (5) - (6)	0.11	US$/L
Total profit per day	69.9	US$/day
Total profit per month	2.097,7	US$/month
Total profit per year	25.172,0	US$/year

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Table 14 shows the cash flow for the investment analysis through the simple payback criterion. It can be concluded that in the fourth year, the investment is fully recovered, totaling US$ 20.896,53 (twenty thousand eight hundred ninety-six dollars and fifty-three cents). In this case, the project is considered economically viable within the horizon of analysis of 5 years.

Table 14. Annual cash flow for the crude palm oil (*Elaeis guineensis*, Jacq) and simple payback analysis.

Year	0	1	2	3	4	5
Cash Flow	-79.791,36	25.171,97	25.171,97	25.171,97	25.171,97	25.171,97
Accumulated Value	-79.791,36	-54.619,39	-29.447,42	-4.275,44	20.896,53	46.068,50

Table 15 shows the cash flow for the investment analysis considering the discounted payback criterion. It can be concluded that in the fourth year, the investment is fully recovered. The cash flow discount rate was 10% p.y. In this case, the project is considered economically viable because 5 years is considered analysis horizon of this project.

Table 15 shows the cash flow for the investment analysis considering the net present value (NPV) criterion. It can be concluded that in the fifth year, there is a capital increase of US$ 15.630,22 (fifteen thousand six hundred and thirty dollars and twenty-two cents) of profit. The cash flow discount rate was 10 % p.y. In this case, the project is considered economically viable because the net present value is positive within the horizon of analysis of 5 years.

Table 15 shows the cash flow for the investment analysis considering the internal rate return (IRR) criterion. It can be concluded that in the fourth year, the accumulated is zero, which represents the IRR of the project as 10,0 % p.y. In this case, the IRR is equal than the minimum attractiveness of the project (10% p.y), which means that the project is economically viable. THILAKARATNE et al., (2014) obtained a minimum fuel selling price (MFSP) of $3.69 per gal (0.98 R$ / L) is estimated assuming 10% internal rate of return.

Table 15 shows the cash flow for the investment analysis considering the profitability index. Using equation (5) and the data from Table 15**,** it is possible to obtain the value of 1,2 (index of profitability). It means that for each dollar invested in the project a return of 1,2 dollars it will occur, within the analysis horizon of 5 years. According to the criteria of this index, the project is considered economically viable.

Table 15. Annual cash flow for the crude palm oil (*Elaeis guineensis*, Jacq) and discounted payback analysis, net present value (NPV) analysis, internal rate of return (IRR) analysis and profitability index analysis.

Year	0	1	2	3	4	5
Cash Flow	-79.791,36	25.171,97	25.171,97	25.171,97	25.171,97	25.171,97
Present value	-79.791,36	22.883,61	20.803,28	18.912,08	17.192,80	15.629,81
Accumulated Value	-79.791,36	-56.907,75	-36.104,47	-17.192,4	0	15.630

Figure 6 corresponds of the sensitivity analysis for 900 L /day, to reach the baseline transportation fuel MFSP of $1.34 / L, the 10% facility IRR is assumed. It is clear that the distillation yield and bio-oil yield are the most significative variable that affect the MFSP. These results are in agreement with BROWN et al., (2013).

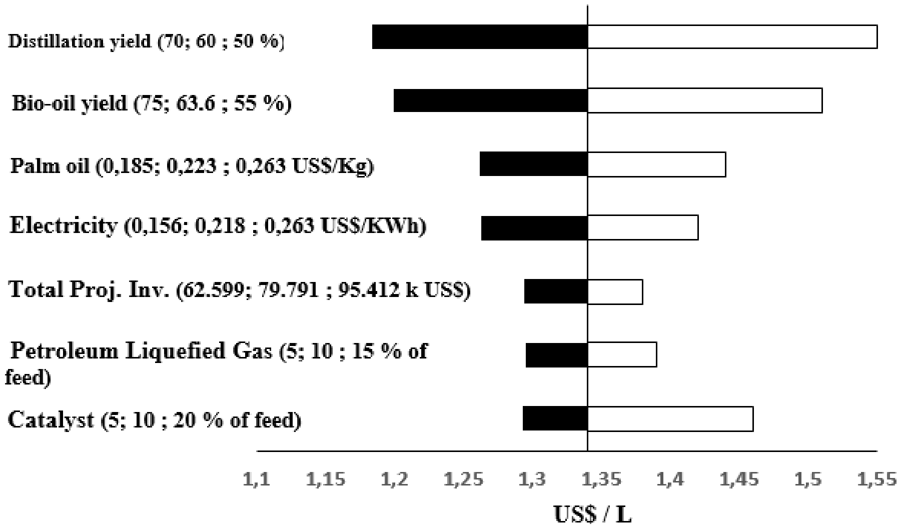

Figure 6. Sensitivity analysis for 900 L /day, to reach the baseline transportation fuel MFSP of $1,34 / L, the 10% facility IRR is assumed.

Operation cost, payback period (PBP) and break even analysis is used to investigate the relationships between the planned project cost and the rate of return. The breakeven point (BEP) is the point at which total cost and total revenue are equal, which means there is a balance of the profit and loss (JAROENKHASEMMEESUK and TIPPAYAWONG, 2015). Table 5.1 presents the cash flow in which the total cost is equal the total revenues and corresponds to nil in the fifth year of cash flow. The value of MFSP obtained was of 1.30 US$ / L.

3.2. Palm oil neutralizing sludge

The results presented is this work were from the pyrolysis of the palm oil neutralizing sludge with 15% of catalyst (Na_2CO_3) at 440ºC (Experiment 5) accomplished in pilot unit. The results presented by SANTOS (2015) of yields related to pyrolysis and distillation are shown in Table 16. One important point to consider is that the pyrolysis availability of 56.25% is low. This occurs because of the high reaction time in the pyrolysis reactor, which results in a low feed rater.

Table 16. Yields results of the pyrolysis and distillation process using palm oil neutralizing sludge, SANTOS (2015).

Pyrolysis Availability	56.25%
Organic Liquid Product / Bio-oil	71.37%
Solid product (coke)	23.55%
Gaseous product (Biogas)	0.48%
Distillation yield	20%

Table 17 presents the physicochemical characteristics of the organic liquid product (bio-oil) of the palm oil neutralizing sludge after the cracking process. These results are compared with the National Agency of Petroleum, Biofuels and Natural Gas of Brazil (ANP).

According to the results presented in Table 17, it was found that the density and viscosity results were close to the established by ANP standard (values below the norm

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may be due to the presence of smaller hydrocarbon chains, which means light compounds). The carbon residue value was above the specified value, however, the increase in this value is expected since the bio-oil have not only hydrocarbon compounds, but also fatty materials, catalyst residue and unsaponifiables from the raw material, which contribute to increase the value of the carbon residue of these samples. The corrosivity values for the copper sheet were in accordance with the ANP standard, characterizing the bio-oil with low capacity to cause corrosion in metallic parts (SANTOS, 2015).

Table 17. Physicochemical characteristics of the organic liquid product (bio-oil) of the palm oil neutralizing sludge after the cracking process.

Characteristics	Exp. 5	Diesel S10 (ANP Nº65)
Acidity index [mg KOH / g]	1.07	Note
Refractive index	1.45	-
Saponification index [mg KOH / g]	27.52	-
Kinematic viscosity [cSt]	1.90	2,0 – 4,5
Density [g/ mL]	0.8	0,82 – 0,85
Corrosiveness	1	1
Melting point [ºC]	>71	38 minimum
Carbon residue [%]	0.466	0,25 (máximo)
Yield of bio-oil* (%)	71.37	-
Sulphur content	24	10 ppm (max)
Color	4	3 (max)
Aspect	Approved	Not approved**

Source: SANTOS (2015).

* Yield obtained in dry basis (without the water mass generated in the process).

** Clear and free from impurities.

Table 18 presents the percentage composition of hydrocarbons and oxygenated compounds of the bio-oil of the experiment 5. Analyzing the results presented in the Table 13, an effective deoxygenation of organic liquid products resulting from the pyrolysis reaction with the use of sodium carbonate catalyst was found, indicated by the high percentage of hydrocarbons with the percentage of 91.22 %, as well as the low percentage of oxygenated compounds (8.78%). The main hydrocarbons present in the petroleum diesel are alkanes, olefins, naphthenics and aromatics (SZKLO and ULLER, 2008).

Table 18. Composition of the Liquid organic product (bio-oil) – Experiment 5 (15% of Na_2CO_3), using the neutralizing sludge as raw material.

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Compounds	Composition [%] of Bio-oil
Hydrocarbons	**91.22**
Paraffins	30.75
Olefíns	53.72
Naphthenicos	4.5
Aromatics	2.25
Oxygenated compounds	**8.78**
Alcohols	2.27
Ketones	5.34
Ether	1.17

Source: SANTOS (2015).

The distillation of the organic liquid product from experiment 5 was carried out on a pilot scale using a distillation column in order to obtain cur-off fractions in the range of gasoline (biogasoline) (40 ºC - 175 ºC) and kerosene (biokerosene) (175º C – 235 ºC). The physicochemical characteristics of the biofuels obtained after distillation on pilot scale are present in Table 19.

The results obtained for the acidity index in Table 19 also demonstrated relatively low values when compared to the distilled fractions of organic liquid products (bio-oils) from oilseeds. The corrosivity values to the copper sheet of this fractions were considered as having low corrosive capacity in metallic parts. The results of density and viscosity parameters for the biogasoline and biokerosene were lower than the S10 diesel specified by ANP Nº 65. This behavior occurs due to the composition of these fractions being formed from smaller hydrocarbon chains (approximate chains of $C_4 – C_{12}$). The results of the sulfur content of the biogasoline fraction had a content close to the that of mineral diesel S10. However, when comparing it with the sulfur content of common Type A biogasoline established by ANP Nº 57, whose value is 800 ppm, a low sulfur content of the biogasoline fraction was found in relation to commercial Type A gasoline (SANTOS, 2015).

Table 19. The physicochemical characteristics of the biofuels obtained after distillation on pilot scale (Experiment 5) - fractions of biogasoline (40 ºC – 175 ºC) and biokerosene (175 ºC – 235 ºC).

Characteristics	Light fractions		Residue	Diesel S10 (ANP Nº65)
	(40 – 175ºC)	(175ºC – 235ºC)	-	Note
Acidity Index [mg KOH / g]	3.489	4.046	5,52	2.0 – 4.5
Viscosity [cSt]	0.14	0.17	5.52	2.0 – 4.5
Density [g/ mL]	0.74	0,76	0.85	0.82 – 0.85
Corrosiveness	1	1	1	1
Flash point [ºC]	37	22	81	38 minimum

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Sulphur content [ppm]	16			10 [max]
Color	1	-	-	3 [max]
Aspect	Approved			Approved*
Carbon residue**	1.3	-	-	0.25 [max]

Source: SANTOS (2015).

* Clear and free from impurities.

** Obtained with 10 % ends of the curve of distillation.

Table 20 shows the percent hydrocarbon composition of gasoline (40 ºC – 175 ºC) obtained in the pilot scale distillation of the organic liquid product (bio-oil) from Experiment 5 (15 % Na_2CO_3 at 440 ºC). According to the results, all components of this biogasoline were hydrocarbons constituted mainly by olefins (51.09 %) and paraffinic (34,64 %). Aromatic and naphthenic hydrocarbons showed low percentages. The composition of aromatic hydrocarbons in this fraction was found in accordance with the specification of ANP Nº 57 (2011) for type C gasoline derived from petroleum, which establishes a maximum percentage of 45 % (v/v) for aromatics, however, the amount of olefins showed a result above the stipulated maximum of 30 % (v/v). It is suitable highlight that this percentage value of the maximum contents of aromatic and olefinic hydrocarbons must be met after adding anhydrous ethanol to automotive gasoline, as recommended by ANP Nº 57 (2011).

Table 20. Chemical compositional analysis of the fraction of 40ºC - 175ºC (biogasoline) regarding the content of oxygenated and hydrocarbons.

Compounds	Composition [%]
Paraffins	34.64
Olefíns	51.09
Aromatics	5.85
Naphthenicos	8.42
Total de Hidrocarbonetos	100

Source: SANTOS (2015).

Table 21 presents the analysis of the revenues and expenses using the palm oil neutralizing sludge in the pyrolysis and distillation processes. The low availability of the cracking reactor due to the high reaction time negatively affects the profit margin, as demonstrated below. Another negative aspect is the low yield at the distillation stage, which results in low biofuel production.

Table 21. Revenues and expenses for using palm oil neutralizing sludge as raw material.

Revenue		
Feed rate_56.25% (Availability)_Cracking	450.00	L/day_
Organic liquid product (Bio-oil) _71.37% (1)	321.17	L/day (feed distilled)
Solid product (coke)_23.55% (2)	23.80	US$/day
Gaseous product (Biogas)_0.48% (3)	2.96	US$/day
Distilled biofuel _20% (4)	64.2	L/day
Sale price of biofuel (5)	1.34	US$/L

Total expenses (6) = (7)+(8)+(9)+(10)+(11)+(12)+(13)+(14)	1.47	US$/L
Raw material (palm oil neutralizing sludge)_15% (7)	0.086	US$/L
Decant (NaCl_10%) (8)	0.003	US$/L
Dehydration _5 KW (9)	0.012	US$/L
Catalyst _ 15% (10)	0.481	US$/L
Liquefied petroleum gas (LPG)_10% (11)	0.100	US$/L
Manpower (12)	0.216	US$/L
Distillation (Heating)_5 KW (13)	0.435	US$/L
Federal tax rate_10% (14)	0.134	US$/L
Profit margin (15) = (5) - (6)	-0.12	US$/L

4. Conclusions

Starting from the feasibility project criteria indicators, it is possible to confirm the termocatalytic cracking project feasibility of the crude palm oil to the production of biofuls, coke and mathane gas.

The availability used for the project evaluation criteria with the crude palm oil was of 75%. This means that for each shift of 8h of work 2h it will be used to load and unload the equipment. With this, the results of the project´s evaluation indicators can be all improved, starting from the optimization of the pilot plant availability.

Considering the viable process (palm oil raw material), the minimum fuel selling price (MFSP) obtained is this work for the biofuels was 1.34 US$ / L (this is currently practiced in Brazil). The literature mentioned in this work presents values from 0.68 up to 0.98 US$ / L.

Considering the viable process (palm oil raw material) it was obtained the IRR of the project as 10 % p.y. In this case, the IRR is equal the minimum attractiveness of the project (10% p.y), which means that the project is economically viable. THILAKARATNE et al., (2014) obtained 10% internal rate of return.

Sensibility analysis demonstrated the pyrolysis yield and distillation yield are the parameters that most affect the MFSP. The break even point obtained it was of 1.30 US$ / L.

As a result, the unfeasibility of the project with the neutralizing sludge of crude palm oil was obtained, mainly due to the long cracking time per batch (resulting in low cracking plant availability 56.25%) and also due to the low yield of the bioifuels produced in distillation (around 20%).

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