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Economic Feasibility Assessment of the Thermal Catalytic Process of Wastes: Açaí Seeds (*Euterpe oleracea*) and Scum from Grease Traps

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Abstract: In this work, a techno-economic assessment of the production of bio-oil, coke and gas, via thermo-catalytic pyrolysis followed by distillation, is accomplished. The raw materials were two solid wastes: lipid-based material (residual fat/scum from a fat retention box from the University Restaurant at the Federal University of Pará—UFPA) and a lignin-cellulosic material of açaí seed (*Euterpe oleracea* Mart.). From the literature, a review is made of the physicochemical analysis of the raw materials, of the bio-oil, and of the chemical composition of the biofuels produced (kerosene, light diesel, and heavy diesel). The bio-oil yields for each experiment of pyrolysis and distillation are also presented and compared with the literature. The economic indicators for the evaluation of the most viable cracking (pyrolysis) and distillation process of bio-oils were: (a) the simple payback criterion, (b) discounted payback, (c) net present value (NPV), (d) internal rate of return (IRR), and (e) index of profitability (IP). The analysis of the indicators showed the economic viability of the lipid-based material and unfeasibility for the açai seed (*Euterpe oleracea* Mart.). The breakeven point obtained was 1.28 USD/L and the minimum fuel selling price (MFSP) obtained in this work for the biofuels was 1.34 USD/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: scum from fat box; açaí seeds; thermal processing; biofuels; economic analysis; technical feasibility

1. Introduction

The world has a dependence on nonrenewable energy sources, mainly fossil fuels, such as coal and petroleum-based fuels (such as natural gas, diesel, and gasoline), which are related to global climate change.

As a result of this dependence, global warning occurs, caused by greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), intensifying the criticism associated with its polluting nature and the search for new, cleaner, and more sustainable energy sources [1,2].

It is estimated as a direct cause of approximately 150,000 additional deaths per year [3], an increasing risk of hunger for millions of people, floods, and water shortages, in addition to the increased occurrence of diseases such as malaria [4–6].

Energy efficiency and diversification of the energy matrix are the keys to balancing energy demand and supply, as well as minimizing environmental problems. In this context, other forms of energy, mainly renewable, must be studied and developed in order to reduce or even eliminate the environmental impacts caused during the stages of energy production, from the raw material to the final consumer [1,2]. The use of a renewable energy source contributes to reducing the emission of greenhouse gases, such as carbon dioxide. These gases are essential for maintaining the stability of the climate and terrestrial ecosystems, being responsible for having the capacity to retain heat in the atmosphere. In this way, the use of biofuels allows the short carbon cycle to be complete, in which carbon dioxide is absorbed in the plant growth process and released in the combustion of the biofuel in the engine [1,2].

Biofuel is a renewable source of energy produced from natural raw materials [7]. The concerns with the environmental aspects indicate that the use of biomass as technology for energy production is that which best fits the concept of sustainable development, due to the neutral process regarding carbon dioxide total emissions [8]. In this scenario, biofuels have been proposed as sustainable technological alternatives to replace fossil fuels. Thus, fuels derived from renewable sources, such as biomass, including vegetable oils, as well as palm oil, soybean oil, sunflower oil, cottonseed oil, in addition to residues from frying oils and even lipid material from fat boxes, have been intensively studied in recent years [9,10].

Biofuels, including bioethanol, charcoal, biodiesel, bio-oil, biogasoline, biogas, and biokerosene, are defined as solid, liquid, or gaseous fuels, produced from renewable biomass, in partial replacement or total to fossil fuels [11,12], being used mainly in internal combustion engines in motor vehicles as well as in electric power motor generators [13]. The process of thermal decomposition of triacyl-glycerides (in the absence of oxygen) is denominated as pyrolysis or cracking [11], which can be accomplished in the presence or absence of catalysts, resulting in a mixture of hydrocarbons, consisting mainly of molecules of linear chains, rich in fractions similar to gasoline, kerosene, and diesel of fossil origin [12,13].

Due to the characteristics of the molecules of triacyl-glycerides present in vegetable oils or animal fats, the pyrolysis process occurs in two successive steps: in the first stage occurs the formation of fatty acids, and in the second stage occurs the formation of hydrocarbons [14,15].

The oils and fats used in the food-frying process generate a considerable amount of waste [16]. It is known that a liter of frying oil released into the sewer system, or released into a “body of water”, has the property of inconveniently contaminating its treatment, as due to increased population in urban areas, it is necessary to increase the demand for drinking water—this being a product considered of high need for human beings [17]. In commercial establishments (restaurants, cafeterias, etc.), as well as in homes, the residual oils and fats from frying are collected in grease bins, being generally disposed of in sanitary landfills, generating significant volumes of residues. In this sense, these wastes, rich in lipid material and of low cost, have been investigated as a raw material for the production of biofuels [18], enabling the obtainment of biofuels from lipid residues from fat boxes, as well as the reduction in the quantity and volume of waste deposited in sanitary landfills [19].

In this context, the present work investigated the feasibility of producing fractions of biofuels similar to green kerosene, light diesel, and heavy diesel via catalytic thermal cracking of the residual fat (lipid material) from fat retention boxes from the University Restaurant of UFPA, using sodium carbonate (Na_2CO_3) in the proportion of 10% (wt.) as a catalyst, followed by distillation of organic liquid product (OLP) using a pilot distillation unit.

In the State of Pará (Brazil), the açai fruit is one of the most consumed products in the northern region of the county, whose residue is the seed, which is an environmental liability, mainly in the city of Belém-Pará. The production of açai fruit is 1,072,740 tons/year, which makes Pará State the largest national producer. The seeds, still without an adequate economic destination, are being discarded without any treatment in rivers and dumps [20]. With this, the vast amount of solid waste generated in Belém-Pará makes the study of the production of biofuels from açai seeds a promising alternative, considering the amount of raw material available, enabling the reuse of these residues for the generation of renewable energy [1,2].

In this context, this work proposes to investigate the process of biofuel production, via pyrolysis of açai seed chemically impregnated with sodium hydroxide (NaOH) at the pilot scale, evaluating the quality and the yield of reaction products obtained at 450 °C, followed by the fractional distillation of organic liquid products to produce biokerosene and light diesel using a pilot unit. The chemical composition of these products and yields are also presented [1,2].

Among the alternative renewable energy sources that are mature enough to be used commercially, only biomass has been identified with high technological efficiency [21]. Biomass has the flexibility to generate both electric energy and transportation fuels [21].

In recent years, several works have been accomplished studying the economic feasibility assessment of biofuel production starting from biomass and fat residues, 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 follows:

Wright et al. [22] presented a study to produce bio-oil through fast pyrolysis using corn stover as raw material, obtaining naphtha and diesel biofuels. The production considered for the plant was 2000 (two thousand) dry tons/day, in two scenarios: the first one producing hydrogen and the second one producing merchant hydrogen from the bio-oil. The fuel product value obtained was US$ 0.82 and US$ 0.56 per liter. The estimated product values considering the construction of a fast pyrolysis and upgrading biorefinery were US$ 1.73 and US$ 0.90 per liter.

Brown et al. [23] presented, in 2010, a study to produce biofuels through fast pyrolysis and hydroprocessing using biomass as feedstock. The economic feasibility analysis resulted in an MFSP of 2.11 US$/gallon (0.56 US$/L). In 2013, the same authors obtained an MFSP of 2.57 US$/gallon (0.68 US$/L) considering a facility of 2000 MTPD and corn stover as feedstock. In this study, gasoline and diesel biofuels were obtained. Another study was accomplished to produce transportation fuels (gasoline and diesel), monosaccharides and hydrogen via a fast pyrolysis and upgrading pathway, using the software Aspen Plus. As result, an internal rate of return (IRR) of 11.4% was obtained based on market prices of gasoline and 0.64 US$/L diesel, 3.33 US$/kg-hydrogen, and 2.92 US$/gallon (0.77 US$/L).

In the pyrolysis process, results of 50–75% bio-oil are presented in the literature (although yields above or below this range are not uncommon, depending on operational conditions, kind of feedstock, and reactor employed [24], some results such as 15–25% char (wt.) and 10–20% (wt.) gas are also presented [25,26]).

Mota [15] presented results of bio-oil production via thermal cracking and thermal–catalytic cracking of palm oil at different scales of production. Part of the product obtained was distilled using a laboratory Vigreux column and a Raschig-rings-packed pilot scale column. The author investigated the effect of different types of catalyst and the content of catalyst on the yield of liquid products (bio-oil). Results for the yields of bio-oil, coke, and gas of 63.6% (wt.), 8% (wt.), and 28.4% (wt.), respectively, were obtained.

Thihakaratme et al. [27] presented a study of biofuel production (hydrocarbon-based) via mild catalytic pyrolysis (CP) and upgrading of the partially deoxygenated pyrolysis. The raw material used was woody biomass. The economic feasibility assessment resulted in an MFSP of 3.69 US$/gallon (0.98 US$/L), assuming a 10% internal rate of return. The process gave a product fuel yield of 17.7% (wt.).

Jaronenkhasemmesuk et al. [28] mention that the fast pyrolysis process to produce bio-oil has a great potential to become one of the main renewable energy resources. A plant of 20–30 dm^3/day of bio-oil production was used, where the mass and energy balance were applied to evaluate the performance and improvement in design. The study demonstrated that the cost of crude bio-oil production was about THB 30–35 per dm^3.

Vasalos et al. [29], investigated bio-oil production via thermal–catalytic pyrolysis at 482 °C and using the commercially available ZSM-5 catalyst in a circulating fluid bed (CFB) reactor. The raw material used was woody biomass (beechwood) and was considered a commercial-scale production of 180.000 tons per year with a 90% operating factor. A sensitivity analysis showed that the price of CPO could vary from 615 to 841 US$/MT (22–31 US$/GJ). On a crude oil energy equivalent basis, the bio-oil cost was in the range of 36–49 US$/GJ.

Wang and Jan [30] presented a study of bio-oil production at 400 and 450 °C using rice husk as raw material, in a fluidized bed fast pyrolysis process. The results indicated that the major components of bio-oil contain n-hexadecanoic acid, octadecaoic acid, 9-octadecenoic acid, and decanoic acid. The analyses of GC-MS/FID and GC-TCD showed that the major components of noncondensable gas are CO, CO_2, H_2, CH_4, and N_2. The techno-economic analyses resulted in an MFSP of 0.55 US$/liter for the plant size of 1000 tons/day.

Im-Orb et al. [31], presented a study of synthesis gas and bio-oil production via an integrated biomass pyrolysis and gasification (IBPG) process for the case where rice straw is a considered feedstock. The software Aspen was used in the simulations. The IBPG process with a pyrolysis temperature of 700 °C showed the best technical performance. Analysis indicated that the IBPG process with a pyrolysis temperature of 400 °C or 500 °C and conventional biomass gasification is technically feasible. The economic analysis, which considered only the reaction-related equipment, indicated that the IBPG process with a pyrolysis temperature of 500 °C offers synthesis gas and bio-oil production rates of 1.185 and 0.2044 kmol h^{-1}, respectively, and an energy efficiency of 68.86% is most economically feasible.

Xia et al. [32], investigated the pyrolysis process using Chinese chestnut (CNS) and Jatropha curcas shells (JCS), respectively, to determine the optimum operating temperature. At low temperatures (250–450 °C), CO_2 was the main component of the pyrolytic gas, and high-acidity oil was obtained. When the temperature increased to 550–650 °C, phenol-enriched oil and high-LHV biochar (~26 MJ/kg) were obtained; H_2 and CO yields increased. At high temperatures (750–950 °C), heavy oil and high-LHV pyrolytic gas (~15 MJ/m^3) were obtained. CNS and JCS biochars showed different tendencies with regard to their structure evolution. An economic analysis was performed, which suggested that the optimum operating temperatures were 450°C for CNS and 350 °C for JCS.

Martis et al. [33], presented a study to produce biofuels from palm waste, using the software Aspen Plus v.10, where the pyrolysis, gasification, and fermentation were investigated. The calculation base was 1 ton of biomass feed, where the result was 56 kg of hydrogen and 233 kg of ethanol (fermentation). The net consumption of energy in the pyrolysis was 37 KJ/ton of biomass feed, in the fermentation was 725 KJ, and for fermentation was 7481.5 KJ per ton of biomass feed. Another result showed that the bioethanol fuel price was 1.85 US$/L. The economic analysis indicated that pyrolysis and gasification are economically more feasible than fermentation.

Badger et al. [34], highlight that biomass is defined as organic matter that is renewable and biodegradable. Biomass can be converted to either ethanol or bio-oil. Pyrolysis is the chemical decomposition of organic materials by heat (around 500 °C) in the absence of oxygen [35]. 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 [15,36].

Cheng et al. [37], presented a study of biochar production through slow pyrolysis using machine learning approaches, life cycle assessment (LCA), and economic analysis. The results demonstrated three important metrics: energy return on investment (EROI), net global warming potential (GWP), and minimum product selling price (MPSP).

The slow pyrolysis of crop residues and woody wastes holds promise as an energy-producing negative-emissions technology, with EROI values from 1.90 to 3.60 (without substitution) and 2.40 to 4.30 (with substitution), and GWP values from 470 kg CO_2 eq/t to 200 kg CO_2 eq/t (without substitution) and 1050 kg CO_2 eq/t to 770 kg CO_2 eq/ton (with substitution). The MSPS values evaluated in this study range from 774.00–1256.00 USD/ton, depending on temperature and feedstocks. Techno-economic analysis, life cycle assessment, and technology readiness are also presented by Sorunmu et al. [38].

Lan et al. [39], presented a study of economic feasibility analysis to produce biofuels through fast pyrolysis, fed with blended pine residues and switchgrass. The minimum fuel selling price (MFSP) of biofuel was USD 3.92–4.33 per gallon gasoline equivalent (GGE), while the MFSP for the centralized biorefinery at the same capacities ranged between 3.75 and 4.02 USD/GGE. Scenario analysis indicated decreased MFSP with increasing biorefinery capacities.

Castro et al. [1], presented a study of bio-oil production (in different scales) through pyrolysis followed by distillation for producing biofuels, using the biomass of açaí seeds (*Euterpe oleracea* Mart.) at 450 °C and 1.0 atmosphere as feedstock. The distillation of bio-oil produced gasoline, light kerosene, and kerosene-like fuel fractions, and the yields were 16.16, 19.56, and 41.89 (wt.%), respectively. The physical-chemistry properties of the distillation fractions increased with temperature. The FT-IR analysis of bio-oils and distillation fractions identified the presence of functional groups characteristic of hydrocarbons (alkenes, alkanes, aromatics, and aromatic rings) and oxygenates (carboxylic acids, ketones, esters, ethers, alcohols, and phenols).

Several studies have presented techno-economic assessments of pyrolysis bio-oil production [25,26,40]. The incentives for producing with thermal–catalytic pyrolysis technology are [41,42]: (1) higher stability in storage and transportation and (2) high energy content (28–30 MJ/kg) [35,40], and (3) some products present lower acidity and as a result are less corrosive. Due to these aspects, it is important to estimate the cost production of bio-oil and their use in commercial applications for either transportation fuels or chemicals. Economic analysis is accomplished based on pilot plant data with a commercially available catalyst (Na_2CO_3) in all experiments evaluated in this work.

Energy from biomass can be produced by thermal–catalytic cracking (pyrolysis) and the distillation process [15]. Pyrolysis of biomass, such as palm oil (*Elaeis guineensis*, Jacq), can produce biofuels. After distillation, the distilled fractions (biofuels) are similar to gasoline, kerosene, and diesel of fossil origin [13].

Although several studies have been reported regarding the economic feasibility of biofuel production, the innovation of this work is related to the assessment of economic feasibility of two raw materials, lipid material and açaí seed, which have been studied to evaluate the best investment alternative. Moreover, this work highlights that 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). In order to evaluate the various influences over the minimum fuel sale price (MFSP), an analysis of sensibility was accomplished. Moreover, the breakeven point of the viable project is presented. It is important to emphasize that the set of these methodologies have not been described in the literature until now.

2. Materials and Methods

2.1. Materials

2.1.1. Lipid-Based Materials

The residual fat/scum from a retention box of the University Restaurant of UFPA was obtained and preprocessed as described in the literature [4–6].

2.1.2. Açai Seeds (*Euterpe oleracea* Mart.)

The seeds of açaí in nature were collected and preprocessed as described in detail in the literature [1,2].

2.2. Thermal Cracking, Thermal–Catalytic Cracking, and Distillation Process

The pyrolysis, thermal–catalytic cracking, and distillation processes of açaí seed (*Euterpe oleracea* Mart.) and lipid-based material from a fat retaining box of the University restaurant of UFPA were described in detail by [4–6] and [1,2], respectively.

2.3. Project Evaluation Criteria

Aiming to assess the economic viability of the distillation and pyrolysis process of the lipid-based material (residual fat/scum from a retention box of the University Restaurant of UFPA) and a lignin-cellulosic material açaí seed (*Euterpe oleracea* Mart.), a classic methodology was applied (use of the economic indicators' viability [24]). Associated with this evaluation, a sensibility analysis was calculated, as well as the breakeven point and the minimum fuel sale price (MFSP) [22,23,27,30,33,39]. The methodology that was applied can be seen in Figure 1.

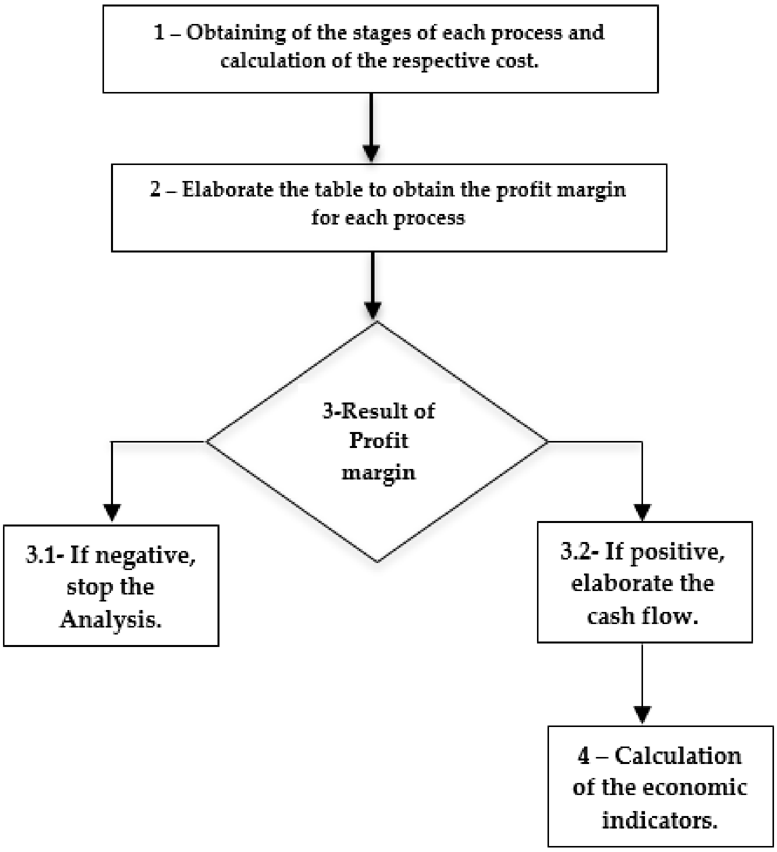

Figure 1. Methodology used to accomplish the economic feasibility assessment.

Figure 2 presents the scheme used in the process by [4–6] to convert the lipid material (residual fat/scum from a fat retention box of the University Restaurant of UFPA) into organic liquid product (bio-oil), coke, and methane gas through the pyrolysis process using 10% (wt.) sodium carbonate as a catalyst at 440 °C, followed by distillation to obtain biofuels (green kerosene, light diesel, and heavy diesel).

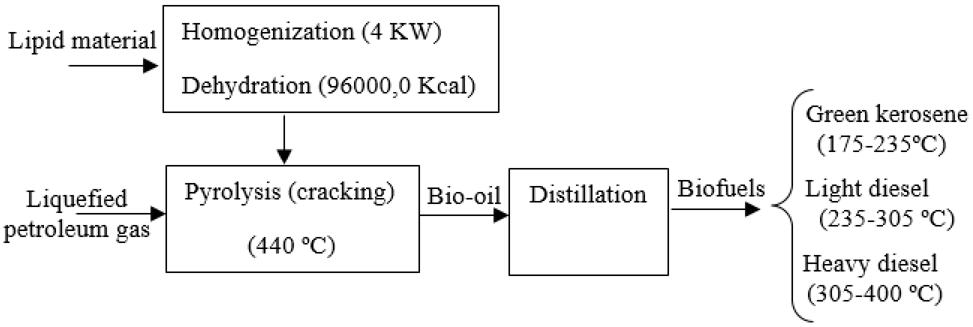

Figure 2. Scheme of conversion of lipid-based material into biofuels.

Figure 3 illustrates the scheme used in the process by [1,2] to convert the açai seeds into organic liquid product (bio-oil), coke, and methane gas though the pyrolysis process at 450 °C, followed by distillation to obtain biofuels (biokerosene and light-green diesel).

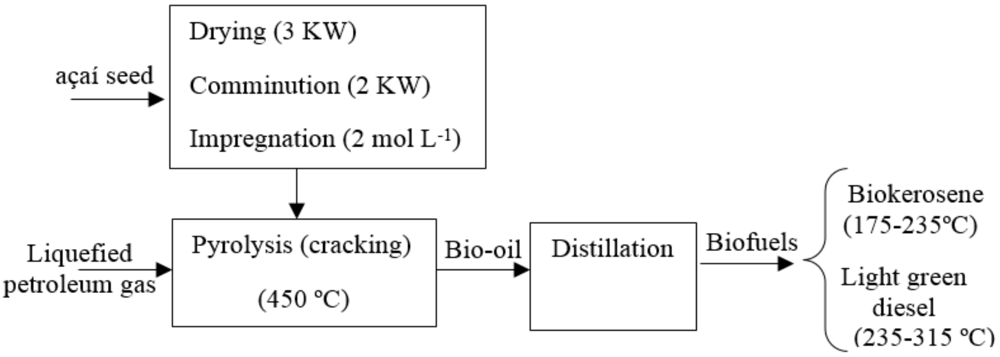

Figure 3. Scheme of conversion of açaí seed (*Euterpe oleracea*) into biofuels.

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 [43]:

- 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 [43]. 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).

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.

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 [43].

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) It 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, point to suffering 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 [43].

IRR Decision-Making Criteria

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

(a) If the cost of capital < IRR, the project must be accepted (NPV > 0).
(b) If the cost of capital = IRR, it can be accepted or not (NPV = 0).
(c) If the cost of capital > IRR, the 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.

2.4. Calculation Methodology

The calculations, from Section 2.4.1 up to Section 2.4.16, are applied to compute the revenues and expenses using lipid-based materials and açai seeds (*Euterpe oleracea* Mart.) as feed. Table 1 shows the parameters used in the equations below.

Table 1. Process data used to compute the economic models.

Process Parameters	Value	Unit
M is the mass of the lipid material	145	Kg
M is the mass of the açai seed	150	Kg
N_{sh} is the number of shifts per day	3	-
N_{bat} is the number of batches per shift using the lipid material considering the feed rate	5	-
N_{bat} is the number of batches per shift using the açaí seed considering the feed rate	3	-
d is the density of the lipid material	$0.98 \cdot 10^{-3}$	kg/L
d is the density of the açai seed	$1.49 \cdot 10^{-3}$	kg/L
Y_{oil} is the pyrolysis process yield of the bio-oil from the lipid material	68.73	%
Y_{oil} is the pyrolysis process yield of the bio-oil from the açaí seed	11.03	%
Y_{coke} is the pyrolysis process yield of coke from the lipid material or açaí seed	5.03	%
Y_{coke} is the pyrolysis process yield of coke from the açaí seed	39.84	%
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 lipid material	26.24	%

Table 1. *Cont.*

Process Parameters	Value	Unit
Y_{gas} is the pyrolysis process yield of methane gas from the açaí seed	31.62	%
P_{LPG} is the price of liquefied petroleum gas	0.503	US$/L
d_{gas} is the methane gas density	$0.72 \cdot 10^{-3}$	kg/L
Y_{bio} is the distillated process yield of lipid material	15.07	%
Y_{bio} is the distillated process yield of the açai seed	73	%
P_{RM} is the price of the raw material of the lipid material (it was considered 10% of the soy oil price)	1.295	US$/kg
P_{RM} is the price of raw material of the açaí seed	0.027	US$/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 batches per day of the lipid material considering the distillation	16	-
N_{bat} is the number of batches per day of the açaí seed 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 the lipid material and açaí seed	1.34	US$/L
N_{bat} is the number of batches per day of the lipid material considering homogenization	15	-
P_{KW} is the power of the homogenization system	4	KW
t is the homogenization operation time per batch	0.33	h
P_{deh} is the power of the boiler	$96 \cdot 10^{6}$	cal
f_{KWh} is the factor of conversion from calories (cal) to KWh	$11.62 \cdot 10^{7}$	KWh/cal
t_{deh} is the time of dehydration per batch	2	h
N_{deh} is the number of dehydration batches per day	3	-
P_{dry} is the power of the equipment of drying	3	KW
t_{dry} is the time of drying per day	24	h
N_{dry} is the number of drying batches per day	12	-
P_{com} is the power of the equipment of comminution	3	KW
t_{com} is the time of comminution per batch	1	h
N_{com} is the number of comminution batches per day	24	-
P_{NaOH} is the price of sodium hydroxide	3.67	US$/L
N_{mol} is the number of moles	2	moles/L
M_{mol} is the molecular mass of sodium hydroxide which is 40	40	kg/Kgmol
V_{sol} is what the sodium hydroxide solution volume was	1	L

2.4.1. Feed Rate

The feed rate is computed using Equation (6).

$$Q = \frac{M * N_{sh} * N_{bat}}{d} \tag{6}$$

where Q is the volumetric flow rate of the lipid material or açaí seed [L/day] and M is the mass of the lipid material or açai seed in [kg] per shift. N_{sh} = number of shifts per day [-]; N_{bat} = number of batches per shift using the lipid material or açaí seed [-]; and d = density of the lipid material or açaí seed in [kg/L].

2.4.2. Flow of Organic Liquid Product (OLP)

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

Q_{bio} = flow of organic liquid product (bio-oil) [L/day]; Y_{oil} = pyrolysis process yield of the bio-oil from the lipid material or açaí seed in [%]; and Q = flow of the lipid material or açai seed [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$/day]; Y_{coke} = pyrolysis process yield of coke from the lipid material or açaí seed in [%]; Q = flow of lipid material or açaí seed in [L/day]; P_{coke} = price of coke [US$/kg]; and d_{coke} = coke density [kg/L].

2.4.4. Flow of Gaseous Product (Biogas)

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

m_{gas} = flow of methane gas [US$/day]; Y_{gas} = pyrolysis process yield of methane gas from the lipid material or açaí seed in [%]; Q = flow of lipid material or açai seed in [L/day]; P_{LPG} = price of liquefied petroleum gas [US$/L]; $f1$ = it was considered that the methane gas flow was 10% of the Y_{gas} pyrolysis process yield of methane gas; $f2$ = it was considered that the price of the methane gas was 50% of the liquefied petroleum gas (L.P.G) [-]; and 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 of the lipid material or açai seed in [%]; and Q_{bio} = flow of the organic liquid product (bio-oil) [L/day].

2.4.6. Cost of Raw Material

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

C_{RM} = cost of raw material of the lipid material or açai seed [US$/L]; P_{RM} = price of raw material of the lipid material (it was considered 10% of the soy oil price) or açaí seed in [US$/kg]; Q = flow of vegetable lipid material or açaí seed in [L/day]; and d_{RM} = density of the lipid material or açaí seed in [kg/L].

2.4.7. Cost of Catalyst

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

C_{cat} = cost of the catalyst Na_2CO_3 in [US$/L]; P_{cat} = price of the catalyst [US$/Kg]; and m_{cat} = percent of the catalyst in relation to the feed rate (10% for the lipid material and 15% for the açai seed) in [%].

2.4.8. Cost of Liquefied Petroleum Gas (LPG)

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

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

2.4.9. Cost of Manpower

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

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 depended on the bio-oil produced in each pyrolysis process. It was considered 120 Kg per unit of distillation for the lipid material and 50 Kg per unit for the açaí seed use (once the flow yield of the process using açaí seed was only 11.03% (wt.), which means a low amount of bio-oil to be distillated).

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

D_c = distillation cost in [US$/L]; N_{bat} = number of batches per day of the lipid material and of açaí seed in [-]; P_{KW} = power of the distillation column in [KW]; t = distillation operation time during one day in [h]; and P_{KWh} = price of the KWh in [US$/KWh].

2.4.11. Tax

$$T = \frac{\%T * SP_{bio}}{100} \tag{16}$$

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

2.4.12. Total Profit per Day

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

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

2.4.13. Homogenization

This calculation is applied to Table 3 (Revenues and expenses using lipid material as raw material).

$$H_c = \frac{N_{bat} * P_{KW} * t * P_{KWh}}{(D_{bio} + m_{coke} + m_{gas})} \tag{18}$$

H_c = homogenization cost in [US$/L]; N_{bat} = number of batches per day of the lipid material in [-]; P_{KW} = power of the homogenization system in [KW]; t = homogenization operation time per batch in [h]; and P_{KWh} = price of the KWh in [US$/KWh].

2.4.14. Dehydration

This calculation is applied to Table 3 (Revenues and expenses using lipid material as raw material).

$$C_{deh} = \frac{P_{deh} * f_{KWh} * t_{deh} * N_{deh} * P_{kwh}}{(D_{bio} + m_{coke} + m_{gas})} \tag{19}$$

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

2.4.15. Drying

This calculation is applied to compute the revenues and expenses using açaí seed as raw material.

$$C_{dry} = \frac{P_{dry} * t_{dry} * N_{dry} * P_{kwh}}{(D_{bio} + m_{coke} + m_{gas})} \tag{20}$$

C_{dry} = cost of drying [US$/L]; P_{dry} = power of the equipment in [KW]; t_{dry} = time of drying per day [h]; N_{dry} = number of drying batches per day [-]; and P_{KWh} = price of the KWh in [US$/KWh].

2.4.16. Comminution

This calculation is applied to compute the revenues and expenses using açaí seed as raw material.

$$C_{com} = \frac{P_{com} * t_{com} * N_{com} * P_{kwh}}{(D_{bio} + m_{coke} + m_{gas})} \tag{21}$$

C_{com} = cost of comminution [US$/L]; P_{com} = power of the equipment (3) in [KW]; t_{com} = time of comminution (1) per batch [h]; N_{com} = number of comminution batches per day (27) [-]; and P_{KWh} = price of the KWh in [US$/KWh].

2.4.17. Cost of Impregnation

This calculation is applied to compute the revenues and expenses using açaí seeds as raw material. The solution used to impregnate the raw material had a concentration of sodium hydroxide of 2 mol/L. For each 32 kg of açaí seed, 64 L of sodium hydroxide solution was used.

$$C_{imp} = \frac{64 * Q * N_{mol} * M_{mol} * V_{sol} * P_{NaOH}}{32 * 10^3 (D_{bio} + m_{coke} + m_{gas})} \tag{22}$$

C_{imp} = cost of impregnation in [US$L]; P_{NaOH} = price of sodium hydroxide [USD/L]; N_{mol} = number of moles [moles/L]; M_{mol} = molecular mass of sodium hydroxide is 40 [Kg/Kgmol]; and V_{sol} = sodium hydroxide solution volume in [L].

3. Results

3.1. Lipid-Based Material

The results presented in this work were those from the pyrolysis of the lipid-based material (Experiment 1) with 10% (wt.) of catalyst (Na_2CO_3) carried out in the pilot scale. The results presented by Almeida [4–6], for the yields of reaction products by pyrolysis and distillation, are shown in Supplementary Materials Table S1.

Supplementary Materials Table S2 presents the results of physicochemical characterization of the lipid material used as raw material in the pyrolysis pilot unit. It can be observed that the saponification index is in agreement with the values reported in the literature by Ratton [18], which found an average value of 189 mg KOH/g. The saponification index indicates that the sample presents large amounts of fatty material, with great potential to form soap to be used in the pyrolysis process. The acidity index indicates the presence of free fatty acids.

The physicochemical characterization of the bio-oil is presented in Supplementary Materials Table S3 and is compared with the specifications of the resolution N° 65 of the Petroleum National Agency, Natural Gas and Biofuels, for petroleum-derived diesel. The result of the acidity index was low and presented a value of 14.97 mg KOH/g, which is in agreement with similar data reported in the literature. The results of density and the flash point were in agreement with the ANP N° 65. The results of the saponification index reduced from 120.19 mg KOH/g (pretreated lipid-based material) to 24.22 mg KOH/g (bio-oil) and the kinematic viscosity reduced from 9.4 cSt (pretreated lipid-based material) to 3.29 cSt (bio-oil).

Supplementary Materials Table S4 presents the composition results of the organic liquid product (bio-oil) obtained through the pyrolysis process, using 10% (wt.) sodium carbonate as a catalyst at 440 °C. It is possible to confirm an effective deoxygenation of the bio-oil resulting from the cracking reaction with the use of catalyst sodium carbonate, indicated by the high percentage of hydrocarbons of 78.98% (wt.), as well as the low concentration of oxygenated compounds equal to 15.72% (wt.).

Supplementary Materials Table S5 presents the percentual composition of hydrocarbons and oxygenated compounds of green kerosene obtained by pyrolysis of the lipid-based material with 10% (wt.) of Na_2CO_3 at 440 °C (Experiment 1). It can be observed that there is a high concentration of hydrocarbons (92.64%), with the highest percentages of olefinic hydrocarbons (44.99%) and paraffin hydrocarbons (29.61%), and an absence of oxygenated compounds [4–6].

Supplementary Materials Table S6 presents the composition of light diesel (235–305 °C) by pyrolysis of the lipid-based material with 10% (wt.) of Na_2CO_3 at 440 °C (Experiment 1). It can be observed that the hydrocarbons of the light diesel obtained were paraffins, olefins, aromatics, and naphthenics. These results show that the highest percentages of hydrocarbons were of olefins (47.12%) and paraffins (33.92%). Furthermore, this fraction of diesel obtained from the distillation of the organic liquid product (bio-oil) did not produce oxygenated compounds in the form of carboxylic acids, only in the form of alcohols (9.79%) [4–6].

Supplementary Materials Table S7 presents the composition of heavy diesel (305–400 °C) by the pyrolysis of lipid-based material with 10% (wt.) of Na_2CO_3 at 440 °C (Experiment 1). It can be observed that the hydrocarbons of the light diesel obtained were paraffins, olefins, aromatics and naphthenics. These results show that the highest percentages of hydrocarbons were olefins (32.61%) and paraffins (25.20%). Aromatic and naphthenic hydrocarbons were present in a small percentage, around 5% (wt.).

Table 2 presents the economic parameters for discounted cash flow analysis. The total project investment was US$ 91,803.95 (ninety-one thousand eight hundred and three dollars and ninety-five cents) and corresponds to the initial investment of the cash flow, based on the similar data reported in the literature [44].

Table 2. Economic Parameters for Discounted Cash Flow Analysis.

Plant Life	**5**	**Years**
Plant size/biomass feed rate (lipid material)	450	L/day
Plant size/biomass feed rate (açaí seed)	906.04	L/day
Discount rate	10	% per year
Financing	100	% equity
Plant recovery period	5	years
Federal tax rate	10	%
Feedstock cost (lipid material)	1.295	US$/L
Feedstock cost (açaí seed)	0.027	US$/L
Availability (lipid material)	50	%
Availability (açaí seed)	93.75	%
On stream time	4320	h
On stream time	8100	h
Reference year	2022	
Electricity price	0.2186	US$/KWh
Total purchased equipment costs (TPEC)	30,951.37	US$
Direct costs (including equipment installation, instruments and controls, electrical piping, and misc. buildings)	18,880.33	US$ (61% TPEC)

Table 2. *Cont.*

Plant Life	**5**	**Years**
Total installed equipment cost (TIEC)	49,831.70	US$ (61% TPEC + TPEC)
Warehouse	747.48	US$ (1.5% TIEC)
Site development	2242.43	US$ (4.5% TIEC)
Total installed cost (TIC)	52,821.60	US$ (TIEC + warehouse + site development)
Indirect field costs (IFC)		
Field expenses	10,564.32	US$ (20% TIC)
Home office and construction fee	13,205.40	US$ (25% TIC)
Project contingency	1584.65	US$ (3% TIC)
Proratable costs	5282.16	US$ (10%TIC)
Total capital investment (TCI)	83,458.13	US$ (TIC + IFC)
Other costs (startup, permits, etc.)	8345.81	US$ (10% TCI)
Total project investment (TPI)	91,803.95	US$ (TCI+ Other costs)

Table 3 presents the total revenue, total expense, and the annual profit of US$ 36,692.0 (thirty-six thousand six hundred and ninety-two dollars) per year. The minimum fuel selling price (MFSP) obtained in this work for the biofuels was 1.34 US$/L. The literature mentioned in this work presents values of 0.68 up to 0.98 (US$/L).

Table 3. Revenues and expenses of using lipid-based material as feed.

Revenue		
Feed rate_56.25% (Availability)_Cracking	450	L/day d = 0.98 kg/m^3
Organic Liquid Product/Bio-oil_68.73%	321.17	L/day (feed distilled)
Solid product (coke)_5.03%	27.04	US$/day
Gaseous product (Biogas)_26.24%	16.28	US$/day
Distilled biofuel_15.07%	183.9	L/day
Sale price of biofuel	1.34	US$/L
Total expense	**1.02**	**US$/L**
Raw material (lipid material)	0.245	US$/L
Homogenization (4 KW)	0.005	US$/L
Dehydration (96,000 Kcal) (2 h)	0.156	US$/L
Catalyst_ 10%	0.046	US$/L
Liquefied petroleum gas (LPG)_10%	0.045	US$/L
Manpower	0.026	US$/L
Distillation (Heating)_5 KW	0.364	US$/L
Federal tax rate 10%	0.134	US$/L
Profit margin	0.32	US$/L
Total profit per day	102.5	US$/day
Total profit per month	3076	US$/month
Total profit per year	36,916	US$/year

Table 4 shows the cash flow for the investment analysis through the simple payback criterion. It can be concluded that in the third year, the investment is fully recovered, totaling US$ 18,942.86 (eighteen thousand nine hundred forty-two dollars and eighty-six cents). In this case, the project is considered economically viable within the horizon of analysis of 5 years.

Table 4. Annual cash flow for the lipid material and simple payback analysis.

Year	0	1	2	3	4	5
Cash flow	−91,803.95	36,915.60	36,915.60	36,915.60	36,915.60	36,915.60
Accumulated value	−91,803.95	−54,888.35	−17,972.74	18,942.86	55,858.46	92,774.06

Table 5 shows the cash flow for the investment analysis considering the discounted payback criterion, the net present value (NPV) criterion, the internal rate return (IRR) criterion, and the profitability index. For the discounted payback criterion, it can be concluded that in the third 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 five years is considered the analysis horizon of the evaluation of the project. For the net present value (NPV) criterion, it can be concluded that in the third year, there is a capital increase of US$ 48,135.23 (forty-eight thousand one hundred and thirty-five dollars and twenty-three 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. For the internal rate return (IRR) criterion, it can be concluded that in the second year, the accumulated value is zero, which represents the IRR of the project as 10.0% p.y. In this case, the IRR is equal to the minimum attractiveness of the project (10.0% p.y), which means that the project is economically viable. According to [27], a minimum fuel selling price (MFSP) of US$ 3.69 per gal was obtained, assuming a 10% internal rate of return. Finally, for the profitability index, it is possible to obtain the value of 1.52 (index of profitability). It means that for each dollar invested in the project, a return of 1.52 dollars it will occur. According to the criteria of this index, the project is considered economically viable.

Table 5. Annual cash flow for the bio-oil produced by pyrolysis of lipid-based material 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	−91,803.95	36,915.60	36,915.60	36,915.60	36,915.60	36,915.60
Present value	−91,803.95	33,559.64	30,508.76	27,735.24	25,213.85	22,921.68
Accumulated value	−91,803.95	−58,244.31	−27,735.50	0	25,213.54	48,135.23

Figure 4 corresponds to the sensitivity analysis for 450 L/day; to reach the baseline transportation fuel MFSP of 1.34 US$/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 [23].

Figure 5 illustrates the MFSP as a function of bio-oil yield by sensitivity analysis for a 450 L/day production. Figure 6 shows the MFSP as a function of distillation yield by sensitivity analysis for a 450 L/day production. Both graphics show that the increase in yield results in a reduction in MFSP. Figure 5 demonstrates that for 75% of bio-oil yield, the MFSP decreases to 1.26 US$/L. Figure 6 demonstrates that when the distillation yield achieves 25%, the MFSP reduces to 1.1 US$/L.

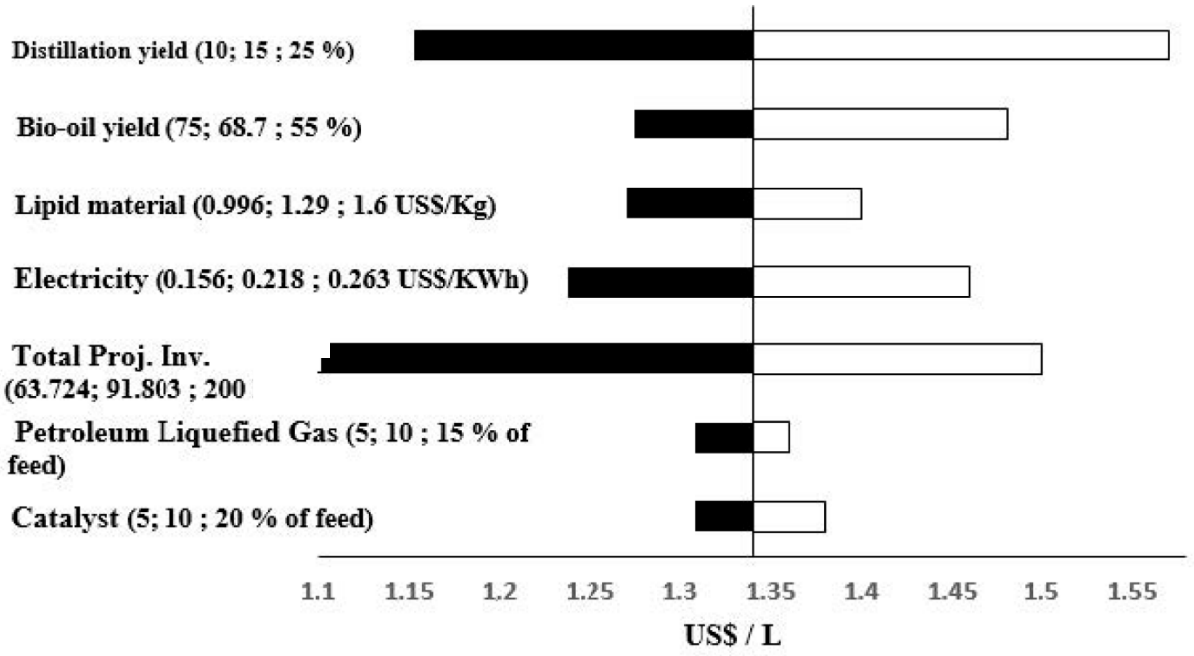

Figure 4. Sensitivity analysis for 450 L/day; to reach the baseline transportation fuel MFSP of 1.34 US$/L, the 10% facility IRR is assumed.

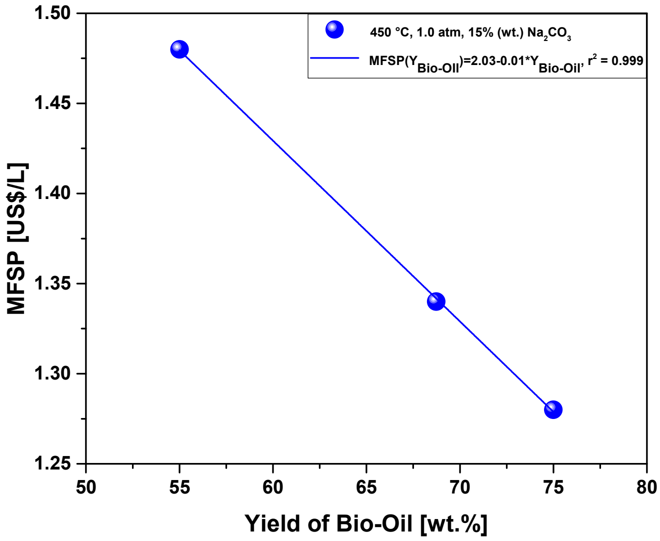

Figure 5. MFSP as a function of bio-oil yield by sensitivity analysis for a 450 L/day production.

Figure 7 is the MFSP as a function of the cost of lipidic material by sensitivity analysis for a 450 L/day production and Figure 8 is the MFSP as a function of project investment by sensitivity analysis for a 450 L/day production. Both graphics demonstrate that the increase in the cost of lipid material and the increase in the total project investment results in an increase in the MFSP. Figure 7 demonstrates that when the cost of lipid material reaches 1.6 US$/Kg, the MFSP achieves 1.4 US$/L. Figure 8 demonstrates that when the total project investment is reduced to around US$ 61,000 (sixty-one thousand dollars), the MFSP is reduced to 1.05 US$/L (which is a value extremely near to that applied in Brazil to biofuels).

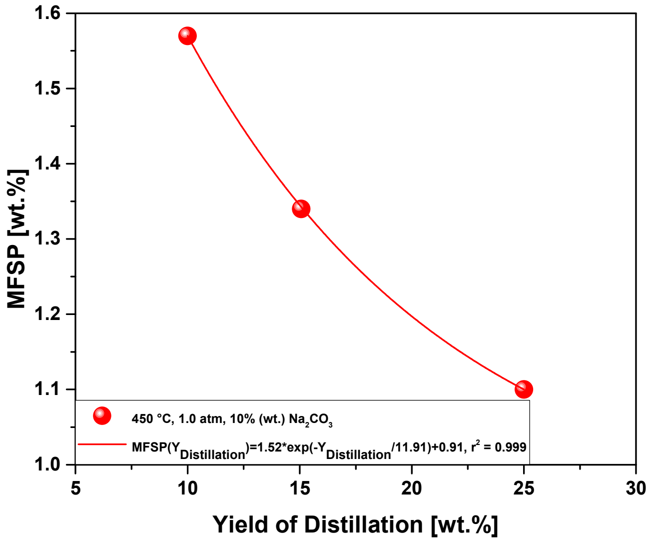

Figure 6. MFSP as a function of distillation yield by sensitivity analysis for a 450 L/day production.

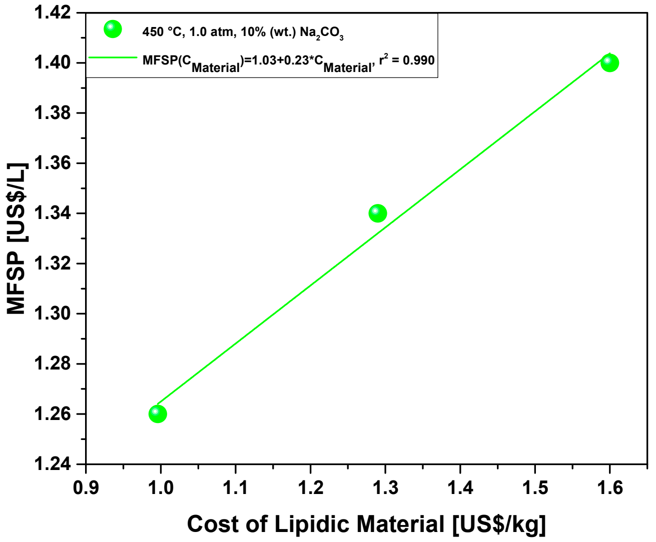

Figure 7. MFSP as a function of cost of lipidic material by sensitivity analysis for a 450 L/day production.

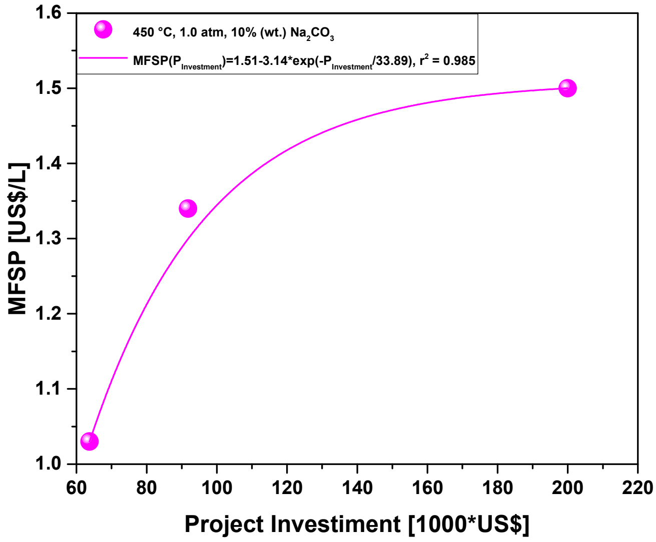

Figure 8. MFSP as a function of project investment by sensitivity analysis for a 450 L/day production.

Operation cost, payback period (PBP), and breakeven analysis are 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 [28]. Table 6 presents the cash flow in which the total cost is equal to the total revenues and corresponds to nil in the fifth year of cash flow. The value of MFSP obtained was 1.30 US$/L.

Table 6. Breakeven point calculation.

Year	0	1	2	3	4	5
Cash flow	−91,803.95	24,217.65	24,217.65	24,217.65	24,217.65	24,217.65
Present value	−91,803.95	22,016.05	20,014.59	18,195.08	16,540.98	15,037.26
Accumulated value	−91,803.95	−69,787.90	−49,773.31	−31,578.23	−15,037.25	0.00

3.2. Lignin–Cellulose-Based Material

The results presented is this work were those obtained by the pyrolysis of açai seed (*Euterpe oleracea* Mart.) at 450 °C carried out in a pilot unit. The results presented in the literature [1,2], for the yields of reaction products are shown in Supplementary Materials Table S8.

The knowledge of the physicochemical characteristics of lignocellulosic raw materials helps the selection of biomasses for thermo-chemical processing in order to obtain products with high added value [1,2]. Supplementary Materials Table S9 shows the physical characterization of the açaí seeds after drying at 105 °C.

Supplementary Materials Table S10 presents the physicochemical characterization of the organic liquid product (bio-oil) obtained by the pyrolysis of açaí seed (*Euterpe oleracea* Mart.).

Supplementary Materials Table S11 presents the yields of the pretreatment of raw material including drying, comminution, and sieving processes, as well as the total yield of the pretreatment process carried out for each batch. The results demonstrated that the raw material collected presented 40% (wt.) moisture in biomass. This is due to the pulping process using water for juice extraction and the inappropriate disposal of seeds in the environment [1,2].

After pretreatments, yields associated with seed moisture can be seen (drying) as mass losses during the process (comminution), as well as the separation of excess fibers (sieving). In addition, the seeds were submitted to chemical impregnation in order to improve the efficiency of pyrolysis processes in terms of the yield and quality of biofuel products. The treatment with sodium hydroxide directly effects the reduction in hemicellulose and lignin in the biomass structure, as it activates the cellulose hydroxyls.

Supplementary Materials Table S12 shows the composition of the bio-oil obtained by the pyrolysis of açaí seed in nature. By analyzing the bio-oil obtained by the pyrolysis of açaí seeds in nature at 450 °C, the chemical compounds identified were aliphatic hydrocarbons (alkanes, alkenes, cycloalkanes, and cycloalkenes), aromatics (benzenes and naphthalenes), and oxygenated compounds (esters, ethers, carboxylic acids, ketones, and aldehydes) [1,2]. It can be observed that there is a presence of 19.804% (area.) aromatic hydrocarbons, 38.081% (area.) aliphatic hydrocarbons, and 39.552% (area.) oxygenates. Percentages of nitrogenous and chlorinated compounds below 3% (area.) can also be observed.

Regarding the procedure of chemical impregnation, a high obtention of hydrocarbons (an increase of 36.36% when compared with the absence of impregnation) was observed as well as a reduction in the formation of oxygenated compounds of 42.59% when using açaí seed in nature [1].

Supplementary Materials Table S13 shows the identification and quantification of the organic groups present in the fraction of biokerosene QVA (175–235 °C) obtained by the distillation of bio-oils. The biokerosene contains aromatics (47.283%), aliphatics (34.072%), ketones (0.685%), alcohols (7.077%), and phenols (10.882%).

Supplementary Materials Table S14 shows the identification and quantification of the organic groups present in the fraction of light-green diesel DVA_L (235–315 °C) obtained by the distillation of bio-oils. The light-green diesel contains aromatics (78.326%), aliphatics (10.081%), ketones (4.058%), alcohols (4.201%), and phenols (3.334%).

Table 7 presents the analysis of the revenues and expenses by the pyrolysis of açaí seeds in nature fallowed by distillation. It is clear that the impregnation of the açaí seeds with sodium hydroxide (2 mol L^{-1}) presented an extremely high cost of 1.812 US$/L, while the price of sale of the biofuels was 1.34 US$/L. Another high cost was drying, at 0.432 US$/L, which contributes to the unfeasibility of the project. Studies presented by Castro et al. [1,2], present the same study (pyrolysis followed by distillation of açaí seeds in nature) without impregnation, which can be used in future economic feasibility studies. Table 7 highlights that the profit margin is negative, −1.49 US$/L, which means that no feasibility study can be accomplished (no generation of positive cash flow).

Table 7. Revenues and expenses by pyrolysis of açaí seeds (*Euterpe oleracea* Mart.) in nature to produce biofuels.

Revenue		
Feed rate_93.75% (Availability)_Cracking	906.04	L/day
Organic liquid product (Bio-oil) _7.20%	65.23	L/day (feed distilled)
Solid product (coke)_41.0%	112.46	US$/day
Gaseous product (Biogas)_32.03%	10.14	US$/day
Distilled biofuel _73%	47.6	L/day
Sale price of biofuel	1.34	US$/L
Total expenses	**2.84**	**US$/L**
Raw material (açaí seed)	0.057	US$/L
Drying_3 KW	0.432	US$/L
Comminution_2 KW (1h)	0.009	US$/L
Impregnation NaOH_2 mol L^{-1}	1.812	US$/L
Liquefied petroleum gas (LPG)_10%	0.100	US$/L
Manpower	0.114	US$/L
Distillation (Heating)_5 KW	0.180	US$/L
Federal tax rate_10%	0.134	US$/L
Profit margin	−1.49	US$/L

4. Conclusions

Starting from the feasibility project criteria indicators, it is possible to confirm the feasibility of thermal catalytic cracking of the lipid-based material (from the fat retention box of the university restaurant of the UFPA) for the production of biofuels, coke and methane gas.

The availability used for the project evaluation criteria with the lipid material was of 56.25%. This means that for each shift of 8 h of work, around 4 h 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, the minimum fuel selling price (MFSP) obtained in this work for the biofuels was 1.34 US$/L. The literature mentioned in this work presents values from 0.68 up to 0.98 (US$/L). By considering the viable process, the IRR of the project was obtained as 10% p.y. In this case, the IRR is equal to the minimum attractiveness of the project (10% p.y), which means that the project is economically viable. Thilakaratne et al. [27] obtained a 10% internal rate of return.

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

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en15207718/s1, Table S1: Yields of reaction products by pyrolysis of lipid-based material and distillation process [4–6], Table S2: Physicochemical characterization of the lipid-based material used as feed [4–6], Table S3: Physicochemical properties of the organic liquid product (bio-oil) produced pyrolysis of lipid-based material [4–6], Table S4: Composition of chemical compounds present in organic liquid product (bio-oil) with 10% (wt.) de Na_2CO_3 (experiment 1) [4–6], Table S5: Composition of the green kerosene (175–235 °C) of experiment 1 [4–6], Table S6: Composition of light diesel (23–305 °C) of experiment 1 [4–6], Table S7: Composition of heavy diesel (305–400 °C) of experiment 1 [4–6], Table S8: Yields of reaction products by pyrolysis of açaí seed (*Euterpe oleracea* Mart.) and distillation process of bio-oils [1,2], Table S9: Physical characteristics of the açaí seed used as raw material to produce bio-oils [1,2], Table S10: Physicochemical characterization of the bio-oil obtained from the açaí seed (*Euterpe oleracea* Mart.) [1,2], Table S11: Yields pre-treatment processes (drying, comminution and sieving) [1,2], Table S12: Composition of the bio-oil obtained by pyrolysis of açaí seed in nature [1,2], Table S13: Composition of the biokerosene (175–235 °C) obtained from the distillation of bio-oil [1,2], Table S14: Composition of the light green diesel (235–315 °C) obtained by distillation of bio-oil [1,2].

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