

Disclaimer/Publisher's Note: The statements, opinions, and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions, or products referred to in the content.

## Article

# Economic Analysis of Thermal Catalytic Process of Palm Oil (*Elaeis Guineensis*, Jacq) and Soap Phase Residue of Neutralization Process of Palm Oil (*Elaeis Guineensis*, Jacq)

Anderson Rocha Amaral<sup>1</sup>, Lucas Pinto Bernar<sup>2</sup>, Caio Campos Ferreira<sup>2</sup>, Anderson Mathias Pereira<sup>1</sup>, Wanderson Gomes dos Santos<sup>1</sup>, Lia Martins Pereira<sup>1</sup>, Marcelo Costa Santos<sup>1</sup>, Fernanda Paula da Costa Assunção<sup>2</sup>, Neyson Martins Mendonça<sup>3</sup>, José Almir Rodrigues Pereira<sup>3</sup>, Sílvio Alex Pereira da Mota<sup>4</sup>, Andréia de Andrade Mâncio<sup>4</sup>, Sergio Duvoisin Jr.<sup>5</sup>, Luiz Eduardo Pizarro Borges<sup>6</sup>, Nélio Teixeira Machado<sup>1,2,3\*</sup> and Douglas Alberto Rocha de Castro<sup>7</sup>

<sup>1</sup> Graduate Program of Natural Resources Engineering of Amazon, Campus Profissional-UFPA, Universidade Federal do Pará, Rua Augusto Corrêa N° 1, Belém 66075-110, Brazil: [arochaamaral@hotmail.com](mailto:arochaamaral@hotmail.com) (A.R.A.); [wandersonq@hotmail.com](mailto:wandersonq@hotmail.com) (W.G.d.S); [lucas.bernar7@gmail.com](mailto:lucas.bernar7@gmail.com) (L.P.B.); [caiocf7@hotmail.com](mailto:caiocf7@hotmail.com) (C.C.F.); [andersonpereira@ufam.edu.br](mailto:andersonpereira@ufam.edu.br) (A.M.P.); [liapereira@ufpa.br](mailto:liapereira@ufpa.br) (L.M.P.); [marcelo.santos@ufpa.edu.br](mailto:marcelo.santos@ufpa.edu.br) (M.C.S.)

<sup>2</sup> Graduate Program of Civil Engineering, Campus Profissional-UFPA, Universidade Federal do Pará, Rua Augusto Corrêa N° 1, Belém 66075-110, Brazil: [fernanda.assuncao.itec@gmail.com](mailto:fernanda.assuncao.itec@gmail.com) (F.P.d.C.A.);

<sup>3</sup> Faculty of Sanitary and Environmental Engineering, Campus Profissional-UFPA, Universidade Federal do Pará, Rua Corrêa N° 1, Belém 66075-900, Brazil: [neysonmm@ufpa.br](mailto:neysonmm@ufpa.br) (N.M.M.); [rpereira@ufpa.br](mailto:rpereira@ufpa.br) (J.A.R.P.)

<sup>4</sup> Graduate Program of Chemistry, Universidade Federal do Sul e Sudeste do Pará, Folha 31, Quadra 7, Lote Especial - Nova Marabá, CEP: 68.507.590, Marabá/PA, Brasil: [silviomota@unifesspa.edu.br](mailto:silviomota@unifesspa.edu.br) (S.A.P.d.M.); [lucas.bernar7@gmail.com](mailto:lucas.bernar7@gmail.com) (A.d.A.M.);

<sup>5</sup> Faculty of Chemical Engineering, Universidade do Estado do Amazonas-UEA, Avenida Darcy Vargas N°. 1200, Manaus 69050-020, Brazil: [sjunior@uea.edu.br](mailto:sjunior@uea.edu.br) (S.D.Jr.)

<sup>6</sup> Laboratory of Catalyst Preparation and Catalytic Cracking, Section of Chemical Engineering, Instituto Militar de Engenharia-IME, Praça General Tibúrcio N°. 80, Rio de Janeiro 22290-270, Brazil: [luiz@ime.eb.br](mailto:luiz@ime.eb.br) (L.E.P.B.)

<sup>7</sup> Centro Universitário Luterano de Manaus – CEULM/ULBRA, Avenida Carlos Drummond de Andrade N°. 1460, Manaus 69077-730, Brazil: [douglascastro87@hotmail.com](mailto:douglascastro87@hotmail.com) (D.A.R.d.C.)

\* Correspondence: [machado@ufpa.br](mailto:machado@ufpa.br); Tel.: +55-91-984-620-325

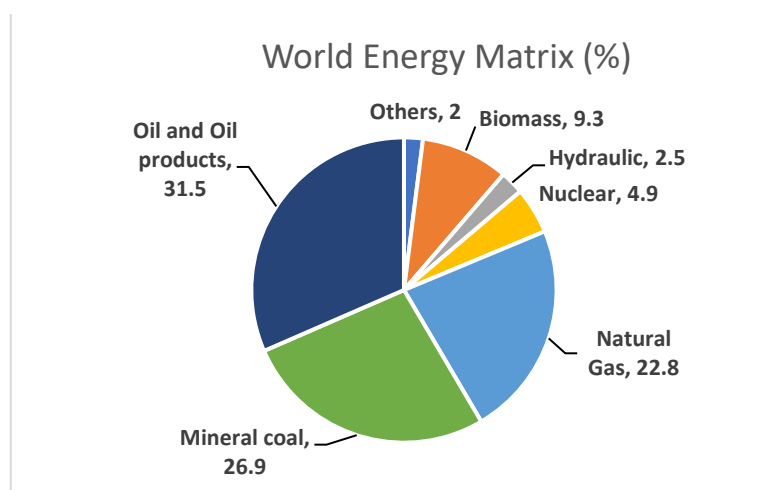
**Abstract:** Palm oil is, from an economic, environmental, and social point of view, the vegetable oil with great potential, and the State of Pará-Brazil, Brazilians great producer. In addition, a soap phase residue or palm oil neutralizing sludge (PONS), a by-product of the neutralization step of chemical refining of palm oil, produced, posing a huge problem of waste disposal and management in the production process of refined palm oil (RPO). In this context, this work aims to investigate systematically the economic analysis of thermal catalytic process of crude palm oil (CPO) and palm oil neutralizing sludge (PONS). The thermo-catalytic processes of CPO and PONS carried out in pilot scale and their economic feasibility analyzed. The yields of biofuels produced by fractional distillation were also presented. The physicochemical properties of CPO and PONS, as well as those of organic liquid products obtained by thermal catalytic process of CPO and PONS were taken into account in the economic analysis. In addition, the chemical composition organic liquid products obtained by thermal catalytic process of CPO and PONS, as well as its distillation fractions (green-gasoline, green-kerosene, green light-diesel and heavy-diesel), used as key factors/indicators on the economic analysis. The analysis of the key factors/indicators by thermo-catalytic processes of CPO and PONS showed economic viability for both crude palm oil (*Elaeis guineensis*, Jacq) and palm oil neutralization sludge. The minimum fuel selling price (MFSP) obtained in this work for the biofuels was 1.59 US\$/L using crude palm oil (CPO) and 1.34 US\$/L using palm oil neutralizing sludge (PONS). The best breakeven point obtained was of 1.24 US\$/L considering the PONS. The sensibility analysis demonstrated that the pyrolysis and distillation yields are the most important variables to affect the minimum fuel-selling price (MFSP) in both economic analysis.

**Keywords:** Palm oil; Palm oil neutralizing sludge, Thermal-catalytic process; Biofuels; Economic analysis; Technical feasibility.

## 1. Introduction

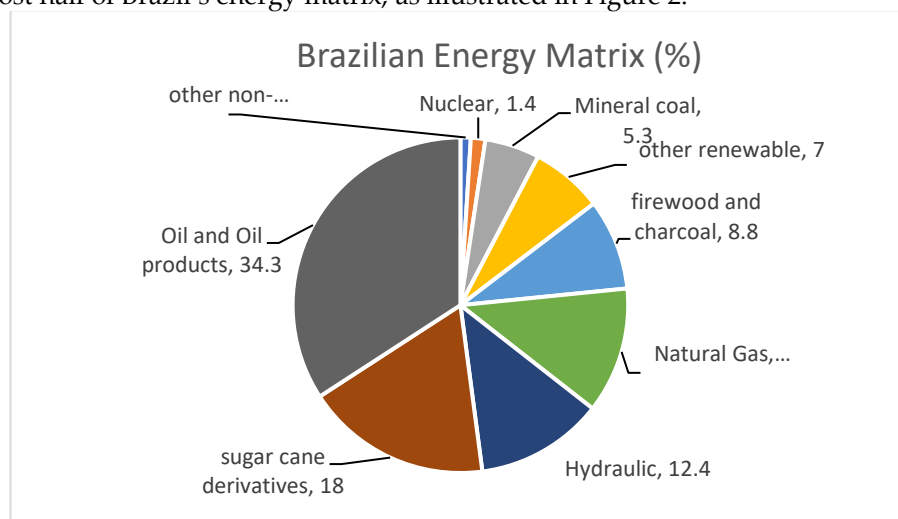
The Needs for energy of modern consuming society has grown tremendously in the last decades. Energy is used to run industrial processes, for domestic consumption in homes, for transportation, and for various other purposes. This energy, coming from different sources, form a system referred to as *energy matrix*. The *energy matrix* represents all the sources available in a country, state, or in the world, to supply the need (demand) for energy [1].

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 [1]. Renewable sources such as solar, wind, and geothermal energy, account for only 2.0% of the world energy matrix (marked as "others" in the pizza graph of Figure 1). Combined with hydraulic energy and biomass, only about 14.0% of the global energy sources are renewable.



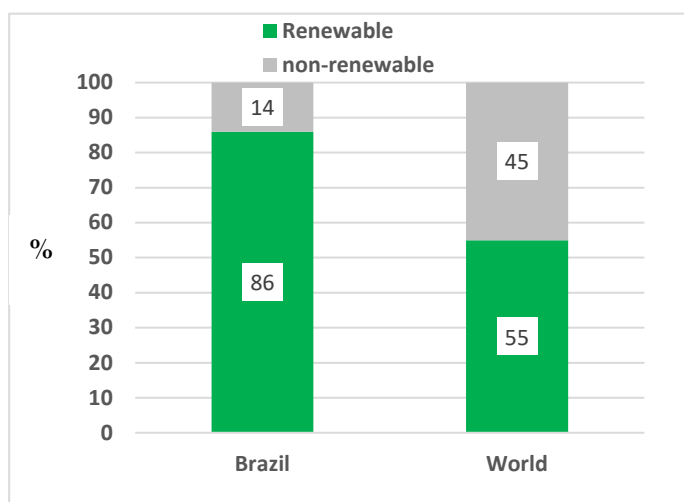
**Figure 1.** World Energy Matrix 2018 [1].

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, account for 46.2%, or almost half of Brazil's energy matrix, as illustrated in Figure 2.



**Figure 2.** Brazilian *energy matrix* 2019 [1].

Brazil's consumption of renewable energy is higher than the rest of the world's renewable energy consumption, as shown in Figure 3.



**Figure 3.** Percentage of renewable and non-renewable sources in Brazil and in the world [1].

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 [1].

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 [2]. 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.

In the last years, several works investigated the economic feasibility assessment of biofuel production using biomass as raw material (such as palm oil) and residues (such as palm oil neutralizing sludge), through the pyrolysis and distillation process. A summary of the most recent studies reported in the literature on techno-economic evaluation is presented synthetically as follow.

Abnisa *et al.* [3], presented a study of bio-oil production by pyrolysis using palm shell as feedstock, in a fluidized-bed reactor at 400, 500, 600 and 800 °C and with N<sub>2</sub> carrier gas at 1, 2, 3, 4 and 5 L/min. In order to optimize the palm shell production, it was studied the effects of temperature, flow rate of N<sub>2</sub>, particle size and reaction time. The maximum yield of bio-oil obtained was 47.3 wt.% (500 °C, 2 L/min of N<sub>2</sub> flow, 60 minutes reaction time). The most important parameter it was the temperature over the bio-oil yield.

Abnisa *et al.* [4], investigated the production of bio-oil and bio-char using the three palm oil residues by pyrolysis, in a fixed-bed reactor at 500 °C, N<sub>2</sub> flow rate of 2 L/min and reaction time of 60 min. The yields obtained of bio-oil production was 16.58-43.50 wt.% and of bio-char was 28.63-36.75 wt.%. These results are affected by the cellulose, hemicellulose, volatiles, fixed carbon and ash in the samples. The energy density of the bio-char was found to be higher than that of the bio-oil. The highest energy density of the bio-char was obtained from a palm leaf sample (23.32 MJ/kg), while that of the bio-oil was obtained from a frond sample (15.41 MJ/kg).

Do *et al.* [5], presented a study of bio-oil production using empty fruit bunches (EFB) as feedstock, a main residue of the palm oil industry, via fast pyrolysis, in a fluidized-bed reactor. It was used a model to the commercial process simulations. The total capital investment (TCI) was estimated for five different plant sizes. The EFB bio-oil plant was analyzed in terms of the specific capital cost (SCC), payback period (PBP), return on investment (ROI), and the product value (PV). The minimum profitable plant size was found to

be 20 kton-dry EFB/yr at a PV of 0.47 \$/kg of bio-oil including 39% of water. Sensitivity analysis demonstrated that the plant size and the bio-oil yield are major influence on the PV. In the most optimistic scenario investigated in this study, bio oil can be produced at a PV of 0.27 \$/kg.

Moncada *et al.* [6], presented a study of biodiesel, ethanol and poly-3-hydroxybutyrate production by a bio refinery based palm oil, evaluating the techno-economic and environmental aspects. The configuration with the best economic and environmental performance was the multiproduct portfolio plus mass integration. For this case, the obtained economic margin was 64.5% (1.33 fold higher than standalone ethanol production), the potential environmental impact (PEI) was 156.42 PEI/t products and 0.51 t CO<sub>2</sub> eq/m<sup>3</sup> of biodiesel. On the other hand, the feedstock transportation was included to measure the influence on economics and carbon footprint indicator. For a travelled distance of 300 km, the economic margin is decreased to 1.31%, and the carbon footprint increased up to 0.59 t CO<sub>2</sub> eq/m<sup>3</sup> of biodiesel for scenario 4.

Peryoga *et al.* [7], investigated the bio-oil production using the empty fruit bunch (EFB) as feedstock by pyrolysis. Production cost assessment was based on palm oil mill of 30 metrics tons FFB/h capacity (that produced EFB residue at app. 20 wt.% of the initial FFB fed to the plant). The process included in this calculation is chopping, drying, grinding, pyrolysis, solid removal, bio-oil recovery, and storage. The sensitivity analysis shows that feedstock price drives the production cost. The result demonstrated that the bio-oil production cost, from palm empty fruit bunch, seems promising to be implemented in Indonesia. The best option is to have the bio-oil plant integrated with the palm oil mill, where in this case the EFB can be kept at no cost.

Mabrouki *et al.* [8], investigated the biofuel production using three palm oil residues, namely palm shell (PS), empty fruit bunch (EFB) and mesocarp fiber (MF), by a process simulator called SuperPro Designer (SPD). The simulation includes pretreatment, fast pyrolysis, product collection, and upgrading sections. The results were validated with literature data of wood oak in fluidized-bed reactor. The maximum bio-oil production was obtained at 550 °C. Comparison of the different residues indicates that the higher yield of liquid fraction was obtained from the EFB and MF while pyrolysis of the PS produced a higher yield of char.

Thangalazhy-Gopakumar *et al.* [9], studied the bio-oil and bio-char production using palm oil sludge as feedstock by pyrolysis. The bio-oil yield obtained was 27.4 ± 1.7 wt.% having a heating value of 22.2 ± 3.7 MJ/kg and a negligible ash content of 0.23 ± 0.01 wt.%. The pH of bio-oil was in alkaline region. The bio-char yielded 49.9 ± 0.3 wt.%, which was further investigated for sorption efficiency by adsorbing metal (Cd<sup>2+</sup> ions) from water. The removal efficiency of Cd<sup>2+</sup> was 89.4 ± 2%, which was almost similar to the removal efficiency of a commercial activated carbon. The adsorption isotherm was well described by Langmuir model.

Lee *et al.* [10], investigated the bio-char production using palm kernel shell (PKS), empty fruit bunch (EFB) and palm oil sludge (POS), residues from the palm oil industry, as feedstock by slow pyrolysis (50 mL min<sup>-1</sup> of N<sub>2</sub> at 500 °C). PKS and EFB had higher lignin, volatiles, carbon and HHV, and lower ash than POS. The thermochemical conversion had enhanced the biofuel quality of PKS-char and EFB-char exhibiting increased HHV (26.18–27.50 MJ kg<sup>-1</sup>) and fixed carbon (53.78–59.92%), and decreased moisture (1.03–2.26%). The kinetics of pyrolysis were evaluated by thermogravimetric at different heating rates (10–40 °C). The activation energies determined by Kissinger-Akahira-Sunose and Flynn-Wall-Ozawa models were similar, and comparable with literature data. The findings implied that PKS and EFB are very promising sources for bio-chars synthesis, and the obtained char's possessed significant biofuel potential.

Li *et al.* [11], presented a study of biofuel and bio-char production using different biomass by fast pyrolysis. The study it was evaluate 346 different feedstocks, which were grouped into five types: woody, stalk/cob/ear, grass/plant, organic residue/ product and husk/shell/pit. The results show that biomass ash content of 0.3–7.7 wt.% increases biochar yield from 0.13 to 0.16 kg/kg of biomass, and decreases biofuel yields from 87.3 to 40.7

gallons per ton. Higher ash content of biomass increases minimum fuel selling price (MFSP). The impact of ash and O/C ratio of biomass on GHG emissions are not consistent for all feedstocks.

Shemfe *et al.* [12], investigated the bio-oil production via biomass fast pyrolysis and subsequent bio-oil upgrading via zeolite cracking. The techno-economic assessment was accomplished of two conceptual catalyst regeneration for the zeolite cracking process. (i) a two-stage regenerator operating sequentially in partial and complete combustion modes (P-2RG) and (ii) a single stage regenerator operating in complete combustion mode coupled with a catalyst cooler (P-1RGC). It was used the Aspen Plus software to the simulations, which was considered a production of 72 t/day of pine wood fast pyrolysis and zeolite cracking plant and compared in terms of energy efficiency and profitability. The energy efficiencies of P-2RG and P-1RGC were estimated at 54% and 52%, respectively with corresponding minimum fuel selling prices (MFSPs) of £7.48/GGE and £7.20/GGE. Sensitivity analysis demonstrated that the MFSPs of both designs are mainly sensitive to variations in fuel yield, operating cost and income tax.

Lam *et al.* [13], presented a study of bio-char production using banana and orange peels as feedstocks by pyrolysis at 400-500 °C. The pyrolysis generated 30.7-47.7 wt.% yield of a dark biochar, which contained no Sulphur, low volatile content (34 wt.%), and high amounts of fixed carbon (72 wt.%). The use of the biochar as adsorbent to treat the Palm oil mill effluent (POME) showed a removal efficiency of up to 57% in reducing the concentration of biochemical oxygen demand (BOD), chemical oxygen demand COD, total suspended solid (TSS) and oil and grease (O&G) of POME to an acceptable level below the discharge standard. The biochar showed a surface area of 105 m<sup>2</sup>/g and a porous structure containing mesopores, indicating its potential to provide many adsorption sites for use as an adsorbent.

Giwa *et al.* [14], presented a study of bio-char production using date palm waste and simulated using SuperPro Designer v8.5. A comparison between the production with conventional process (electric heating-based pyrolysis) and concentrated solar energy was accomplished analyzing the economic and environmental sustainability aspects. Economic analysis shows that this process is more economically viable than the conventional process, with payback time (PBT) of 4 years and 132 days, internal rate of return (IRR) of 14.8%, return on investment (ROI) of 22.9% and gross margin of 35.5%. Environmental impact assessment shows that CO<sub>2</sub> emissions from concentrated solar energy-based pyrolysis accounts for only 38% of that of the conventional pyrolysis. Sensitivity analysis shows that PBT is more sensitive to changes in biochar selling price than changes in the cost of acquiring date palm waste.

Lama *et al.* [15], investigated the fuel production by microwave vacuum pyrolysis compared with conventional pyrolysis, using waste plastic and used cooking oil simultaneously. The pyrolysis demonstrated beneficial process features with respect to high heating rate (29 °C/min) to provide fast heating, high process temperature for extensive cracking (581 °C), short process time (20 min), and low electrical energy consumption (0.38 kWh). The combined use of microwave vacuum pyrolysis and activated carbon reaction bed produced up to 84 wt.% yield of liquid oil, containing light hydrocarbons and higher heating value (49 MJ/kg) than diesel and gasoline. The techno-economic analysis indicated that this pyrolysis approach showed low production cost (US\$ 0.25/L compared to US\$ 0.523/L of diesel price in Malaysia).

Battle *et al.* [16], presented a study to compare and evaluate alternatives to convert a conventional palm oil mill into a bio refinery. It was considered three scenarios: the first (I), the base case, consists of a traditional palm oil mill; the second (II) considers the fast pyrolysis process for the production of bio-oil and biochar; and the third (III) considers a bio refinery that, besides incorporating the pyrolysis process, has an extraction/ transesterification stage for the production of biodiesel and glycerin in the palm oil mill. The surplus electricity index was calculated for the three scenarios, and scenario III was the most favorable, achieving 110.23 kW per ton of fresh fruit bunch with an overall efficiency of

82.69%. The environmental assessment carried out for scenario III indicates that environmental impacts of bio-oil production are 32.5% lower than the ones to produce electricity (climate change category) and 14.2% lower than environmental impacts to produce bio-diesel (resources category), demonstrating that the production of bio-oil using fast pyrolysis result in lower environmental impacts compared with the other products obtained in the bio refinery. Finally, the Net Energy Ratio was calculated for the scenario with the best thermodynamic performance (scenario III: 21.17) and compared with previously published studies, resulting in a gain of total energy flow of up to 17.77.

Vasu *et al.* [17], presented a study to produce bio-oil using blends of palm oil sludge (POS) and palm kernel shell (PKS) (10, 20, 35 and 50 wt.% POS with PKS) by fast co-pyrolysis with the aim to produce bio-oil with improved pH. The corresponding blends were pyrolyzed at  $507\pm 13$  °C in a fixed bed reactor. As the amount of POS in the blends increased from 0 to 100 wt.%, a negative synergistic effect (SP) was observed and so a decrease in bio-oil yield. The observation was attributed to the presence of AAEMs found in POS. The total acid number (TAN) of bio-oils decreased with increasing POS ratio in the blends as well. At PKS to POS mass ratio of 50:50, the pH value of the bio-oil produced was  $4.6\pm 0.1$ . Based on the yield and physical properties of bio-oil, the blend with 20 wt.% of POS was chosen as the desired ratio as it yielded  $40.8\pm 3.7$  wt.% of bio-oil with a slight negative synergistic effect (SP) of 3.26.

Yeo *et al.* [18], studied the development of bio refineries using the biomass from palm oil industry by simulations. To evaluate the techno-economic feasibility of the sustainable circular economy, a mathematical model demonstrating the biomass network with consideration of recycling is developed in this work. Besides, Process Graph (P-graph) is incorporated to perform the combinatorial optimization of the biomass network, which targets three common resources: fertilizer, steam, and electricity for regeneration and recycling. Although the result shows that the linear economy model is preferred in terms of profitability, the circular economy model shows potential in reducing 39.292% of the imported steam and 13.469% of the imported electricity, while being 0.642% lower in terms of the gross profit.

Yahya *et al.* [19], investigated the bio-oil, char, and burnable gases production using biomass waste of date palm by fast pyrolysis. Previous studies concluded that at an optimum temperature of 525 °C, the maximum bio-oil, char and gases obtained from pyrolysis of date palm waste contributed 38.8, 37.2 and 24% of the used feedstock material (on weight basis), respectively. Based on the pyrolysis product percentage, the economic analysis estimated the net saving of US\$ 556.8 per ton of the date palm waste processed in the pyrolysis unit. It was further estimated that Saudi Arabia could earn US\$ 44.77 million per annum, approximately, if 50% of the total date palm waste were processed through fast pyrolysis, with a payback time of 2.57 years. Besides that, this intervention will reduce 2029 tons of greenhouse gas emissions annually, contributing towards a lower carbon footprint.

Kaniapan *et al.* [20], presented a review regarding the transportation fuel use and energy production from the biomass of palm oil industry (and its residues) as a sustainable alternative to renewable resources, which can producer cleaner, cheaper and readily energy sources in the future. Assessment and evaluation on the feasibility of palm oil and its residues were made on the current valorization methods such as thermochemical and biochemical techniques.

Terry *et al.* [21], presented a review of bio-oil production using oil palm biomass (OPB) as lignocellulosic feedstock, as well as presents a discussion of the chemical compositions of different OPB and their effects to the bio-oil yield and quality obtained from pyrolysis process, followed by discussing the addition of plastics and catalysts into the pyrolysis for bio-oil upgrading, and lastly summarizing the existing techno-economic and environmental studies and the potential use of process integration. Polypropylene (PP), low-density polyethylene (LDPE), and high-density polyethylene (HDPE) have been commonly used in co-pyrolysis of OPB, which can effectively increase the heating value of bio-oil up to 80.0% that of diesel.

Pires *et al.* [22], investigated the fuels and chemicals production by pyrolysis using biomass as feedstock and the process graph (P-graph) methodology for the synthesis of pyrolysis oil refineries. The work presents the profitability of various bio refinery designs by using data reported in the literature and providing information on how the introduction of new technologies to the database will affect the formation of profitable bio refinery concepts. The work shows a methodology for the addition of new unit operations to the database generated from the literature. The addition of a centrifuge for water extraction and a wet oxidation system for acetic acid production resulted in the generation of several bio refinery configurations, seven of which have a profitability ranging from US\$ 1,650 to US\$ 23,666/h with acetic acid and levoglucosan as the main products, respectively.

Detchusananard *et al.* [23], presented a study of techno-economic assessment of the multi-biofuels production using the empty fruit bunch (EFB) biomass residual, from palm oil milling process, by pyrolysis and gasification integrated process. The modeling is accomplished using the Aspen Energy Analyzer and the economic performance indicators, such as, payback period (PB), net present value (NPV), and internal rate of return (IRR), of the process are obtained using Aspen Process Economic Analyzer. The results show that the integrated process should be operated at steam to biochar mass ratio of 2.7, gasifier temperature of 900 °C, steam to syngas mass ratio of 3.0, and WGS temperature of 240 °C to produce the maximum hydrogen, gases, gasoline, naphtha, kerosene and diesel at 140, 290, 657, 729, 298 and 811 kg h<sup>-1</sup>, respectively. Furthermore, in terms of heat integration, the minimum hot and cold utilities are required at 21.554 and 5.247 MJ h<sup>-1</sup>, respectively. The economic analysis results indicate that the proposed process is economically feasible and attractive with 5.98 years of PB, \$ 249,951,964 of NPV, and 22.0% of IRR.

Attasophonwattana *et al.* [24], presented a study of hydro char's production using empty fruit bunch (EFB) as feedstock by a pilot-scale hydrothermal carbonization (HTC), washing and gasification processes, as well as anaerobic digestion of the HTC liquid product. In terms of air gasification, char and tar products accounted for 22.7–33.8% and 17.3–28.8%, respectively while CO<sub>2</sub>/O<sub>2</sub> gasification resulted in 31.3–36.6% for char and 8.5–30.8% for tar. In general, hydro char (HT-EFB) gave the lower tar content compared to wash hydro char (HTW-EFB). Major tar components from HT-EFB and HTW-EFB were aliphatic and monoaromatic hydrocarbons, respectively. Syngas products from air gasification of hydro chars were 39.9–56.5%, 11.4–21.4%, and 9.0–14.4% for CO, H<sub>2</sub> and CH<sub>4</sub>, respectively while CO<sub>2</sub>/O<sub>2</sub> gasification products yielded 45.1–56.6%, 11.6–24.3%, and 9.4–14.0% for CO, H<sub>2</sub> and CH<sub>4</sub>, respectively. The lower heating value of syngas was in the range of 4.7–6.6 MJ/Nm<sup>3</sup> and cold gas efficiency was approximately 39.1–55.1%.

Parthasarathy *et al.* [25], presented a study of bio-oil production using oil palm wastes (OPW) such as palm kernel shell (PKS), empty fruit bunches (EFB), and oil palm frond (OPF), and their blends, by pyrolysis. According to the economic analysis, PKS-based pyrolysis has the highest capital expenses (CAPEX), while EFB-based pyrolysis has the lowest CAPEX of all tested feedstocks. Furthermore, PKS has the highest operating expenses (OPEX) due to its relatively higher market price as well as higher moisture content, which necessitates more energy input during the drying stage. Among the feedstocks, OPF has delivered the highest profit of US\$ 17 M/year, with a 22.0% return on investment (ROI). In terms of investment capital payback period, all OPW feedstocks demonstrated a reasonable period of 4–6 years. Bio-oil is the most valuable pyrolysis product, with the highest market value when compared to biochar and syngas.

In this work, the economic feasibility of thermal catalytic process of crude palm oil (CPO) and palm oil neutralizing sludge (PONE), followed by distillation of organic liquid products to produce biofuels, has been studied not only to evaluate the best investment alternative, but also to evaluate the viable project according criteria of project evaluation [26]. The economic feasibility analysis based on the following economic methods: simple payback criterion, discounted payback, net present value (NPV), internal rate of return (IRR), and index of profitability (IP), as described in details by Rocha *et al.* [26]. It was also calculated the breakeven-point, the minimum sale price (MFSP) and an analysis of sensitivity for each process [26].

## 2. Materials and Methods

### 2.1. Materials

#### 2.1.1. Palm oil (*Elaeis guineensis*, Jacq)

Palm and palm kernel oils have low concentrations of polyunsaturated carboxylic acids. Palm oil contains saturated (44% palmitic acid, 5% stearic acid) and unsaturated fatty acids (39% oleic acid). In comparison, palm kernel oil is 54–70% unsaturated, and includes a large amount of lauric acid [27-28]. Table 1 shows the chemical composition, in terms of fatty acids esters, of palm oil and palm kernel oil [28].

**Table 1.** Chemical composition of common fat acids of the palm oil and of the palm kernel [28].

Fat acids	Representation	Palm oil	Palm olein	Palm stearin	Palm kernel oil
Lauric	C12:0	< 0.4	0.1 – 0.4	0.1 – 0.4	41.0 – 55.0
Myristic	C14:0	0.5 – 2.0	0.5 – 1.0	1.1 – 1.8	14.0 – 16.0
Palmitic	C16:0	41.0 – 47.0	34.0 – 39.0	48.4 – 73.8	6.5 – 10.0
Palmitoleic	C16:1	< 0.6	< 0.5	0.05 – 2.0	-
Stearic	C18:0	3.5 – 6.0	2.0 - 3.0	3.9 – 5.6	1.3 – 3.0
Oleic	C18:1	36.0 – 44.0	43.0 – 50.0	15.6 – 36.0	12.0 – 19.0
Linoleic	C18:2	6.5 – 12.0	9.0- 13.0	3.2 – 9.8	1.0 – 3.5
Linoleic	C18:3	< 0.5	< 0.1	0.1 – 0.6	-
Arachid	C20:1	< 1.0	-	0.3 – 0.6	

Palm oil can be broken down into two fractions, after refining, namely olein (60%) and stearin (40%). Olein is a liquid oil, intended for cooking and stearin can be used as fat in 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 [28]. Table 2 shows the physicochemical properties of the crude palm oil [29-34].

**Table 2.** Physicochemical characterization of crude palm oil (CPO) used as raw renewable material by thermal catalytic processes in pilot scale [27, 29-34].

Properties	CPO
Density (g/cm <sup>3</sup> )	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

The physicochemical properties of the crude palm oil (CPO), described in Table 2, and are according to those reported in the literature [27, 29-34].

**Table 3.** Physicochemical properties range of crude palm oil (CPO) [27, 29-31].

Properties	Units	Range
Specific mass (50 °C/20 °C)	g/cm <sup>3</sup>	0.891 – 0.899
Refractive index	-	1.454 – 1.456
Iodine index	G I <sub>2</sub> /100g	50 - 60
Saponification index	mg KOH/g	190 - 209
Melting point	°C	33 - 40
Acid index	mg KOH/g	10.0

#### 2.1.2. Palm oil neutralizing sludge

Palm oil neutralization sludge or soap phase residue of neutralization process of palm oil is an aqueous alkaline lipid emulsion that contains approximately 50% (wt.) water, with free fatty acids, phosphatides, triglycerides, pigments, and other non-polar compounds [35-38]. Neutralization sludge is generated at a rate of approximately 6% (vol.) of the refining volume of the crude palm oil [36-38]. 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 [36-37]. Table 4 presents the results of physico-chemical 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 °C.

**Table 4.** Physicochemical characterization of the palm oil neutralizing sludge (soap phase residue of neutralization process of palm oil) used as raw material in the pyrolysis pilot plant [36-37].

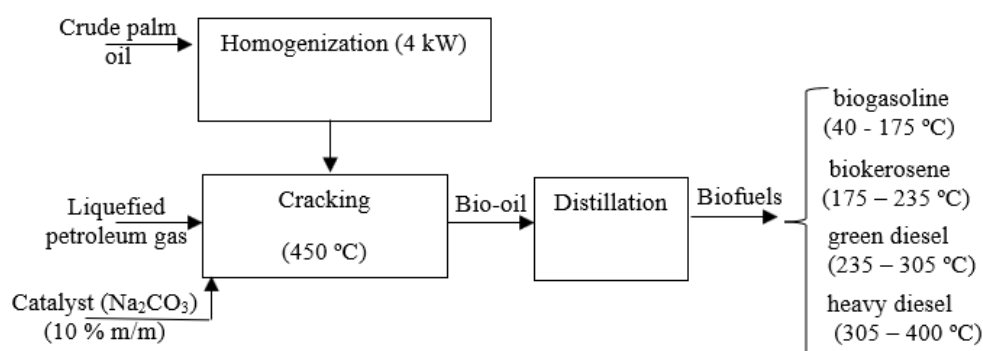
Properties	PONS
Acidity index (mg NaOH / g)	6.64
Saponification index (mg KOH / g)	56.32
pH	7.16
Water content Exp. 5 (%)	32.8

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

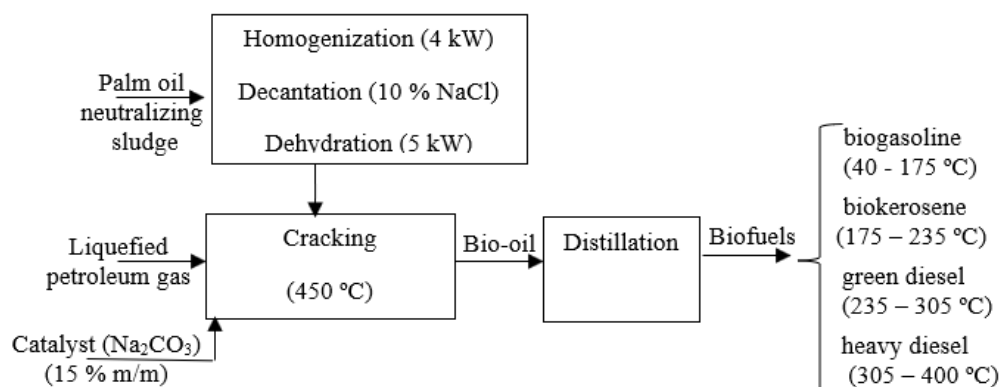
The thermal-catalytic cracking and distillation processes of crude palm oil (*Elaeis guineensis*, Jacq) and palm oil neutralization sludge, described in details elsewhere [27,29-34, 36-37].

## 2.3. Project evaluation criteria

The indicators of project evaluation were described in details by Amaral et al. [26]. The indicators used were the simple payback, discounted payback, net present value (NPV), internal rate return (IRR) and index of profitability (IP). For each indicator it was also presented the criterias of project evaluation. The breakeven-point, the minimum fuel sale price (MFSP) and the analysis of sensibility were also calculated. Figure 4 presents the scheme used in the process to convert the palm oil into organic liquid product (bio-oil), coke and methane gas by pyrolysis process using 10% (wt.%) sodium carbonate as a catalyst at 450 °C and 1 atm, followed by distillation to obtain biofuels (biogasoline, biokerosene, green diesel, heavy diesel). Figure 5 illustrates the scheme used to convert the palm oil neutralizing sludge into organic liquid product (bio-oil), coke and methane gas though pyrolysis process at 450 °C and 1 atm followed distillation to obtain biofuels (biogasoline, biokerosene, green diesel, heavy diesel).



**Figure 4.** Process scheme of palm oil (*Elaeis guineensis*, Jacq) conversion into in biofuels.



**Figure 5.** Process scheme of conversion of palm oil neutralizing sludge in biofuel.

#### 2.4. Calculation Methodology

The calculation methodology, described in details by Amaral *et al.* [26], was applied to compute revenues and expenses using crude palm oil (*Elaeis guineensis*, Jacq) and using palm oil neutralizing sludge as raw material. The additional process step to include the cost of desiccant and dehydration are given in items 2.4.1 and 2.4.2, respectively.

**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	$0.97 \cdot 10^{-3}$	kg/L
$d$ is the density of the palm oil neutralizing sludge	$0.97 \cdot 10^{-3}$	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	U\$\$/kg
$d_{coke}$ is the coke density	$1 \cdot 10^{-3}$	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	U\$\$/L
$d_{gas}$ is the methane gas density	$0.72 \cdot 10^{-3}$	kg/L
$Y_{bio}$ is the distilled process yield of palm oil	60	%
$Y_{bio}$ is the distilled process yield of neutralizing sludge	73	%
$P_{RM}$ is the price of raw material of palm oil	0.23	U\$\$/L
$P_{RM}$ is the price of raw material of the palm oil neutralizing sludge (it was considered 15% of the palm oil price)	0.0345	U\$\$/L
$P_{cat}$ is the price of catalyst	0.52	U\$\$/L
$C_m$ is the cost of manpower in thirty days	1562.5	U\$\$/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 distillation	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	1.59	U\$\$/L
$SP_{bio}$ is the sale price to the biofuels produced with palm oil neutralizing sludge	1.34	U\$\$/L
$\%NaCl$ is the percentage of sodium chloride in m/m	10	%
$P_{NaCl}$ is the price of sodium chloride	0.005	U\$\$/L
$P_{deh}$ is the power of the dehydration equipment	5	kW
$t_{deh}$ is the time of dehydration	1	h

#### 2.4.1. Cost of Dessecant (NaCl<sub>10%</sub>)

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

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

#### 2.4.2. Dehydration

$$C_{deh} = \frac{P_{deh} * f_{KWh} * t_{deh} * N_{deh} * P_{kwh}}{(D_{bio} + m_{coke} + m_{gas})} \quad (20)$$

$C_{deh}$  = cost of dehydration [U\$\$/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 [U\$\$/kWh].

### 3. Results

#### 3.1. Palm oil (*Elaeis guineensis*, Jacq)

The results presented in this work were those described in the literature for thermal catalytic cracking of crude palm oil with 10 % of catalyst ( $Na_2CO_3$ ) in pilot unit [27,29-34]. The results for the yields of thermal catalytic cracking of crude palm oil and distillation of organic liquid products [27,29], are shown in supplementary Table S0. 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 60% to the stand experiments according [26-31]. Supplementary Table S1 presents the characterization of crude palm oil used as raw material by thermal catalytic cracking with 10% (wt.) of catalyst ( $Na_2CO_3$ ) in pilot scale [27,29]. Supplementary Table S2 presents the chemical composition of green gasoline, in terms of hydrocarbons and oxygenates. Among the identified and quantified hydrocarbons there are normal paraffin's, branched paraffin's, naphthenics, aromatics and olefins, the main components present in distillation fractions of fossil fuels (petroleum), as reported elsewhere [39-40].

Supplementary Table S3 presents the chemical composition of the distillation fraction of 175 °C – 235 °C (bio kerosene), in terms of oxygenates and hydrocarbons. The bio kerosene is composed by hydrocarbons including aromatics, normal paraffin's, naphthenics and mainly olefins, besides there are oxygenated compounds. The percentage of hydrocarbons and of oxygenated correspond to 86.37% (area.) and 13.63% (area.), respectively.

Supplementary Table S4 presents the results of distillation fraction from 235 °C – 305 °C, corresponding to green diesel. It has been identified a mixture rich in hydrocarbons, composed mainly by normal paraffin's and olefins. The total percentage of hydrocarbons corresponds to 91.38% (area.) and oxygenated 8.62% (area.).

Supplementary Table S5 presents the results of distillation fraction from 305 °C – 400 °C, corresponding to heavy diesel. It has been identified a mixture rich in hydrocarbons composed mainly by normal paraffin's and olefins. The total percentage of hydrocarbons

correspond to 70.78% (area.) and oxygenated 29.22% (area.). The results are in agreement with those reported in the literature [39-40].

Table 6 presents the economic parameters for discounted cash flow analysis. The total project investment is U\$\$ 79791.36 (seventy-nine thousand seven hundred and ninety-one dollars and thirty-six cents) and corresponds to the initial investment of the cash flow.

**Table 6.** Economic Parameters for Discounted Cash Flow Analysis.

Plant life	5	years
Plant size/biomass feed rate (palm oil)	900	L/day
Plant size/biomass feed rate (neutraling sludge)	450	L/day
Discount rate	10	% per year
Financing	100	% equity
Plant recovery period	5	years
Federal tax rate	10	%
Feedstock cost (palm oil)	0.230	U\$\$/L
Feedstock cost (neutraling sludge)	0.034	U\$\$/L
Availability (palm oil)	75.0	%
Availability (neutraling sludge)	56.25	%
On stream time (palm oil)	6.480	h
On stream time (neutraling sludge)	4.860	h
Reference year	2022	
Electricity price	0.2186	U\$\$/kWh
Total purchased equipment costs (TPEC)	66000.00	U\$\$
Direct costs (including equip installation, instruments and controls, piping electrical and misc. buildings)	40260.00	U\$\$ (61% TPEC)
Total installed equipment cost (TIEC)	106260.00	U\$\$ (61% TPEC + TPEC)
Warehouse	1593.90	U\$\$ (1.5% TIEC)
Site development	4781.70	U\$\$ (4.5% TIEC)
Total installed cost (TIC)	112635.60	U\$\$ (TIEC + warehouse + site development)
Indirect Field Costs (IFC)		
- field expenses	22527.12	U\$\$ (20% TIC)
- home office & construction fee	28158.90	U\$\$ (25% TIC)
- Project contingency	3379.07	U\$\$ (3% TIC)
- proratable costs	11263.56	U\$\$ (10% TIC)
Total capital investment (TCI)	177964.25	U\$\$ (TIC + IFC)
Other costs (startup, permits, etc.)	17796.42	U\$\$ (10% TCI)
Total Project Investment (TPI)	195760.67	U\$\$ (TCI+ Other costs)

Note: This is the same base of [41].

Table 7 presents the total revenue, total expense and the annual profit of U\$\$ 52500.2 (fifty two thousand five hundred and two cents) per year. The minimum fuel selling price (MFSP) obtained in this work for the biofuels was 1.59 U\$\$/L. The literature mentioned in Amaral *et al.* [26] presents values of 0.68 up to 1.34 U\$\$/L.

**Table 7.** 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/m <sup>3</sup>
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)	1.59	US\$/L

<b>Total expenses (6) = (7)+(8)+(9)+(10)+(11)+(12)+(13)</b>	1.23	US\$/L
Raw material (palm oil) (7)	0.470	US\$/L
Homogeneização_4 kW (8)	0.004	US\$/L
Catalyst_ 10% (9)	0.104	US\$/L
Liquefied petroleum gas (LPG)_10% (10)	0.103	US\$/L
Manpower (11)	0.12	US\$/L
Distillation (Heating)_5 kW (12)	0.297	US\$/L
Federal tax rate 10% (13)	0.165	US\$/L
Profit margin (14) = (5) - (6)	0.34	US\$/L
Total profit per day	145.8	US\$/day
Total profit per month	4375.0	US\$/month
Total profit per year	52500.2	US\$/year

Table 8 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 U\$\$ 14240.31 (fourteen thousand two hundred and forty and thirty-one cents). In this case, the project is considered economically viable within the horizon of analysis of 5 years.

**Table 8.** Annual cash flow for the crude palm oil (*Elaeis guineensis*, Jacq) and simple payback analysis.

Year	0	1	2	3	4	5
Cash Flow	-195760.67	52500.25	52500.25	52500.25	52500.25	52500.25
Accumulated Value	-195760.67	-143260.43	-90760.18	-38259.93	14240.31	66740.56

Table 9 shows the cash flow for the investment analysis considering the discounted payback criterion. It can be concluded that in the fifth 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 9 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 U\$\$ 3256.57 (three thousand two hundred fifty six and fifty-seven cents). The cash flow discount rate was 10.0% 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.

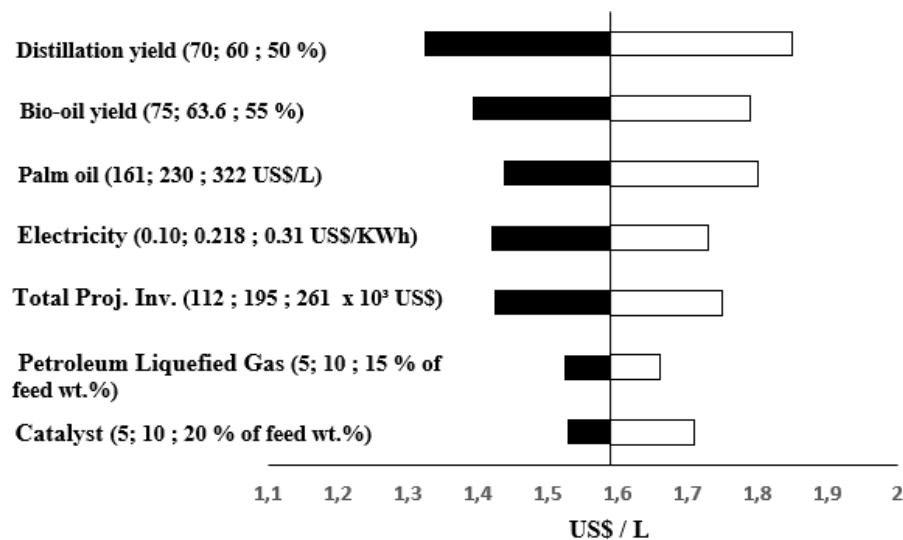
Table 9 shows the cash flow for the investment analysis considering the internal rate return (IRR) criterion. It can be concluded that in the fourth to fifth year occur inversion of signal, which represents the IRR of the project as 10.0% p.y. In this case, the IRR is equal than the minimum attractiveness of the project (10% p.y), which means that the project is economically viable. Thilakaratne *et al.* [42] obtained a minimum fuel-selling price (MFSP) of U\$\$3.69 per gal (0.98 U\$\$/L) and Amaral *et al.* [26] of 1.34 U\$\$/L is estimated assuming 10% internal rate of return.

Table 9 shows the cash flow for the investment analysis considering the profitability index. Based on the computed index of profitability, equal to 1.02, for each dollar invested in the project a return of 1.02 dollars it will occur, within the analysis horizon of 5 years. According to the criteria of this index, the project is considered economically viable.

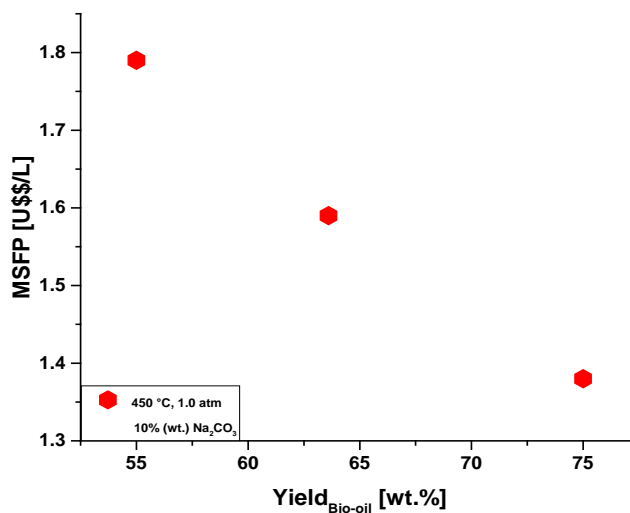
**Table 9.** Annual cash flow for the crude palm oil (*Elaeis guineensis*, Jacq) and discounted payback analysis, net present value (NPV) analysis, internal rate of return (IRR) analysis and profitability index analysis.

Year	0	1	2	3	4	5
Cash Flow	-195760.67	52500.25	52500.25	52500.25	52500.25	52500.25
Present value	-195760.67	47727.50	43388.63	39444.21	35858.37	32598.52
Accumulated Value	-195760.67	-148033.18	-104644.54	-65200.33	-29341.96	3256.57

Figure 6 corresponds of the sensitivity analysis for 900 L/day, to reach the baseline transportation fuel MFSP of 1.59 U\$\$/L, the 10% facility IRR is assumed. It is clear that the distillation yield and bio-oil yield are the most significant variable that affect the MFSP. These results are in agreement with Brown *et al.* [43] and Amaral *et al.* [26].

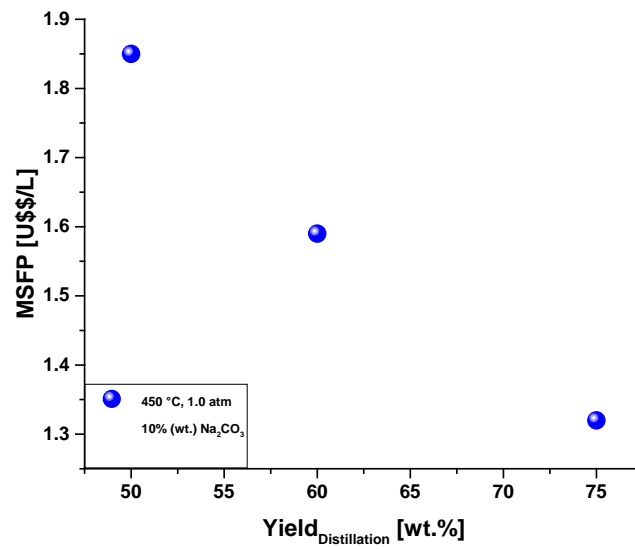


**Figure 6.** Sensitivity analysis for 900 L/day, to reach the baseline transportation fuel MFSP of 1.59 U\$\$/L, the 10% facility IRR is assumed.

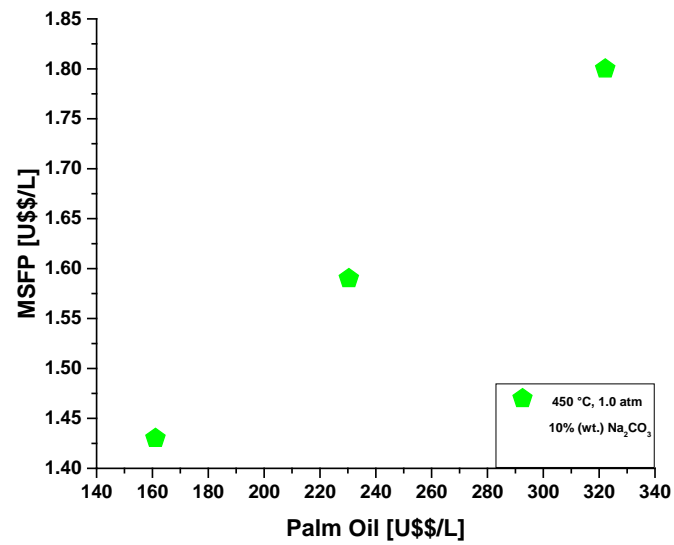


**Figure 7.** MFSP as a function of bio-oil yield by sensitivity analysis for a 900 L/day production.

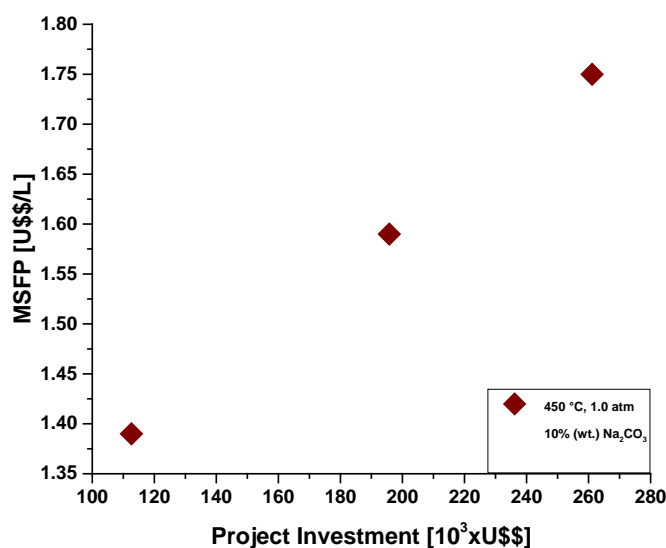
Figure 7 illustrates the MFSP as a function of bio-oil yield by sensitivity analysis for a 900 L/day production. Figure 8 shows the MFSP as a function of distillation yield by sensitivity analysis for a 900 L/day production. Both graphics shows that the increase of yield results in reduction of MFSP. Figure 9 illustrates that for 75% (wt.) of bio-oil yield the MFSP decrease to 1.38 U\$\$/L. Figure 10 shows that when the distillation yield achieve 75% (wt.), the MFSP reduce to 1.32 U\$\$/L.



**Figure 8.** MFSP as a function of distillation yield by sensitivity analysis for a 900 L/day production



**Figure 9.** MFSP as a function of cost of crude palm oil by sensitivity analysis for a 900 L/day production.



**Figure 10.** MFSP as a function of project investment by sensitivity analysis for a 900 L/day production.

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 [43-44]. Table 9 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 breakeven point obtained was of 1.58 U\$/L.

### 3.2. Palm oil neutralizing sludge

The results presented in this work were from the pyrolysis of the palm oil neutralizing sludge with 15% (wt.) of catalyst ( $\text{Na}_2\text{CO}_3$ ) at 450 °C. The results presented by [36-37] of yields related to thermal catalytic cracking and distillation are shown in Supplementary S6. One important point to consider is that thermal catalytic cracking availability of 56.25% is low. This may occur because of the high reaction time in the reactor, resulting in a low feed rate.

Supplementary Table S7 presents the physicochemical properties of organic liquid product (bio-oil) of the palm oil neutralizing sludge after thermal catalytic cracking process. The results compared with the National Agency of Petroleum, Biofuels and Natural Gas of Brazil (ANP).

According to the results presented in Supplementary Table S7, one observes that density and viscosity-measured values were close to those established by ANP standard (values below the norm 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 [36-37].

Supplementary Table S8 presents the chemical composition of hydrocarbons and oxygenated compounds of the bio-oil of *experiment 5* [36-37]. The chemical analysis identified a high concentration of hydrocarbons with 91.22% (area.), as well as a low concentration of oxygenated compounds with 8.78% (area.). The main hydrocarbons present in the petroleum diesel are alkanes, olefins, naphthenics and aromatics [39-40].

The distillation of the organic liquid product from *experiment 5* was carried out using a pilot scale using a distillation column in order to obtain cut-off fractions of biofuels [36-37]. The physicochemical characteristics of the biofuels obtained after distillation in pilot scale are present in Supplementary Table S9.

The results obtained for the acidity index in Supplementary Table S9 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 these fractions were considered as having low corrosive capacity in metallic parts. The results of density and viscosity parameters for the bio gasoline and bio kerosene were lower than the S10 diesel specified by ANP N° 65. This behavior occurs due to the composition of these fractions being formed from smaller hydrocarbon chains (approximate chains of C<sub>4</sub> – C<sub>12</sub>). The results of the sulfur content of the bio gasoline fraction had a content close to the that of mineral diesel S10. However, when comparing it with the sulfur content of common Type A bio gasoline established by ANP N° 57, whose value is 800 ppm, a low sulfur content of the bio gasoline fraction was found in relation to commercial Type A gasoline [36-37].

Supplementary Table S10 presents the percentage composition in hydrocarbons in the range of heavy diesel (175 °C – 235 °C) obtained from the distillation in bench scale of the bio-oil, *experiment 5*. The results demonstrate a high content of hydrocarbons with 96.5% (area.) and a low amount of other compounds with 3.5% (area.).

Supplementary Table S11 presents the percentage composition in hydrocarbons in the range of heavy diesel (305 °C – 400 °C) obtained from the distillation in bench scale of the bio-oil [36-37]. The results demonstrate a high content of hydrocarbons with 93.21% (area.) and a low amount of oxygenated compounds with 6.79% (area.).

Supplementary Table S12 presents the percentage composition in hydrocarbons in the range of light diesel (235 °C – 305 °C) obtained from the distillation in bench scale of the bio-oil [36-37]. The results demonstrate a high content of hydrocarbons with 98.76% (area.) and a low amount of oxygenated compounds with 1.24% (area.).

Supplementary Table S13 shows the percent hydrocarbon composition of gasoline (40 °C – 175 °C) obtained in the pilot scale distillation of the organic liquid product (bio-oil) from *Experiment 5* (15 % Na<sub>2</sub>CO<sub>3</sub> at 440 °C) [36-37]. According to the results, all components of this bio gasoline were hydrocarbons constituted mainly by olefins with 51.09% (area.) and paraffinic with 34.64% (area.). Aromatic and naphthenic hydrocarbons showed low percentages. The composition of aromatic hydrocarbons in this fraction was found in accordance with the specification of ANP N° 57 (2011) for type C gasoline derived from petroleum, which establishes a maximum percentage of 45% (vol.) for aromatics, however, the amount of olefins showed a result above the stipulated maximum of 30% (vol.). It is suitable highlight that this percentage value of the maximum contents of aromatic and olefin hydrocarbons must be met after adding anhydrous ethanol to automotive gasoline, as recommended by ANP N° 57 (2011).

Table 10 presents the total revenue, total expense and the annual profit of US\$ 59278.0 (fifty nine thousand two hundred eight dollars) per year. The minimum fuel selling price (MFSP) obtained in this work for the biofuels was 1.34 U\$\$ / L. The literature mentioned in Amaral *et al.* [26] presents values of 0.68 up to 1.34 U\$\$ / L.

**Table 10.** Revenues and expenses 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 U\$\$/day
Gaseous product (Biogas)_0.48%	(3)	3.70 U\$\$/day
Distilled biofuel _73.0 %	(4)	234.5 L/day
Sale price of biofuel	(5)	1.34 U\$\$/L
<b>Total expenses (6) = (7)+(8)+(9)+(10)+(11)+(12)+(13)+(14)+(15)</b>		0.75 U\$\$/L
Raw material (palm oil neutralizing sludge)_15%	(7)	0.074 U\$\$/L

Homogenization_4 kW	(8)	0.002	U\$\$/L
Decant (NaCl_10%)	(9)	0.001	U\$\$/L
Dehydration_5 kW	(10)	0.009	U\$\$/L
Catalyst_15%	(11)	0.098	U\$\$/L
Liquefied petroleum gas (LPG)_10%	(12)	0.065	U\$\$/L
Manpower	(13)	0.148	U\$\$/L
Distillation (Heating)_5 kW	(14)	0.224	U\$\$/L
Federal tax rate_10%	(15)	0.134	U\$\$/L
Profit margin	(16) = (5) - (6)	0.59	U\$\$/L
Total profit per day		164.7	U\$\$/day
Total profit per month		4940.0	U\$\$/month
Total profit per year		59278.0	U\$\$/year

Table 11 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 U\$\$ 41352.10 (forty one thousand three hundred and fifty two dollars and ten cents). In this case, the project is considered economically viable within the horizon of analysis of 5 years.

**Table 11.** Annual cash flow for the crude palm oil (*Elaeis guineensis*, Jacq) and simple payback analysis.

Year	0	1	2	3	4	5
Cash Flow	-195760.67	59278.19	59278.19	59278.19	59.278.19	59278.19
Accumulated Value	-195760.67	-136482.48	-77204.29	-17926.10	41352.10	100630.29

Table 12 shows the cash flow for the investment analysis considering the discounted payback criterion. It can be concluded that in the fifth 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 12 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 U\$\$ 28950.31 (twenty eight thousand nine hundred fifty dollars and thirty-one cents). 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.

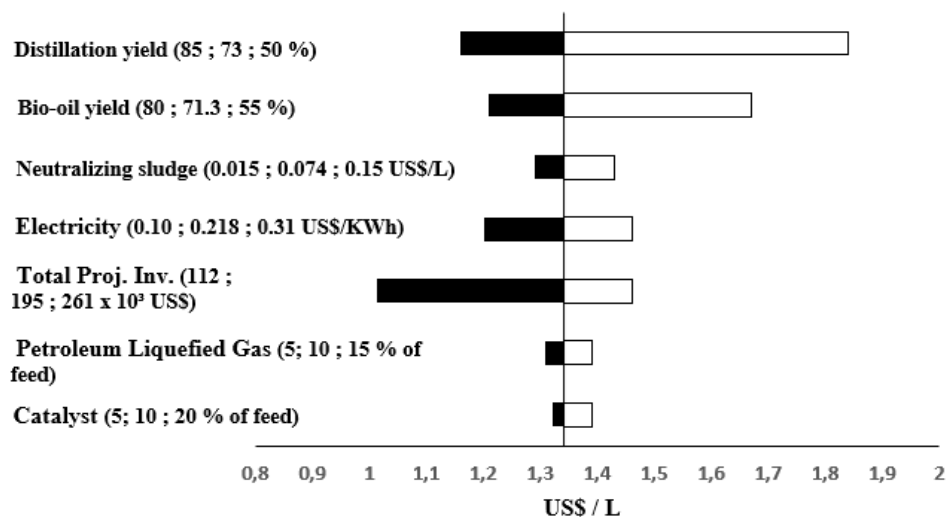
Table 12 shows the cash flow for the investment analysis considering the internal rate return (IRR) criterion. It can be concluded that in the fourth to fifty year occur inversion of signal, which represents the IRR of the project as 10,0 % p.y. In this case, the IRR is equal than the minimum attractiveness of the project (10% p.y), which means that the project is economically viable. Thilakarathne et al. [41] obtained a minimum fuel selling price (MFSP) of U\$\$3.69 per gallon (0.98 U\$\$/L) and Amaral *et al.* [26] of 1.34 U\$\$/L is estimated assuming 10% internal rate of return.

Table 12 shows the cash flow for the investment analysis considering the profitability index. Based on the computed index of profitability, equal to 1.15, for each dollar invested in the project a return of 1.15 dollars it will occur, within the analysis horizon of 5 years. According to the criteria of this index, the project is considered economically viable.

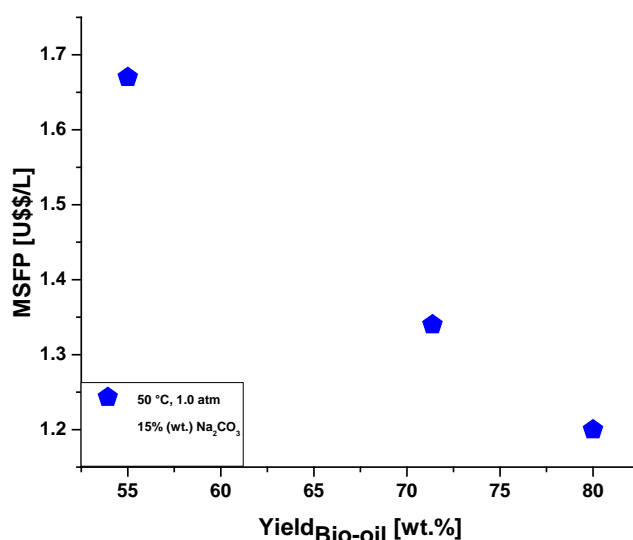
**Table 12.** Annual cash flow for the crude palm oil (*Elaeis guineensis*, Jacq) and discounted payback analysis, net present value (NPV) analysis, internal rate of return (IRR) analysis and profitability index analysis.

Year	0	1	2	3	4	5
Cash Flow	-195760.67	59278.19	59278.19	59278.19	59278.19	59278.19
Present value	-195760.67	53889.27	48990.24	44536.58	40487.80	36807.09
Accumulated Value	-195760.67	-141871.41	-92881.17	-48344.58	-7856.78	28950.31

Figure 11 corresponds of the sensitivity analysis for 450 L/day, to reach the baseline transportation fuel MFSP of 1.34 U\$\$/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.* [43] and Amaral *et al.* [26].



**Figure 11.** Sensitivity analysis for 450 L/day, to reach the baseline transportation fuel MFSP of 1.34 U\$\$/L, the 10% facility IRR is assumed.



**Figure 12.** MFSP as a function of bio-oil yield by sensitivity analysis for a 450 L/day production.

Figure 12 illustrates the MFSP as a function of bio-oil yield by sensitivity analysis for a 450 L/day production. Figure 13 shows the MFSP as a function of distillation yield by sensitivity analysis for a 450 L/day production. Both graphics shows that the increase of yield results in reduction of MFSP. Figure 14 demonstrated that for 80% (wt.) of bio-oil yield the MFSP decrease to 1.20 U\$\$/L. Figure 15 demonstrate that when the distillation yield achieve 85% the MFSP reduce to 1.18 U\$\$/L.

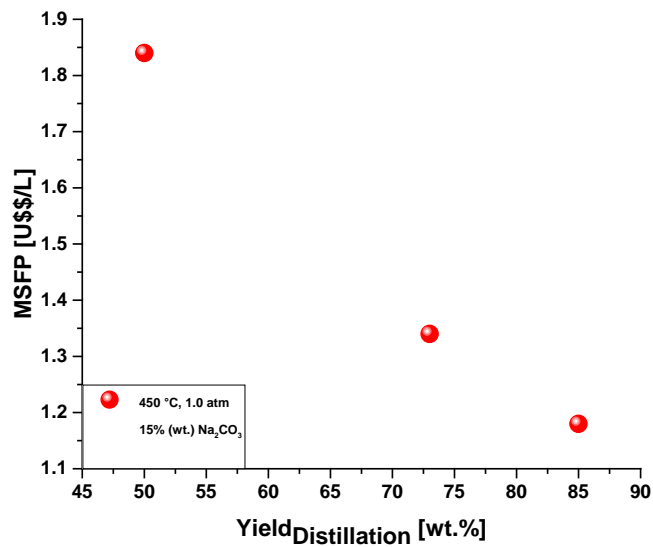


Figure 13. MFSP as a function of distillation yield by sensitivity analysis for a 450 L/day production.

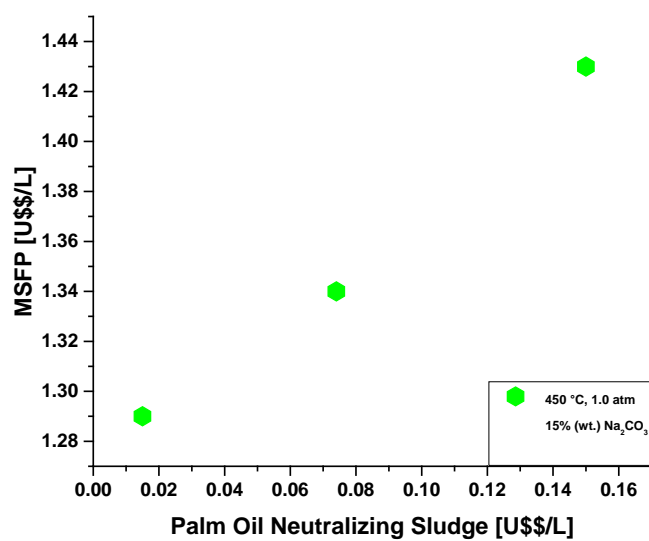
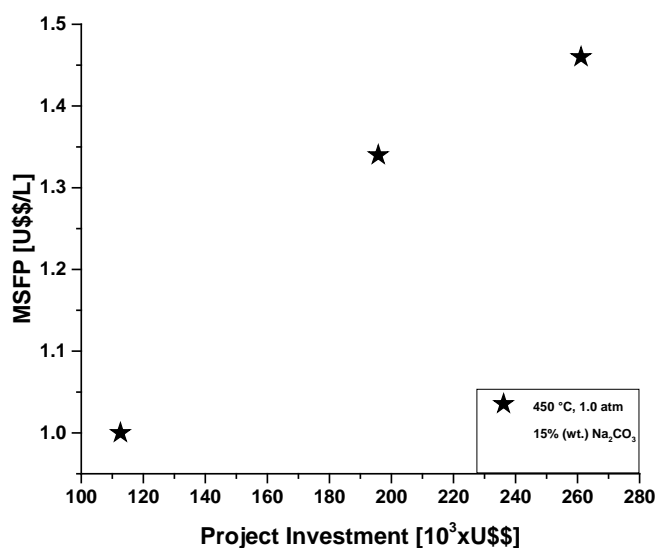


Figure 14. MFSP as a function of cost of palm oil neutralizing sludge by sensitivity analysis for a 450 L/day production.



**Figure 15.** MFSP as a function of project investment by sensitivity analysis for a 450 L/day production.

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 [43-44]. Table 12 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 breakeven point obtained was of 1.24 U\$\$.

#### 4. Conclusions

Starting from the feasibility project criteria indicators, it is possible to affirm that thermal-catalytic cracking process of the crude palm oil to the production of biofuels, coke and methane gas is feasible. The same conclusion it was obtained to the economic feasibility assessment to the process using palm oil neutralizing sludge

The availability used for the project evaluation criteria with the crude palm oil and to the palm oil neutralizing sludge were 75% and 56.25%, respectively. This means that some time 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.

The minimum fuel selling price (MFSP) obtained to the process using palm oil was 1.59 U\$\$/L. The literature mentioned in this work presents values from 0.68 up to 1.34 US\$/L. The main negative aspect that effected this result was the palm oil price in market, which effected the costs. The MFSP obtained using the palm oil neutralizing sludge was 1.34 U\$\$/L, although more stages are necessary in this process, the low estimation of the feedstock contributed to this result.

The internal rate return (IRR) obtained in both projects was 10% pay. In this case, the IRR is equal the minimum attractiveness of the project (10% pay), which means that the project is economically viable. Amaral et al. [26], obtained 10% internal rate of return. Based on the computed index of profitability, equal to 1.15, for each dollar invested in the project a return of 1.15 dollars it will occur, within the analysis horizon of 5 years. According to the criteria of this index, the project is considered economically viable.

Sensitivity analysis demonstrated the pyrolysis yield and distillation yield are the parameters that most affect the MFSP, in both projects. It also demonstrated that reduction of the electrical energy could reduce the MFSP. One alternative is the use of photovoltaic energy.

**Author Contributions:** The individual contributions of all the co-authors are provided as follows: (A.R.A.) contributed with formal analysis and writing original draft preparation, investigation and methodology, (W.G.d.S.) contributed with investigation and methodology, (L.P.B.) contributed with investigation and methodology, (C.C.F.) contributed with investigation and methodology, (A.M.P.) contributed with investigation and methodology, (L.M.P.) contributed with investigation and methodology, (M.C.S.) contributed with investigation and methodology, (F.P.d.C.A.) contributed with investigation and methodology, (N.M.M.) contributed with investigation and methodology, (J.A.R.P.) contributed with resources, chemical analysis, (A.d.A.M.) contributed with investigation and methodology, (S.A.P.d.M.) contributed with investigation and methodology, (D.A.R.d.C.) contributed with investigation, methodology and co-supervision, (S.D.J.) contributed with resources, chemical analysis, (L.E.P.B.) with investigation, methodology, and resources, and (N.T.M.) contributed with supervision, conceptualization, and data curation. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Acknowledgments:** I would like to acknowledge and dedicate this research in memory to Hélio da Silva Almeida, he used to work at the Faculty of Sanitary and Environmental Engineering/UFPa, and passed away on 13 March 2021. His contagious joy, dedication, intelligence, honesty, seriousness, and kindness will always be remembered in our hearts.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Matriz Energética, E., and ELÉTRICA (2018). Empresa de pesquisa energética. Acesso em: 14 de janeiro de 2021. Disponível em: <https://www.epe.gov.br/pt/abcdenergia/matriz-energetica-e-eletrica>
2. Suarez, P. A. Z., Santos, A. L. F., Rodrigues, J. P., and Alves, M. B. (2009). *Biocombustíveis* a partir de óleos e gorduras: Desafios tecnológicos para viabilizá-los. *Quim. Nova* 32, 768–775. DOI: [10.1590/S0100-40422009000300020](https://doi.org/10.1590/S0100-40422009000300020)
3. Abnisa, F., Wan Daud, W. M. A., Husin, W. N. W., Sahu, J. N. Utilization possibilities of palm shell as a source of biomass energy in Malaysia by producing bio-oil in pyrolysis process. *biomass and bioenergy* 35 (2011) 1863-1872. doi:10.1016/j.biombioe.2011.01.033
4. Abnisa, F., Arami-Niya, A., Wan Daud, W.M.A., Sahu, J. N., Noor, I. M. Utilization of oil palm tree residues to produce bio-oil and bio-char via pyrolysis. *Energy Conversion and Management* 76 (2013) 1073–1082. <http://dx.doi.org/10.1016/j.enconman.2013.08.038>
5. Do, T. X., Lim, Y., Yeo, H. Techno-economic analysis of biooil production process from palm empty fruit bunches. *Energy Conversion and Management* 80 (2014) 525–534. <http://dx.doi.org/10.1016/j.enconman.2014.01.024>.
6. Moncada, J., Tamayo, J., Cardona, C. A. Evolution from biofuels to integrated biorefineries: techno-economic and environmental assessment of oil palm in Colombia. *Journal of Cleaner Production* 81 (2014) 51-59. <http://dx.doi.org/10.1016/j.jclepro.2014.06.021>.
7. Peryoga, Y., Solikhah, M. D., Raksodewanto, A. A. Production Cost Assessment of Palm Empty Fruit Bunch Conversion to Bi Oil via Fast Pyrolysis. *International Journal on Advanced Science Engineering Information Technology*. Vol.4 (2014) No. 6 ISSN: 2088-5334.
8. Mabrouki, J., Abbassi, M. A., Guedri, K., Omri, A., Jeguirim, M. Simulation of biofuel production via fast pyrolysis of palm oil residues. *Fuel* 159 (2015) 819–827. <http://dx.doi.org/10.1016/j.fuel.2015.07.043>.
9. Thangalazhy-Gopakumar, S., Al-Nadheri, W. M. A., Jegarajan, D., Sahu, J. N., Mubarak, N. M., Nizamuddin, S. Utilization of palm oil sludge through pyrolysis for bio-oil and bio-char production. *Bioresource Technology* 178 (2015) 65–69. <http://dx.doi.org/10.1016/j.biortech.2014.09.068>.
10. Lee, X. J., Lee, L. Y., Gan, S., Thangalazhy-Gopakumar, S., Ng, H. K. Biochar potential evaluation of palm oil wastes through slow pyrolysis: Thermochemical characterization and pyrolytic kinetic studies. *Bioresource Technology* 236 (2017) 155–163. <http://dx.doi.org/10.1016/j.biortech.2017.03.105>.
11. Li, W., Dang, Q., Brown, R. C., Laird, D., Wright, M. M. The impacts of biomass properties on pyrolysis yields, economic and environmental performance of the pyrolysis-bioenergy-biochar platform to carbon negative energy. *Bioresource Technology* 241 (2017) 959–968. <http://dx.doi.org/10.1016/j.biortech.2017.06.049>.
12. Shemfe, M., Gu, Sai., Fidalgo, B. Techno-economic analysis of biofuel production via bio-oil zeolite upgrading: An evaluation of two catalyst regeneration systems. *Biomass and Bioenergy* 98 (2017) 182-193. <http://dx.doi.org/10.1016/j.biombioe.2017.01.020>.
13. Lam, S. S., Liew, R. K., Cheng, C. K., Rasit, N., Ooi, C. K., Ma, N. L., Ng, J. H., Lam, W. H., Chong, C. T., Chase, H. A. Pyrolysis production of fruit peel biochar for potential use in treatment of palm oil mill effluent. *Journal of Environmental Management* 213 (2018) 400-408. <https://doi.org/10.1016/j.jenvman.2018.02.092>.
14. Giwa, A., Yusuf, A., Ajumobi, O., Dzidzienyo, P. Pyrolysis of date palm waste to biochar using concentrated solar thermal energy: Economic and sustainability implications. *Waste Management* 93 (2019) 14–22. <https://doi.org/10.1016/j.wasman.2019.05.022>.
15. Lama, S. S., Maharib, W, A. W., Okc, Y. S., Penga, W., Chongd, C. T., Mae, N. L., Chasef, H.A., Liewg, Z., Yusuph, S., Kwoni, E. E., Tsangj, D. C. W. Microwave vacuum pyrolysis of waste plastic and used cooking oil for simultaneous waste reduction and

- sustainable energy conversion: Recovery of cleaner liquid fuel and techno-economic analysis. *Renewable and Sustainable Energy Reviews* 115 (2019) 109359. <https://doi.org/10.1016/j.rser.2019.109359>.
16. Batlle, E. A. O., Santiago, Y. C., Venturini, O. J., Palacio, J. C. E., Lora, E. E. S., Maya, D. M. Y., Arrieta, A. R. A. Thermodynamic and environmental assessment of different scenarios for the insertion of pyrolysis technology in palm oil biorefineries. *Journal of Cleaner Production* 250 (2020) 119544. <https://doi.org/10.1016/j.jclepro.2019.119544>.
  17. Vasu, H., Wong, C. F., Vijaietnam, N. R., Chong, Y. Y., Thangalazhy-Gopakumar, S., Gan, S., Lee, L. Y., Ng, H. K. Insight into Co-pyrolysis of Palm Kernel Shell (PKS) with Palm Oil Sludge (POS): Effect on Bio-oil Yield and Properties. *Waste and Biomass Valorization* (2020) 11:5877–5889. <https://doi.org/10.1007/s12649-019-00852-1>.
  18. Yeo, J. Y. J., How, B. S., Teng, S. Y., Leong, W. D., Ng, W. P. Q., Lim, C. H., Ngan, S. L., Sunarso, J., Lam, H. L. Synthesis of Sustainable Circular Economy in Palm Oil Industry Using Graph-Theoretic Method. *Sustainability* (2020), 12, 8081. doi:10.3390/su12198081.
  19. Yahya, S. A. I., Iqbal, T., Omar, M. M., Ahmad, M. Techno-Economic Analysis of Fast Pyrolysis of Date Palm Waste for Adoption in Saudi Arabia. *Energies* (2021), 14, 6048. <https://doi.org/10.3390/en14196048>.
  20. Kaniapan, S., Hassan, S., Ya, H., Nesan, K. P., Azeem, M. The Utilisation of Palm Oil and Oil Palm Residues and the Related Challenges as a Sustainable Alternative in Biofuel, Bioenergy, and Transportation Sector: A Review. *Sustainability* (2021), 13, 3110. <https://doi.org/10.3390/su13063110>.
  21. Terry, L. M., Li, C., Chew, J. J., Aqsha, A., How, B. S., Loy, A. C. M., Chin, B. L. F., Khaerudini, D. S., Hameed, N., Guan, G., Sunarso, J. Bio-oil production from pyrolysis of oil palm biomass and the upgrading technologies: A review. *Carbon Resources Conversion* 4 (2021) 239–250. <https://doi.org/10.1016/j.crcon.2021.10.002>.
  22. Pires, A. P. P., Martinez-Valencia, L., Tanzil, A. H., Garcia-Perez, M., García-Ojeda, J. C., Bertok, B., Heckl, I., Argoti, A., Friedler, F. Synthesis and Techno-Economic Analysis of Pyrolysis-Oil-Based Biorefineries Using P-Graph. *Energy & Fuels* (2021), 35, 16, 13159–13169.
  23. Detchusananard, T., Wuttipisan, N., Limleamthong, P., Prasertcharoensuk, P., Mar'echal, F., Arpornwichanop, A. Pyrolysis and gasification integrated process of empty fruit bunch for multi-biofuels production: Technical and economic analyses. *Energy Conversion and Management* 258 (2022) 115465. <https://doi.org/10.1016/j.enconman.2022.115465>.
  24. Attasophonwattana, P., Sittichirachat, P., Siripaiboon, C., Khaobang, T. K. C., Panichnumsin, P., Ding e, L., Areeprasert, C. Evolving circular economy in a palm oil factory: Integration of pilot-scale hydrothermal carbonization, gasification, and anaerobic digestion for valorization of empty fruit bunch. *Applied Energy*. 324 (2022) 119766. <https://doi.org/10.1016/j.apenergy.2022.119766>.
  25. Parthasarathy, P., Alherbawi, M., Shahbaz, M., Mackey, H. R., McKay, G., Al-Ansari, T. Conversion of oil palm waste into value-added products through pyrolysis: a sensitivity and techno-economic investigation. *Biomass Conversion and Biorefinery* (2022) <https://doi.org/10.1007/s13399-022-03144-2>.
  26. Amaral, A. R., Bernar, L. P., Ferreira, C. C., Oliveira, R. M. de., Pereira, A. M., Pereira, L. M., Santos, M. C., Assunção, F. P. da Costa., Bezerra, K. C. A., Almeida, H. S., Mendonça, N. M., Tavares, A. N., Pereira, J. A. R., Mota, S. A. P. da., Castro, D. A. R. de., Duvoisin Jr, Sergio., Borges, L. E. P., Machado, N. T. Economic feasibility assessment of the thermal catalytic process of wastes: Açai seeds (*Euterpe Oleracea*) and Scum from grease traps. *Energies* 2022, 15(20), 7718; <https://doi.org/10.3390/en15207718>
  27. Mota, S. A. P. (2013). **Craqueamento Termo-catalítico de óleos vegetais em diferentes escalas de produção** [Tese] (Doutorado em Engenharia de Recursos Naturais). Universidade de Federal do Pará (Belém).
  28. Barnwal, B. K.; Sharma, M. P. Optimization of Biodiesel Production by Sunflower Oil Transesterification. *Bioresource Technology*. V. 9, p. 363-378, 2005.
  29. S.A.P. da Mota, A.A. Mancio, D.E.L. Lhamas, D.H. de Abreu, M.S. da Silva, W.G. dos Santos, D.A.R. de Castro, R.M. de Oliveira, M.E. Araújo, Luiz E.P. Borges, N.T. Machado. Production of green diesel by thermal catalytic cracking of crude palm oil (*Elaeis guineensis* Jacq) in a pilot plant, *Journal of Analytical and Applied Pyrolysis* 110 (2014) 1-11. <https://doi.org/10.1016/j.jaap.2014.06.011>.
  30. Mancio, A.A., Costa, K.M.B. da., Ferreira, C.C., Santos, M.C., Lhamas, D.E.L., Mota, S.A.P. da., Leão, R.A.C., Souza, R.O.M.A. de., Araújo, M.E., Borges, L.E.P., Machado, N.T. Thermal catalytic cracking of crude palm oil at pilot scale: Effect of the percentage of Na<sub>2</sub>CO<sub>3</sub> on the quality of biofuels. *Industrial Crops and Products* 91 (2016) 32–43. <http://dx.doi.org/10.1016/j.indcrop.2016.06.033>.
  31. Mancio, A.A., Costa, K.M.B. da., Ferreira, C.C., Santos, M.C., Lhamas, D.E.L., Mota, S.A.P. da., Leão, R.A.C., Souza, R.O.M.A. de., Araújo, M.E., Borges, L.E.P., Machado, N.T. Process analysis of physicochemical properties and chemical composition of organic liquid products obtained by thermochemical conversion of palm oil. *Journal of Analytical and Applied Pyrolysis* 123 (2017) 284-295. <http://dx.doi.org/10.1016/j.jaap.2016.11.017>.
  32. Ferreira, C.C., Costa, E.C., Castro, D.A.R. de., Pereira, M.S., Mancio, A.A., Santos, M.C., Lhamas, D.E.L., Mota, S.A.P. da., Leão, R.A.C., Duvoisin Jr, S., Araújo, M.E., Borges, Luiz E.P., Machado, N.T. Deacidification of organic liquid products by fractional distillation in laboratory and pilot scales. *Journal of Analytical and Applied Pyrolysis* 127 (2017) 468–489. <http://dx.doi.org/10.1016/j.jaap.2017.06.016>.
  33. Mota, S. A. P. da., Mota, A. A. M. da., Machado, N. T. Influence of fractional distillation on the yield and quality of biofuels obtained through thermal catalytic cracking of crude palm oil. *Revista DYNA*, 88 (218), pp. 62-71, (2021), ISSN 0012-7353. DOI: <https://doi.org/10.15446/dyna.v88n218.90154>.

34. Mancio, A.A., Mota, S.A.P. da., Ferreira, C.C., Carvalho, T.U.S., Netod, O.S., Zamiand, J.R., Araújo, M.E., Borges, L.E.P., Machado, N.T. Separation and characterization of biofuels in the jet fuel and diesel fuel ranges by fractional distillation of organic liquid products. *Fuel* 215 (2018) 212-225. <https://doi.org/10.1016/j.fuel.2017.11.029>.
35. Natali, A. A. "Dendê: nascido para dar muito óleo". *Agrianual*, São Paulo, 219-226, 1996.
36. Santos, M. C. (2015). **Estudo do processo de craqueamento termo-catalítico da borra de neutralização do óleo de Palma na produção de biocombustível** [Tese] (Doutorado em Engenharia de Recursos Naturais). Universidade de Federal do Pará (Belém-Pará-Brazil).
37. Santos, M.C., Lourenço, R.M., Abreua, D.H. de., Pereira, A.M., Castro, D.A.R. de., Pereira, M.S., Almeida, H.S., Mancio, A.A., Lhamas, D.E.L., Mota, S.A.P. da., Souza, J. A. da Silva., Júnior, S. D., Araújo, M.E., Borges, L.E.P., Machado, N.T. Gasoline-like hydrocarbons by catalytic cracking of soap phase residue of neutralization process of palm oil (*Elaeis guineensis* Jacq). *Journal of the Taiwan Institute of Chemical Engineers* 71 (2017) 106-119. <http://dx.doi.org/10.1016/j.jtice.2016.11.016>.
38. Haas, M. J. (2005). Improving the economics of biodiesel production through the use of low value lipids as feedstocks: Vegetable oil soapstock. *Fuel Process. Technol.* 86, 1087-1096. DOI: [10.1016/j.fuproc.2004.11.004](https://doi.org/10.1016/j.fuproc.2004.11.004).
39. Szklo, A. S., Uller, V. C. Fundamentos do refino do petróleo: tecnologia e economia. 2ª Ed. rev. e ampl. – Rio de Janeiro: interciência, 2008.
40. Farah, M. A. *Petróleo e seus derivados: definição, constituição, aplicação, especificações, características de qualidade*. Rio de Janeiro: LTC, 2012.
41. Spath, P. L., Dayton, D. C. (2003). Preliminary screening - Technical and economic assessment of synthesis gas to fuels and chemicals with emphasis on the potential for biomass - Derived Syngas in Report NREL/TP-510-34929, National Renewable Energy Laboratory, U.S. Department of Energy laboratory.
42. Thilakaratne, R., Brown, T., Li, Y., Hu., Brown, R. (2014). Mild catalytic pyrolysis of biomass for production of transportation fuel: a techno-economic analysis. *Green Chem.* 16. 627.
43. Brown, T. R., Thilakaratne, R., Brown, R. C., Hu, G. (2013). Techno-economy analysis of biomass to transportation fuels and 742 electricity via fast pyrolysis and hydroprocessing. *Fuel*, 106, 463-469.
44. Jaroenhasemmesuk, C., Tippayawong, N. Technical and Economic Analysis of a Biomass Pyrolysis Plant. *Energy Procedia* 79 (2015) 950 – 955. doi: 10.1016/j.egypro.2015.11.592.