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Energy, economic, and environmental assessment of the integrated production of palm oil biodiesel and sugarcane ethanol

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ABSTRACT

The key objective of this study was to evaluate and compare, within the concept of integrated biorefining, the potential environmental gains of the life cycle, economic feasibility and energy balance of the production of bioenergetics from palm and sugarcane. In this context, the research model developed in this work involved several assessment techniques; in terms of environmental assessment, the tool used was the Life Cycle Assessment (LCA) from the Well-To-Tank perspective, which is based on the LCA "cradle-to-gate" assignment method. The environmental assessment was performed using SimaPro v.8.0.3 software and the impacts were quantified using the IMPACT 2002+ method. On the other hand, energy performance evaluation was based on the 1st law indicators. Likewise, economic feasibility was based on the evaluation of the fixed capital investment index and the estimate of investment costs for the entire integrated system. Two different scenarios were proposed in order to compare and evaluate traditional systems with the integrated biorefinery. The first conversion scenario (baseline scenario) consisted of a traditional palm oil extraction plant in addition to an ethanol and sugar plant, concerning the use of fossil fuels in all stages of production. The second conversion scenario (improved scenario) explored the substitution of fossil energy sources as well as the energy recovery of residual biomass in more efficient energy conversion systems. The results indicated significant reductions of 29.5% and 29.1% in the global warming impact category when the baseline scenario was compared to the improved scenario. Additionally, the improved scenario achieved a reduction of 2.1 g CO_{2eq} MJ^{-1} (ethanol) and 2.61 g CO_{2eq} MJ^{-1} (biodiesel). On the other hand, the improved scenario presented better energy rates since it showed an increase of 3.82% in the global efficiency of the system and produced 106.32 kWh more per ton of processed raw material. Finally, when considering the Life Cycle Energy Efficiency, an increase of 83% was observed and in the case of the Renewability Factor showed an increase of 7.12 energy units. Integration is also economically feasible; however, it could be significantly improved through fiscal incentives founded on the reduction of fossil energy use, enhanced conversion yielding, and improvements in conversion technologies.

1. Introduction

At present, the search for alternative scenarios to fossil fuels can be observed in all economic spheres, but with greater impetus in the transportation sector as this sector is mainly supplied with petroleum products (93%), making it the least non-renewable sector (Nogueira et al., 2020). This was responsible for more than 28% of global energy consumption and more than 30% of CO_2 emissions in the year 2018 (U. S. Energy Information Administration, 2018). A panorama through which renewable sources are seen as alternatives to mitigate environmental problems should highlight biomass feedstock since it is very versatile, ensuring several ways to use it efficiently in integrated complexes called biorefineries - facilities capable of simultaneously converting biomass into biofuels, bioelectricity, chemical inputs, and food, in addition to contributing the real possibility of creating new

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Nomenclature

Abbreviations

BPT	Backpressure steam turbine
CEST	Condensing extraction steam turbine
CHP	Combined heat and power
CPKO	Crude Palm Kernel Oil
CPO	Crude Palm Oil
EFB	Empty Fruit Bunch
FFB	Fresh Fruit Bunch
FAME	Fatty Acid Methyl Esters
FAEE	Fatty Acid Ethyl Esters
FCI	Fixed capital investment
ICE	Internal Combustion Engine
LCA	Life Cycle Assessment
LCI	Life-Cycle Inventory
LHV	Lower Heating Value
NER	Net Energy Ratio
PKC	Palm Kernel Cake
POM	Palm Oil Mill
POME	Palm Oil Mill Effluent
RF	Renewability Factor

Symbols

P_{ele}	Production electricity index ($kWh_{el}\ t_{PRM}^{-1}$)
η_{glo}	Global efficiency of the system (%)
$\eta_{\circ}$	Global thermal efficiency (%)
$\dot{m}$ fuel	Mass flow of fuel ($kg\ s^{-1}$)
W_{net}	Net electrical power generated (kW_{el})
Q_u	Useful thermal energy (kW_{th})
t_{PRM}	Ton of raw material processed ($ton\ h^{-1}$)

value-added chains for biomass (Hingsamer and Jungmeier, 2018).

The use of biofuels has been supported by several nations through plans and targets that require their participation in greater volume (Saravanan et al., 2020) as they offer a potentially attractive solution that reduces carbon intensity in the transportation sector and addresses energy security issues. The two liquid biofuels most commonly used are biodiesel and bioethanol (derived from biomass), which respectively replace fossil diesel and gasoline (REN21, 2018).

Naturally, there are several published papers in which different types of biomass are evaluated to obtain these biofuels (Ambat et al., 2018; Bušić et al., 2018; Pereira et al., 2019; Sitepu et al., 2020). Nonetheless, it has been shown through different research (Manochio et al., 2017; Pereira et al., 2018) that the most suitable raw materials for the production of ethanol and biodiesel are sugarcane and oil palm (African palm) since these crops have high yields of biofuels, 7.6 $m^3\ ha^{-1}\ year^{-1}$ ethanol (O'Hara and Mundree, 2016) and 5 $t\ ha^{-1}\ year^{-1}$ oil (Mat Yasin et al., 2017). Moreover, these crops have a large availability of lignocellulosic residues, which represents a tangible opportunity to create a portfolio of potentially marketable bio-based products and bioenergy/biofuels produced from the biorefining of these residues as advocated by the IEA Bioenergy Task 42 vision "Biorefining in a Circular Economy" (IEA Bioenergy, 2019), whose goal is to facilitate the commercialization and market deployment of environmentally friendly, socially acceptable, and cost-competitive biorefinery systems and technologies. However, the sustainable transformation of this type of industrial facility is a complex aspect to analyze because the concept converges environmental, as well as economic and social, variables (Verma and Kuila, 2020). Therefore, in order to quantitatively assess sustainable, economic, social, and environmental indicators, these values are calculated independently (Venturini et al., 2020). Through these indicators it is possible to carry out a comparison of different integrated production schemes, thus providing decision tools for the implementation of a project or not. It is within this context that Life Cycle Assessment (LCA) presents itself as a valuable and timely methodology (Bezergianni and Chrysikou, 2020) as its objective and standardized approach can study the behavior of products, processes, or systems throughout their life cycles, and provide a quantitative estimation of potential impacts on the environment, resources, and human health.

In the last few years, several studies related to the assessment of the sustainable performance of biorefineries have been published in which the integration of several quantitative methods (energy, exergetic, economic, exergoeconomics, etc.) with LCA have been implemented.

In this sense, some studies have evaluated the energy and environmental potential like those carried out by (Ocampo Batlle et al., 2020), who conducted a thermal-environmental evaluation of the insertion of pyrolysis technology through three different configurations of palm oil biorefinery (Beaudry et al., 2018). quantified employing an LCA the CO_{2eq} of the best palm waste biomass treatment options in the case of Thailand. A study developed by (Hosseini-Fashami et al., 2019) presented an Energy-Life cycle assessment on applied solar technologies for greenhouse strawberry production. Using the same research approach, other papers can be found, such as those by (Chrysikou et al., 2018; Corona et al., 2018; Khoshnevisan et al., 2020; Monteiro et al., 2020).

Other papers, however, incorporate economic and social assessments like (Vaskan et al., 2018), who carried out an evaluation from a technical-economic and an environmental point of view of two biorefinery configurations based on the utilization of empty fruit bunches (EFB) (Aristizábal-Marulanda et al., 2020). contributed work that evaluated from an economic and social performance point of view of energy production through two biorefineries based on Coffee Cut-Stems (CCS) (Demichelis et al., 2020). developed a sequential three-step methodology for the technical, economic, and environmental assessment (TEEA) of bioethanol production from waste biomass. In the same vein, the works developed by (Garcia-Nunez et al., 2016), (Farzad et al., 2017), (Nabavi-Pelesaraei et al., 2017), and (Hadidi and Altamimi, 2019).

Other studies carried out exergy, energy, economic, and environmental assessments in biorefineries such as (Palacio et al., 2018), who analyzed the situation from an environmental and exergetic point of view in a biorefinery of the sugar and alcohol industry. The research was elaborated by comparing three case studies in the Brazilian scenario, obtaining a result indicative that the case study in which surplus electricity, bioethanol (2G) from lignocellulosic material, bioethanol from juice, and vinasses fodder yeast are produced simultaneously. The research developed by (Saber et al., 2020) conducted an assessment of exergoenvironmental aspects across different paddy production systems, including conventional (CS), low external input (LEI), and organic systems (OS) in Iran (Mostashari-Rad et al., 2021). developed an exergo-environmental damages assessment of horticultural crops, using ReCiPe2016 and cumulative exergy demand frameworks (CExD).

Finally, in broader terms, other research has used optimization techniques in order to identify parameters that determine maximum technical, economic, and environmental performance of feedstock conversion in biorefineries, such as those carried out by (Nieder-Heitmann et al., 2019), (Kaab et al., 2019a), (Kaab et al., 2019b), (Tan et al., 2020), (Furtado Júnior et al., 2020) and (Khanali et al., 2021).

It can be concluded that countless studies have evaluated, predicted, and quantified the potential energy, economic, and environmental gains of so-called biorefinery complexes in which oil palm tree and sugarcane play a fundamental role. Nevertheless, despite such potential in these agribusinesses, several researchers (Kaab et al., 2019a; Munasinghe et al., 2019; Ramirez-Contreras et al., 2020; Rocha et al., 2014;

Tsiropoulos et al., 2014) have pointed out the considerable consumption of non-renewable energy sources in the production chain of biodiesel from palm oil and ethanol from sugarcane, which sometimes compromises the environmental profile of such biofuels. According to (Ocampo Batlle et al., 2020), the integration of sugarcane and palm oil crops could increase the energy portfolio, improve performance, and thus, mitigate the environmental impact of biodiesel production systems of palm oil and sugarcane ethanol. Reasoning that aligns with the assumption by (Speight, 2020) is that the biorefinery of the future will be an integrated complex that generates a diversity of products (e.g. biofuels, chemicals, energy, and proteins) from a variety of raw materials.

In this context, the synergy between the agroindustry of palm oil and sugarcane is evident, a fact that would contribute to the annual national goals established by the *RenovaBio* program (Salina et al., 2020), whose main objective is the decarbonization of the fuel sector in order to encourage the increase in the production and participation of biofuels in the energy matrix of transportation in Brazil. In spite of this, there is a perceived lack of studies to characterize and incorporate the entire integrated processing chain of oil palm and sugarcane crops (compilation of relevant geographical considerations and inventories) in a leading agro-industry country such as Brazil, which according to (Vásquez et al., 2019) is characterized by a large amount of land, developed agricultural techniques, and favorable climatic conditions. Furthermore, there is a clear need to quantify and evaluate the energy performance of the integrated complexes, as stated by (Fritsche et al., 2018). For the aforementioned reasons, the present research carries out a comparative evaluation of the potential energy-environmental and economic benefits of the integrated production of palm oil biodiesel and sugarcane ethanol (1st and 2nd generation) in so-called biorefinery complexes. For this purpose, different thermodynamic, economic and environmental indicators were defined to identify the benefits and challenges to be overcome. This was the principal motivating factor that guided the originality and novelty of such work in this field.

2. Materials and methods

Fig. 1 presents the flowchart that illustrates how this work was carried out in terms of how the research model was applied in order to obtain the results. The process dimensions were based on the feedstock available for each. In light of the input and output data referenced by each multiproduct system process, the model was built around the cogeneration plant using the software GateCycle v6.2.1 to simulate and solve mass and energy balances. Subsequently, an energy assessment was performed, considering the global efficiency of the system and production electricity indicators. For the economic performance, the indicator evaluated was the Fixed Capital Investment (FCI). Finally, using the SimaPro software v.8, Life Cycle Inventories of palm and sugar-cane production were carried out to later carry out an analysis of the main environmental impacts produced by the integrated biorefinery using the IMPACT 2002+ method and a life cycle energy performance analysis, using the Net Energy Ratio (NER) and Renewability Factor concept.

2.1. *Scenarios evaluated*

In order to accomplish the data survey and analysis of each production stage, a review of the background literature, a description of each proposed scenario, and the definition of limits and assumptions of the multi-product system were performed to help characterize the mass and energy balance of the various bioenergy production processes studied, taking into account the problems related to food security, energy supply, and environmental conservation while following guidelines suggested by (Debnath and Babu, 2019).

2.1.1. *Baseline scenario - BSc*

Consisting of a traditional palm oil and sugarcane mill, this scenario is located in the North and Northeast of Brazil with separated production of biofuels and without any energy or agricultural integration. It should

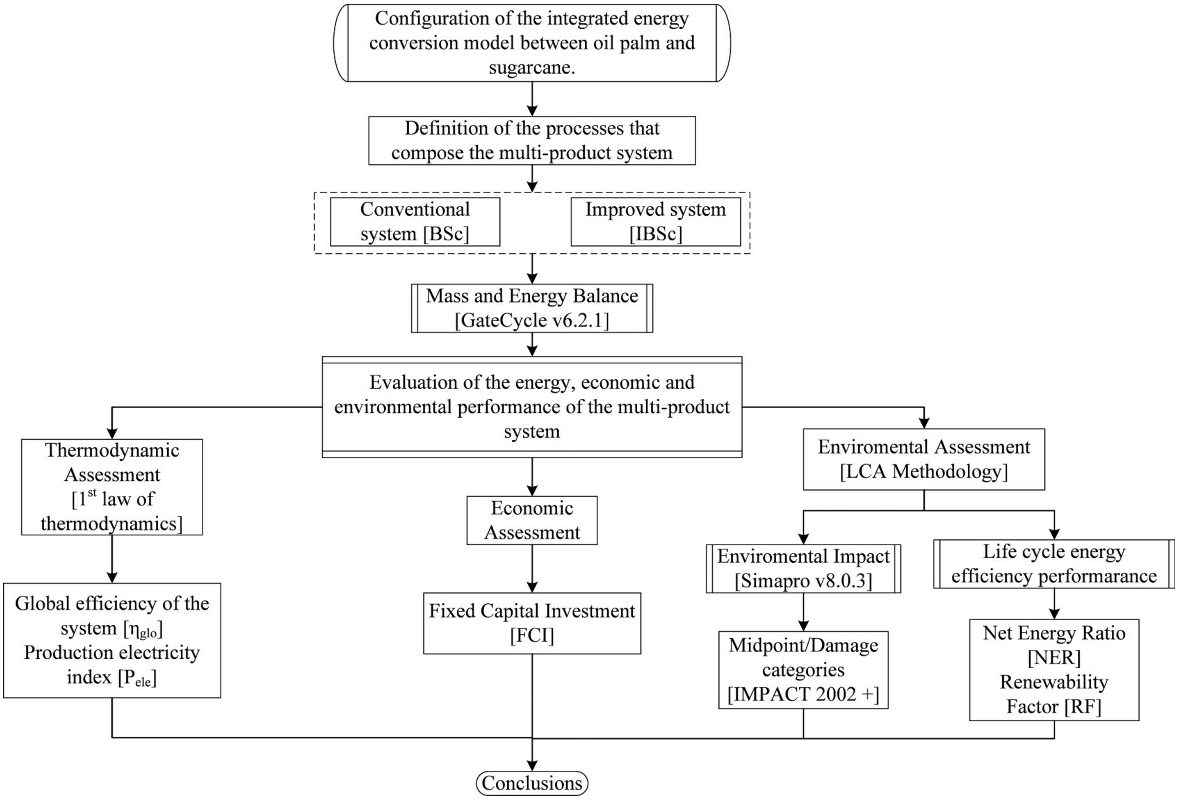

Fig. 1. Research model flowchart.

be noted that the use step was not considered in the evaluation because the CO_2 released is considered neutral based on the absorption of carbon during biomass growth, and thus its combustion would not increase net atmospheric levels (Harris et al., 2018).

The conventional system for producing biodiesel from palm oil consists basically of six life cycle stages (Fig. 2): agriculture, oil extraction, oil refining, biodiesel production (methyl route), combined heat and power production, and transportation. The information adopted regarding the stage of agriculture was obtained from research developed by (Queiroz et al., 2012) since primary agricultural data were collected in the region of interest, in which they considered the use of agrochemicals, water, fertilizers, and fossil fuel consumption (diesel used in tractors and gasoline used in cutting machinery), as well as the use of effluents and potassium-rich organic waste. The crop yield is an average of 19.5 $t_{FFB}\ ha^{-1}$ (tons of fresh fruit bunches per hectare) (Brito and Buecke, 2015). The main inputs adopted for this step are presented in the Supplementary material Table A.

After the FFBs are harvested from the plantations, they are transported by road to a mill located approximately 30 km from the plantation since the processing of the FFBs must take place no later than 48 h after harvesting in order to avoid acidification of the fruit. Upon arrival at the mill, the fruit is submitted to several mechanical processes (sterilization, threshing, digestion, filtering, pressing, clarification, purification, and drying) from which crude palm oil - CPO (20%), crude palm kernel oil - CPKO (1.5%), palm kernel cake - PKC (2.5%), empty fruit bunches - EFB (22%), fiber (13%), shells (7%) and palm oil mill effluents - POME (44%) are obtained according to (Ahmad et al., 2019). Furthermore, the extraction of the oil (Supplementary material, Table B) requires water, steam, and electricity. Before biodiesel is produced, the oil needs to be refined (Supplementary material, Table C) to reduce its acidity, i.e. to eliminate free fatty acids, resulting in an oil composed merely of glycerides. There are two main processing methods: chemical and physical refining. However, the process adopted in this research was the physical one since it has a higher global yield, uses fewer chemicals, and produces less effluent (Lai et al., 2012). The refined palm oil (RBDPO) is then submitted to the transesterification process - the most widely used process in the production of Fatty Acid Methyl Esters (Živković et al., 2017) – which uses homogeneous catalysis (Supplementary material, Table D), with sodium hydroxide (NaOH) being the alkaline catalyst of greater application in the industry (Verma et al., 2016) due to the following: (i) its ability to accelerate the reaction at lower temperatures and pressures; (ii) a higher yield can be achieved in less time and (iii) its abundant availability, which translates into a lower cost.

The cogeneration system (Table 1 and Supplementary material, Table G) supplies the energy needed for operating the plants (extraction, refining, and transesterification) employing a cogeneration system based on a back-pressure steam turbine (BPT), using it as fuel fiber and shell coming from the oil extraction process; the cycle efficiency was obtained through mass and energy balances in the whole plant scheme using GateCycle™ software v.6.2. It is worth mentioning that the configuration of the correlated plants is annexed to the extraction plant, similar to the Agropalma and Biopalma plants, which have an installed processing capacity of around 500 $t_{FFB}\ h^{-1}$ – or, in the range of 111 $m^3{}_{biodiesel}\ h^{-1}$ (Brandão and Schoneveld, 2015). The operational parameters adopted in the process plant and cogeneration system have been summarized in Table 1.

Table 1
Biodiesel Plant operating parameters and cogeneration cycle fuel properties.

Parameters	Value	Unit	Reference
Amount of fiber (37 wt % moisture)	65	$t_{fi}\ h^{-1}$ [a]	Archer et al. (2018)
Amount of shell (21 wt % moisture)	35	$t_{sh}\ h^{-1}$ [b]	Archer et al. (2018)
Steam consumption (3 bar, saturated)	514.20	$kg\ t_{FFB}^{-1}$ [c]	Singh et al. (2013)
Steam consumption (3 bar, saturated)	326.78	$kg\ t_{FFB}^{-1}$	Singh et al. (2013)
POM electricity consumption	30	$kWh\ t_{FFB}^{-1}$	Lee and Ofori-Boateng (2013)
Biodiesel plant electricity consumption	32.69	$kWh\ t_{FFB}^{-1}$	Yusoff et al. (2014)
Biodiesel production	46	$l\ t_{FFB}^{-1}$	Archer et al. (2018)
Glycerin production	59	$kg\ t_{FFB}^{-1}$	Archer et al. (2018)
Cogeneration system			
Boiler pressure	60	bar	Booneimsri et al. (2018)
Boiler temperature	480	°C	
LHV Fiber (37 wt% moisture)	11.48	$MJ\ kg^{-1}$	
LHV Shell (21 wt% moisture)	14.55	$MJ\ kg^{-1}$	
Pumps isentropic efficiency	85	%	Ocampo Batlle et al. (2020)
Generator electric efficiency	92	%	
Cogeneration boiler efficiency (% LHV)	72	%	
Isentropic efficiency (Backpressure steam turbine)	75	%	

[a] t_{fi}: tonne of fiber.
[b] t_{sh}: tonne of shell.
[c] t_{FFB}: tonne of fresh fruit bunch.

On the other hand, traditional sugar and ethanol production consists of five life cycle stages (Fig. 3): agriculture, juice extraction, sugar, and ethanol production, combined heat and power production, and transportation. In the agricultural stage of sugar and ethanol production from

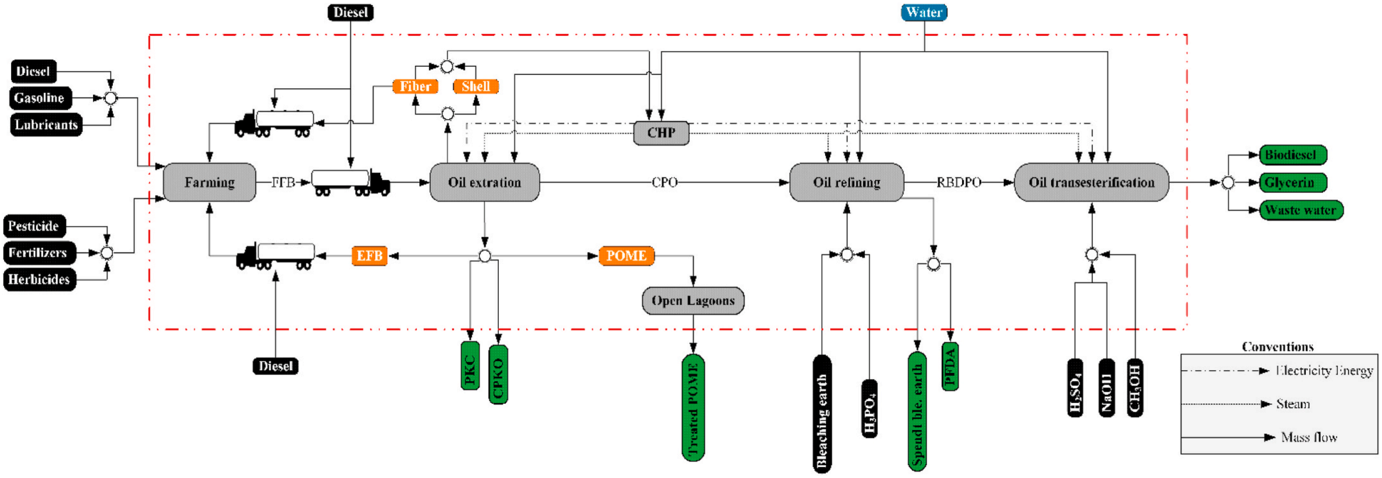

Fig. 2. Scheme of the system boundaries of the biodiesel production from palm oil.

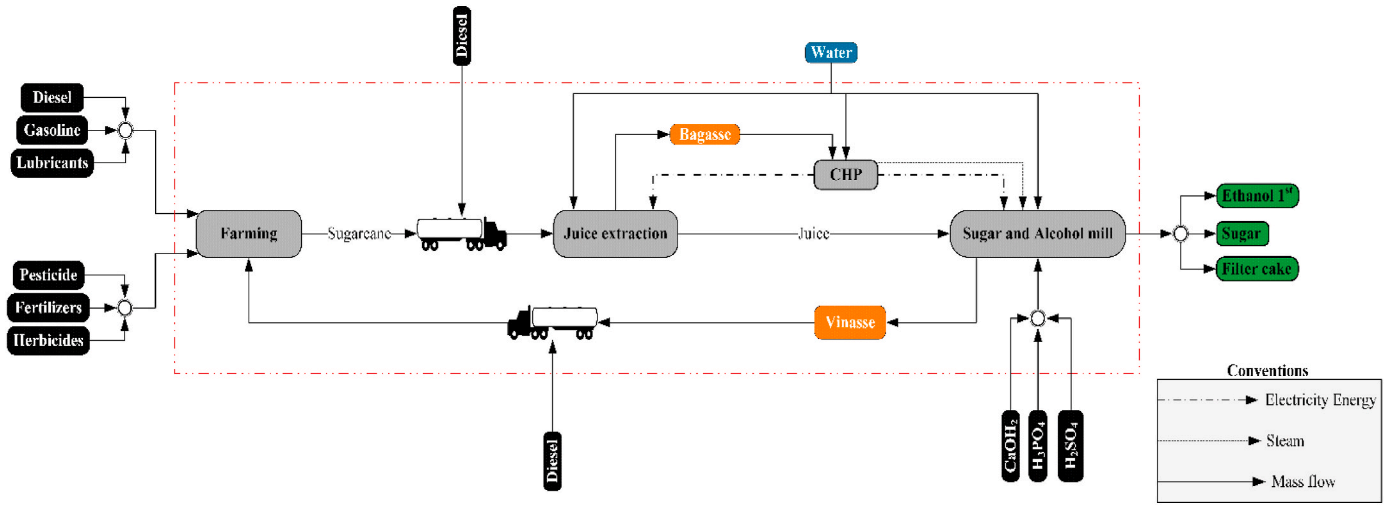

Fig. 3. Scheme of the system boundary of the sugar and alcohol production from sugarcane.

sugarcane, the use of fuels, fertilizers, herbicides, insecticides, and lime is considered. Additionally, the use of vinasse and other co-products of the ethanol industry (filter cake and ash) being commonly used as a complement of chemical fertilizers (Supplementary material, Table A).

After being cut, the sugar cane has to be forwarded promptly to the industrial unit. The assumed distance for this was 30 km for transportation, in which the contribution to the trucks' fuel consumption is as follows: twin-trailer 8%, triple trailer 25% and road train 67% (Santos et al., 2015). Upon arrival at the mill, the mechanically harvested cane is unloaded onto tables and sent to the juice extraction stage (cleaning, chopping, and separation of lignocellulosic material) (Supplementary material, Table E). Approximately 70% of the sugarcane processing units in Brazil are composed of an ethanol distillery attached to the sugar mill due to the great advantages of the simultaneous production of these two products (Pereira et al., 2015). Therefore, it was the configuration adopted in all researched scenarios of this work; as such, a sugar and alcohol plant with a processing capacity of 1.57 million tons of sugarcane per harvest, or 500 $t_c\ h^{-1}$ (tons of cane per hour), was considered under typical conditions in the North and Northeast of Brazil (Conab, 2018). In this step, the use of NaOH, H_2SO_4, $CaOH_2$, H_3PO_4, and lubricants were also taken into account (Supplementary material, Table F).

Furthermore, the plant adopted in this study was energetically self-sufficient so that the electricity produced could feed both the mills (considered electrified mills) and the process equipment such as pumps, agitators, and conveyors, among others and in addition to lighting installations. From each ton of sugarcane that enters the mill, 280 kg of bagasse with 50% moisture content is produced (Leal et al., 2013), in which an amount - corresponding to 10% of the total - is stored in order to be used in the off-season and the rest is used as fuel in steam boilers that operate with conventional parameters of 60 bars and 480 °C (O'Hara and Mundree, 2016; Santos et al., 2015). The mass and energy balance of the plants were performed using Gate Cycle ™ software. The operational parameters adopted in the plant and the cogeneration system are summarized in Table 2.

Table 2
Sugar and Alcohol mill operating parameters.

Parameters	Value	Unit	Reference
Amount of bagasse (50 wt % moisture)	140	$t_b\ h^{-1}$ [a]	Leal et al. (2013)
Steam consumption (3 bar, saturated)	442	kg t_c^{-1} [b]	Tsiropoulos et al. (2014)
Milling electricity consumption	16	kWh t_c^{-1}	Furtado Júnior et al. (2020)
Sugar plant electricity consumption	18	kWh t_c^{-1}	Furtado Júnior et al. (2020)
Ethanol production [c]	46	l t cana^{-1}	Venturini et al. (2020)
Sugar production [c]	59	kg t_c^{-1}	Venturini et al. (2020)
Cogeneration system			
Boiler pressure	60	bar	(O'Hara and Mundree, 2016; Santos et al., 2015)
Boiler temperature	480	°C	(O'Hara and Mundree, 2016; Santos et al., 2015)
LHV Bagasse (50 wt% moisture)	7.5	MJ kg^{-1}	(Mohammadi et al., 2020; Souza et al., 2018)
Pumps isentropic efficiency	85	%	Palacio et al. (2018)
Generator electric efficiency	92	%	Dias et al. (2015)
Cogeneration boiler efficiency (% LHV)	75	%	Palacio et al. (2018)
Isentropic efficiency (Backpressure turbine)	75	%	Palacio et al. (2018)

[a] t_b: tonne of bagasse.
[b] t_c: tonne of sugar cane.
[c] Assuming that 50% of the juice is destined for ethanol production, and 50% for the production of sugar.

2.1.2. *Integrated biorefinery scenario - IBSc*

This section describes the improved scenario under the biorefinery concept, considering the simultaneous culture (palm oil and sugar cane) production and energy integration of the palm oil and sugarcane mills. The integrated biorefinery is represented by Fig. 4.

The first consideration adopted in this scenario was biodiesel production by the ethyl route (Fatty Acid Ethyl Esters - FAEE) (Supplementary material, Table H). That is, the same transesterification technology was applied, but by replacing fossil methanol with the bioethanol produced in the system; according to several types of research (Alejos Altamirano et al., 2016; Chen et al., 2019; Silva et al., 2015; Vieira da Silva et al., 2017), the advantages of this route include: (i) the biodiesel produced has a higher cetane number and greater lubricity, (ii) it has a lower risk of fires, (iii) it is not as toxic as methanol, and (iv) the NO_x emissions are somewhat lower than those produced by the combustion of fossil diesel. The second consideration was the use of biodiesel to displace a fraction of the diesel demanded by the various stages evaluated through the addition of 15% biodiesel content in the blend with mineral diesel (B15) - as provided by the resolution of the National Energy Policy Council - *CNPE n°16, 2018.*

The insertion of lignocellulosic ethanol production was also contemplated (Supplementary material, Table I), aiming to increase the volume of ethanol produced in the system - without the need to increase the planted area; therefore, a fraction of the bagasse produced is used in this phase (Aditiya et al., 2016). The steam explosion pre-treatment with

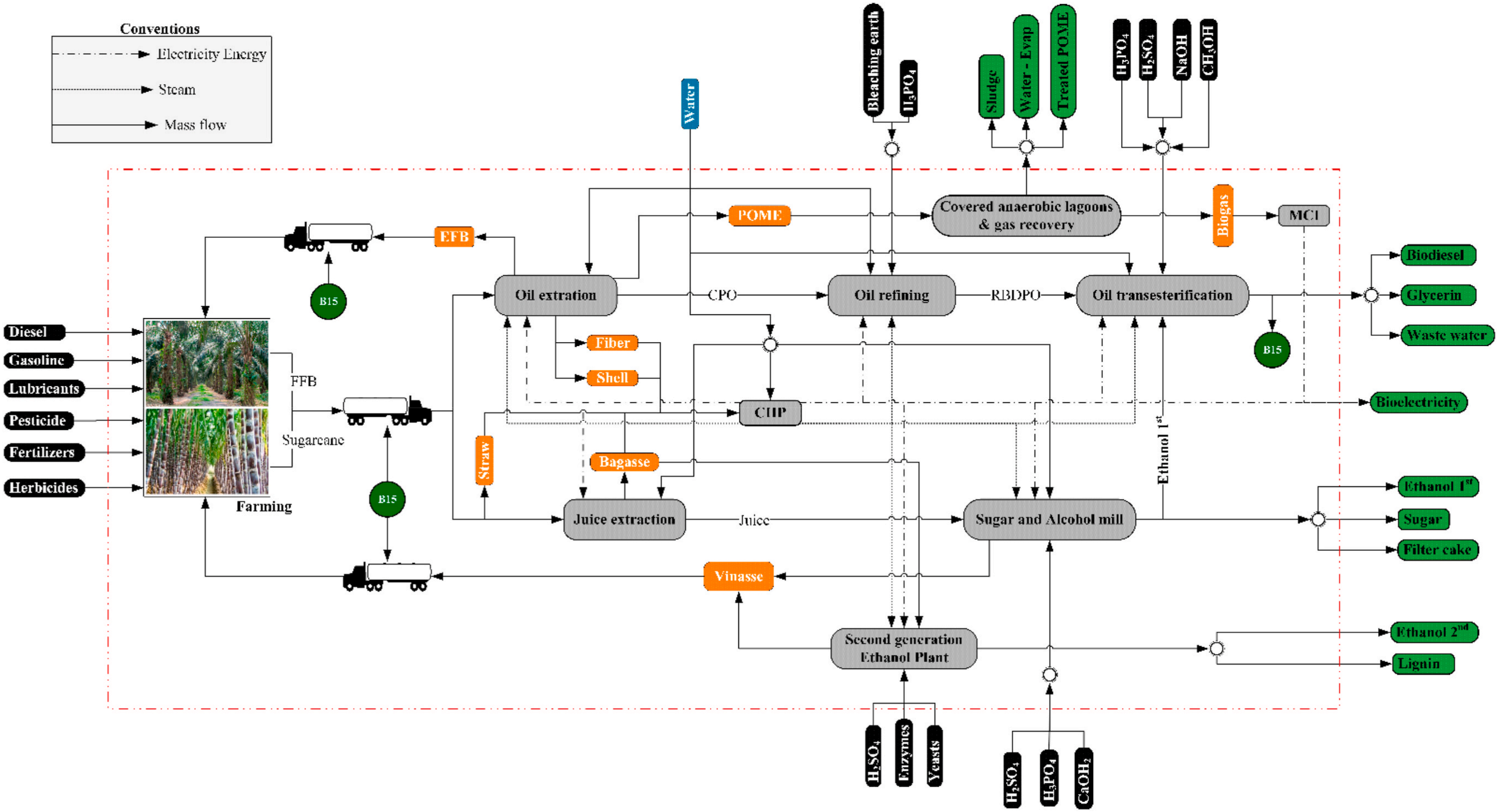

Fig. 4. Integrated system of palm oil biodiesel and ethanol (1st and 2nd generation) sugarcane - IBSc.

diluted acid (physical-chemical process) was considered since it increases the absorbency of water inherent in the biomass both improves the enzymatic hydrolysis and decreases the production of inhibitors such as furfural and hydroxymethylfurfural, in addition to having a relatively low processing time (Chen, 2015; Wertz and Bédué, 2013). To avoid a fuel deficit in the cogeneration system. the use of straw is considered - residue generated during the sugarcane harvest, for each ton of sugarcane 140 kg of straw is produced, and about 30–50% of it can be recovered and used as fuel in the cogeneration process (Furtado Júnior et al., 2020). Consequently, in this research, the use of 50% of the straw generated is considered along with a fraction of bagasse, fiber, and bark; moreover, the insertion of POME (Supplementary material, Table J) treatment through covered anaerobic lagoons - with the intention of biogas recovery - was considered, which compared to other treatment methods, presents the highest GHG reduction potential (Aziz et al., 2019; Ohimain and Izah, 2017); the biogas obtained is then burned in an Internal Combustion Engine - ICE (Supplementary material, Table K) which has an efficiency of 25%, as described by (Sharvini et al., 2020) to obtain the necessary surplus biomass for the 2G ethanol production process. Also, technical improvements were applied to the cogeneration system in order to obtain gains in cycle efficiency and generate surplus electricity for sale to the utilities - a profitable business with relatively low return on investment periods, negligible environmental impacts, and with regulatory advantages over conventional sources. In light of these facts, boilers with higher efficiency (85%) and extraction/condensation steam turbines - CEST (85%) were adopted in substitution of the backpressure turbines to drive the generators, among other measures summarized in Table 3.

2.2. Energy assessment

To quantify and evaluate the bioproducts produced, an energy analysis based on the first law of thermodynamics was performed that aimed to understand their respective energy consumption and provide information on how energy is used. For this analysis, in all such case studies proposed, the performance indicators *Global efficiency of the system* (η_{glo}) and *Production electricity index* (P_{ele}) (Furtado Júnior et al., 2020; Ocampo Batlle et al., 2020) are described below. The η_{glo} is defined as the ratio between the useful energy of the products produced (1G ethanol, sugar, 2G ethanol, biodiesel, glycerin, and bioelectricity), by the energy of the raw materials used (FFB and sugarcane). The P_{ele} is the ratio of net electrical energy produced (W_{net}) kW by the amount of raw material processed (t_{PRM}) in the system in ton h^{-1}.

2.3. Economic assessment

Multi-Product system processes were assumed to be independent. Investment in plant construction is based on installing one by one, relying on the previous plant capacity in the production chain. For calculation of necessary investment for processing plants built-up, costs of commercial plants or process equipment existing and whose capacities are known were used as a reference, which was presented in Table 4 and likewise reported in the literature.

For the calculation of the value of the Fixed Capital Investment (FCI) in each plant, Equation (1), the cost-capacity was used. The values of each reference case reported in the literature were then used. Value of "α" for the type of equipment adopted, and for construction of processing plants, corresponded to 0.6 (Julio et al., 2021). And the Investment costs were corrected through CEPCI indices supplied for Chemical Engineering Magazine, from each reference date to December 2019 (Chemical Engineering Magazine, 2019).

$$\mathrm{Cost}_2 = \mathrm{Cost}_1 \left(\frac{\mathrm{Capacity}_2}{\mathrm{Capacity}_1}\right)^{\alpha} \left(\frac{\mathrm{CEPCI}_{\mathrm{Dec2019}}}{\mathrm{CEPCI}_{\mathrm{Ref.\ \ date}}}\right) \tag{1}$$

The number of raw materials required is contingent on the production capacity of each plant. Furthermore, the material balance of the multi-product system production processes is used as a reference to calculate the utility consumption, which is dependent on the type of process routes and size of equipment employed (Julio et al., 2021). Table 5 shows the methodology used by (Gebremariam and Marchetti, 2018) to calculate operating cost categories for a biodiesel plant, which would be expanded for the whole integrated system. In front of the calculus of the total operating cost, the values for the cost of raw materials and utilities are typically based on latest market prices and literature references. The labor cost estimation is entirely dependent on the total investment cost of the whole plant. The other cost categories included in operating cost such as repair and maintenance costs are taken as percentages of the investment cost, whereas depreciation cost is usually expressed in terms of percentage of equipment purchasing cost.

One of the goals of evaluating these plants throughout their economic performances is to present the unit production cost. This is the minimum selling price or the cost of production that equals expenses and income. It is also a representation of the minimum price that must be practiced in order for the producer not to end up taking a loss.

Table 3
Integrated biorefinery operating parameters and cogeneration cycle fuel properties.

Parameters	Value	Unit	Reference
Amount of bagasse (50 wt % moisture)	140	$t_b\ h^{-1}$	Leal et al. (2013)
Amount of Straw (15 wt% moisture)	40.70	$t_{St}\ h^{-1}$ [a]	(Demichelis et al., 2020; Furtado Júnior et al., 2020)
Amount of POME	295.81	$kg\ t_{FFB}^{-1}$	(Aziz et al., 2019; Ohimain and Izah, 2017)
Amount of fiber (37 wt % moisture)	65	$t_{fi}\ h^{-1}$	Archer et al. (2018)
Amount of shell (21 wt % moisture)	35	$t_{sh}\ h^{-1}$	Archer et al. (2018)
Steam consumption (3 bar, saturated)	686.48	$kg\ t_b^{-1}$	(Aditiya et al., 2016; Demichelis et al., 2020)
Steam consumption (35 bar, saturated)	169.93	$kg\ t_b^{-1}$	(Aditiya et al., 2016; Demichelis et al., 2020)
2G Ethanol plant electricity consumption	92.5	$kWh\ t_b^{-1}$	Furtado Júnior et al. (2020)
2G Ethanol production	149.30	$l\ t_b^{-1}$	Aditiya et al. (2016)
Covered lagoons electricity consumption	20.62	$kWh\ t_{POME}^{-1}$ [b]	(Aziz et al., 2019; Ohimain and Izah, 2017)
Biogas production	28.30	$m^3\ t_{POME}^{-1}$	(Aziz et al., 2019; Ohimain and Izah, 2017)
Cogeneration system and ICE			
Boiler pressure	100	Bar	Venturini et al. (2020)
Boiler temperature	520	°C	Venturini et al. (2020)
LHV Bagasse (50 wt% moisture)	7.5	$MJ\ kg^{-1}$	(Mohammadi et al., 2020; Souza et al., 2018)
LHV Straw (15 wt% moisture)	15.6	$MJ\ kg^{-1}$	Souza et al. (2018)
LHV Fiber (37 wt% moisture)	11.48	$MJ\ kg^{-1}$	Booneimsri et al. (2018)
LHV Shell (21 wt% moisture)	14.55	$MJ\ kg^{-1}$	Booneimsri et al. (2018)
LHV Biogas	20	$MJ\ m^{-3}$	(Aziz et al., 2019; Ohimain and Izah, 2017)
Pumps isentropic efficiency	85	%	Palacio et al. (2018)
Generator electric efficiency	98	%	Palacio et al. (2018)

[a] t_{fi}: tonne of Straw from sugarcane.
[b] t_{sh}: tonne of Palm Oil Mill Effluent.

2.4. Environmental assessment

The methodology applied for the environmental analysis in this research was Life Cycle Assessment (LCA), structured according to the guidelines of ISO 14040 (ISO 14040, 2006, 2006) while including a compilation of the life cycle inventory and calculation of the

Table 4
Reference cost data for investment estimative.

Plant [capacity reference unit]	Cost 1 [M USD]	Capacity 1	Ref. Date	CEPCI Ref. Date	Ref.
Biomass CHP [a] [MW]	249.25	50.00	2016	541.7	(U.S. EIA, 2016)
Biogas CHP [b] [MW]	114.07	85.00	2016	541.7	(U.S. EIA, 2016)
Palm plant					
Palm Oil Extraction [ton h^{-1}]	9.2	5.625	2006	499.6	Vaskan et al. (2018)
Biodiesel plant [ton h^{-1}]	7.42	4.505	2008	575.4	Gebremariam and Marchetti (2018)
Open Lagoons [ton h^{-1}]	0.97	14.00	2010	575.4	Lai et al. (2012)
Covered lagoons and gas recovery [m^3h^{-1}]	0.62	137	2014	580.2	Munasinghe et al. (2019)
Sugarcane plant					
1G-Ethanol plant [ton h^{-1}]	43.27	500.0	2015	537.0	Farzad et al. (2017)
2G-Ethanol plant [ton h^{-1}]	49.85	115.0	2015	537.0	Farzad et al. (2017)

c CEPCI 2019: 607.5.

[a] Steam cycle cogeneration.

[b] Internal combustion engine cogeneration.

Table 5
Methodology to calculate operating cost/annual production cost for the biorefinery. Adapted from (Gebremariam and Marchetti, 2018).

n°	Cost item	Calculation methods used
1	Raw material cost	Palm: 65 USD/t [a] Sugarcane: 23,32 USD/t [b]
2	Miscellaneous materials	1% of FCI
3	Utility cost	From material balance (1) + (2) + (3)
	Variable cost	
4	Maintenance	10% of FCI
5	Operating labor	10% of FCI
6	Labor cost	20% of operating labor
7	Supervision	20% of operating labor
8	Overheads	50% of operating labor
9	Capital charges	15% FCI
10	Insurance, local tax and royalties	4% FCI (4) + (5) + (6) + (7) + (8) + (9) + (10)
	Fixed costs	(Variable cost) + (Fixed cost)
	Direct production cost	
11	General overheads + R&D	5% of the direct production costs
	Annual production costs	Direct production cost + (11)
	Unit production cost	Annual production cost/Plant capacity

[a] (Klein et al., 2018).

[b] (Bressanin et al., 2020).

environmental impacts as well as energy efficiency indicators of the cycle, and finally the normalization and interpretation of the results.

2.4.1. Goal and scope

A comparative life cycle analysis of the type "*cradle-to-gate*" to evaluate the emissions performance between conventional sugarcane ethanol and palm oil biodiesel production (by the methyl route) with an integrated ethanol biorefinery (1st and 2nd generation) sugarcane with palm oil biodiesel (by the ethyl route). The functional unit was defined as 1.0 MJ of energy produced and the co-products were handled by energy allocation (since the function of the system is energy production), based on the individual percentage contribution to the total energy content.

2.4.2. Life cycle inventory – LCI

The inventory data were calculated from primary (mass and energy balance) and secondary sources (see supplementary Materials, Tables A to L). Secondary sources were reviews and scientific papers from Science Direct and Scopus databases. Feedstock transport distance from land to plant area was assumed to equal 30 km and EURO3 diesel trucks were hypothesized to cover the route. The feedstock preparation involved mechanical operations such as milling, mixing, drying, chopping, etc. (see section 2.1). The LCA study was performed in Brazil.

2.4.3. Life cycle impact assessment – LCIA

Emissions were modeled by using the software package SimaPro v.8.0.3 (Pre-Consultants) as it is a widely used LCA tool by practitioners and researchers alike. The impacts were quantified using the *Impact 2002* + method, which is a methodology originally developed at the Swiss Federal Institute of Technology Lausanne (EPFL) in Switzerland. This methodology provides a combined midpoint/endpoint approach, linking all types of life cycle inventory results (elementary flows and other interventions) to the four categories of harm (endpoint) via 14 midpoint categories (Jolliet et al., 2003). In this way, it utilizes the advantages of problem-oriented and harm-based methodologies (Maham et al., 2018; Mahath et al., 2019). However, the results obtained in this research are presented in terms of seven midpoint categories, considered the most relevant for this study: *non-renewable energy, global warming, aquatic eutrophication, aquatic acidification, terrestrial acidification, ozone layer depletion, and respiratory inorganics*. This systematic approach ultimately reveals the potential of the evaluated product and identifies the environmental hot spots in the product chains so that preventive measures can be suggested to reduce the negative environmental impact (Gikonyo, 2015).

Emissions related to land-use change have been omitted due to methodological limitations of incorporating them into the LCA framework. Similarly, capital goods associated with plants, equipment, and machinery are not considered in this document; nor are the uncertainties regarding contextual assumptions. Furthermore, oil palm and sugarcane are considered permanent and annual crops, respectively, of established cultivation areas and intended to expand in pasture areas or degraded lands; according to data obtained from the database of (LAPIG, 2020), there are more than 20 million hectares of pastures with signs of degradation or degraded in the states of Pará (30%) and Bahia (70%), regions where the above-mentioned crops can coexist and be integrated. In fact, according to (Cortez et al., 2015), Brazil has a unique combination of positive factors and resources favorable for sustaining the expansion of biofuel production without compromising food production or the use of protected native vegetation, and therefore the impacts of land-use change may be less relevant than in other global regions.

2.4.4. Life cycle energy efficiency performance

The *Net Energy Ratio* (NER) and *Renewability Factor* (RF) were used in the analysis of life cycle energy efficiency performance and have been described below. The NER is defined as the ratio between total energy production and total energy input. Total energy production consists of the energy content of biofuel, including the energy contribution of byproducts, if used to meet the energy production needs, while total energy input corresponds to non-renewable and renewable energy sources used in production, such as fossil, nuclear, biomass, wind, geothermal and water (Kaushik and Muthukumar, 2018). Moreover, RF is defined as the ratio between the final energy of the fuel relative to the fossil energy required to produce it (Suwanmanee et al., 2020). The two indices are similar, dimensionless, and could be considered efficiency indicators; however, RF measures the degree to which a given fuel is or is not

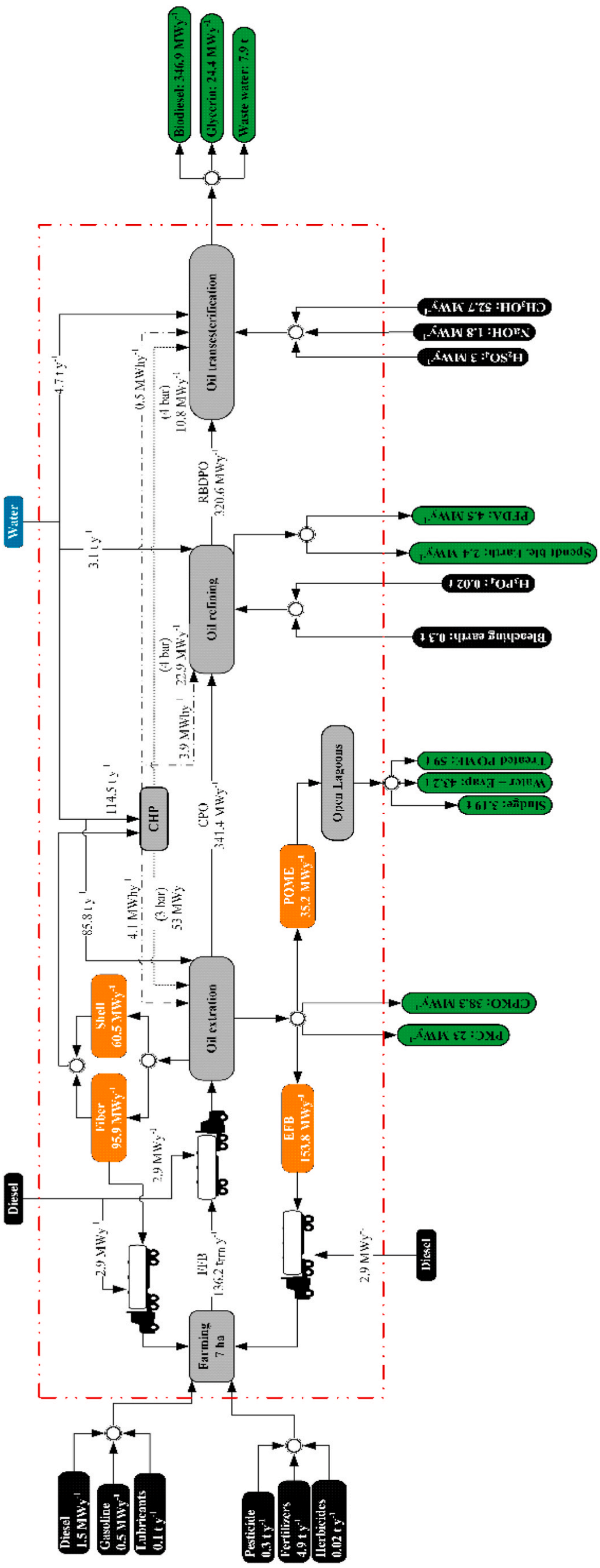

Fig. 5. Mass and energy balance of biodiesel production.

renewable (Mata et al., 2011).

3. Results and discussion

Below are presented for each of the scenarios considered in the main results of the thermodynamic evaluation (mass and energy balances and performance indicators), as well as the results of the economic and environmental evaluation.

The economic performance was made by estimating the system-wide investment costs in order to determine the minimum selling prices of each product for both scenarios.

Then, the potential contribution of each scenario for global warming was considered through the emission of CO_{2eq} per unit of energy of biofuel produced ($gCO_{2eq}\ MJ^{-1}_{biofuel}$). Finally, the impact and damage categories were reviewed along with the NER and RF efficiency indicators. Long-term emissions and infrastructure processes were excluded from the analysis.

3.1. Mass and Energy balances

Considering the operating conditions and the productivity of each process that make up the baseline scenarios described in section 2, an energy and mass balance was elaborated. Its results can be seen in Fig. 5 and Fig. 6. In these figures, and those that follow, the results have been shown by 10 ha of cultivated area (70% for palm oil and 30% for sugarcane). In the baseline scenario (Figs. 5 and 6), one can notice that by using low pressure boilers, the cogeneration system exposes a biomass demand of 7.14 kg s^{-1} of fiber/shell mixture and 18.27 kg s^{-1} of bagasse, whose LHV is19.95 MJ kg^{-1} and 7.52 MJ $kg^{-1,}$ respectively. From the consumption of this energy density, it is possible to generate in the system around 8 MWh (palm) and 9 MWh (sugarcane), quantity demanded by the adopted processes. This amount of energy is obtained after a steam production of around 31.82 and 30.45 kg s^{-1} in the oil palm and sugar cane crops, respectively.

On the other hand, η_{glo} quantifies the way energy is used in the system to produce the bio-based and bioenergy products. In the BSc scenario biodiesel and ethanol account for 68.72% of the energy production of the system, the rest (31.28%) is distributed among the co-products such as glycerin, CPKO, PKC, sugar, filter cake and vinasse. Therefore, the η_{glo} of the system obtained was 56.24%, while the P_{ele} obtained in the BSc scenario was 46.25 kWh ton^{-1}_{PRM}.

Fig. 7 shows the main results of mass and energy balances in the IBSc scenario. It can be seen that by adding the 2G ethanol plant and the anaerobic covered lagoons, the electricity consumption increased by 19.74% (3.56 MW), and the specific steam consumption increased by 11.31% (25.35 $t_{steam}\ h^{-1}$). The main consequence of this increase was the biomass deficit for the cogeneration system. That is, the steam production by the cogeneration system was not enough to meet the steam demand of the proposed system. In numerical terms, the amount of bagasse available is 65.77 $t_b\ h^{-1}$, since 29.60 $t_b\ h^{-1}$ is destined for the 2G ethanol plant, and the amount needed for the cogeneration plant to supply the system's energy demand is 78.47 $t_b\ h^{-1}$. Because of this, high pressure boilers were used with the residual biomass obtained from the palm and sugar cane crops as fuel so that it would be possible to generate around 188 MW_{th} in the cogeneration system at different pressure lines (2.5, 3, 4 and 35 bar). This amount of thermal energy was extracted from extraction and condensation turbines (CEST), which had a net electricity production of 56 MW_{el}, in which 39.3% of the electricity produced was used to meet the electrical demands of the various processes adopted in the integration. Thus, more than 60% of the electricity generated is available, which translates into an installed capacity of 34 MW_{el} that can be sold to the grid. Furthermore, this amount was increased by 4.5 MW_{el}, generated from the direct combustion of biogas captured through the treatment of POME in an ICM, totaling 38.9 MW_{el} of surplus electricity. Consequently, the η_{glo} and P_{ele} indices obtained showed increases of 60.1% and 152.3 kWh ton^{-1}, respectively.

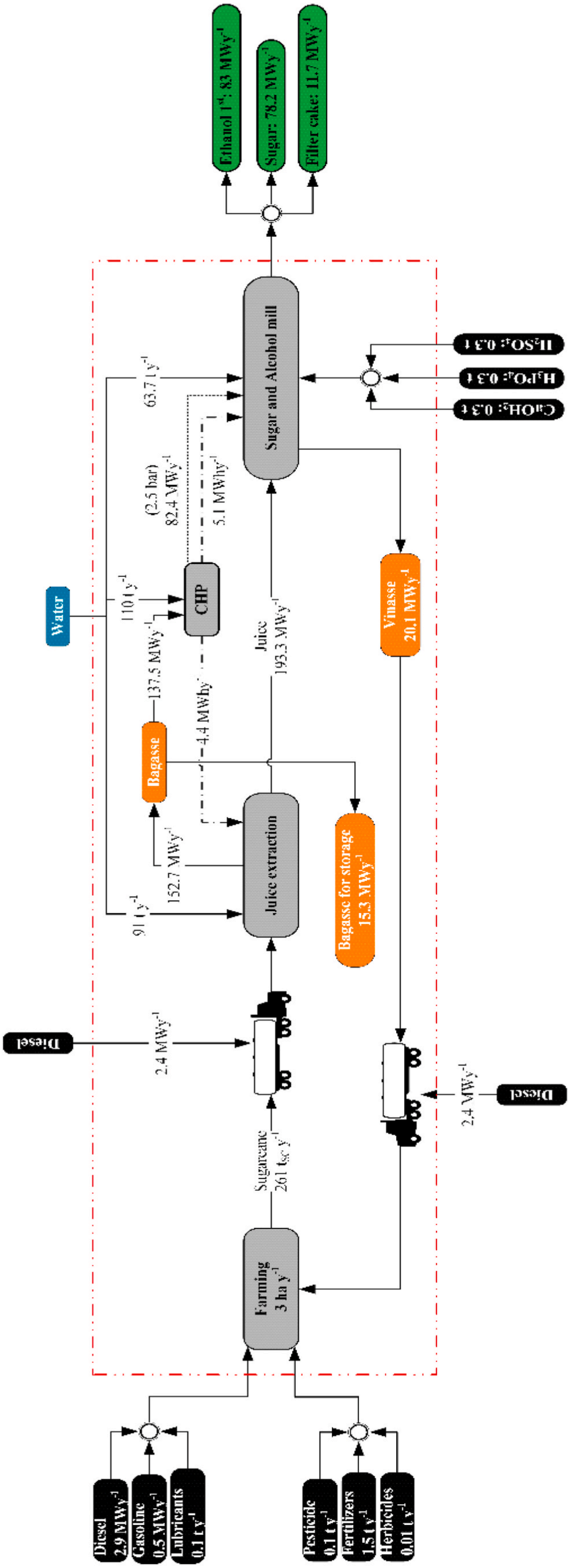

Fig. 6. Mass and energy balance of sugar and alcohol production.

The comparative results of η_{glo} and P_{ele} for each scenario were evaluated, obtained using the first-law performance indicators (see section 2.2) as shown in Fig. 8. It can be seen that the integrated system has better energy indices, showing gains of 3.82% in η_{glo} and 106.32 kWh ton_{PRM}^{-1} in P_{ele}. It can be seen that the P_{ele} of the IBSc showed an unmeasured increase in bioelectricity because improvements were assumed in the cogeneration system with the most preponderant being of the condensing/extraction steam turbines as it showed an increase of 12.8% when compared to the BSc. Moreover, by adding the combustion of the biogas generated by the system, an extra 11.57% electricity production is obtained. Despite this, η_{glo} presented a conservative energy gain. Such a fact is attributed to the remarkable consumption of ethanol in the transesterification process, which is more than 54%. This translates into an annual energy demand of 187.2 GJ more of ethanol if compared to the conventional scenario.

3.2. Economic performance

Based on the production capacity of each multi-product system plant, it is possible to estimate the investment costs for the entire system. This estimate was based on known references data and applied to Equation (1). The investment costs taken from prior references did not correspond to the current costs at the time of writing, and it was therefore necessary to correct these using the most recent CEPCI index, which took inflation into account. Likewise, Table 6 presents the investment expenses in each biorefinery stage and the sum of all, which represents the FCI.

Once the total capital investment, variable operating costs, and fixed operating costs have been determined, an analysis can be used to determine the minimum selling price of each product of the system. Concerning the multi-product break-even analysis to obtain the minimum selling price of the products, a weighted average among the products shall be done. The contribution of each product in a potential annual revenue were calculated based on the most recent price practiced with the final consumer for each product in the Brazilian market, as in the work of (Bressanin et al., 2020). To calculate the potential revenue, the total production of biodiesel, ethanol, electricity and the co-products was considered along with 4152 h of annual work and a plant lifetime of 20 years. These data are presented in Table 7 and Table 8. The minimum selling prices of both scenarios are presented in Table 8.

The minimum selling prices for the Integrated biorefinery scenario are higher for all of the products. This is due to the higher initial investment associated with this system. For biodiesel, both cases shall produce the same number of liters. Thus, the income would eventually be the same. However, for ethanol the circumstances are different. In the IBSc, due to the insertion of the 2G ethanol plant, there was an increase in investment costs; nonetheless, its adoption has also provided a greater amount of biofuel that can also increase the plant's economic cash flow in the long run. The same logic can be applied to the surplus electricity commercialization in the integrated scenario. The amount of kWh available to grid commercialization is much higher than in the baseline scenario. In face of that, a further study to detail the attractiveness of each investment and its risks shall be conducted sequentially. This will help in understanding which is the most viable investment despite the minimum selling price analysis.

Fig. 9 presents how each economic parameter influences the minimum cost obtained for the products of the two scenarios. The factor that contributed the most was the raw material expenses, which is common for first-generation plants like the Baseline Scenario. The costs with capital charges, insurance, taxes, royalties and labor did not present anything notable, being all under 5%, influence when varying its costs in a range of ±10%. The maintenance expenses presented a more notable influence in the final costs, accounting for 4.6 and 5.7% in BSc and IBSc, respectively.

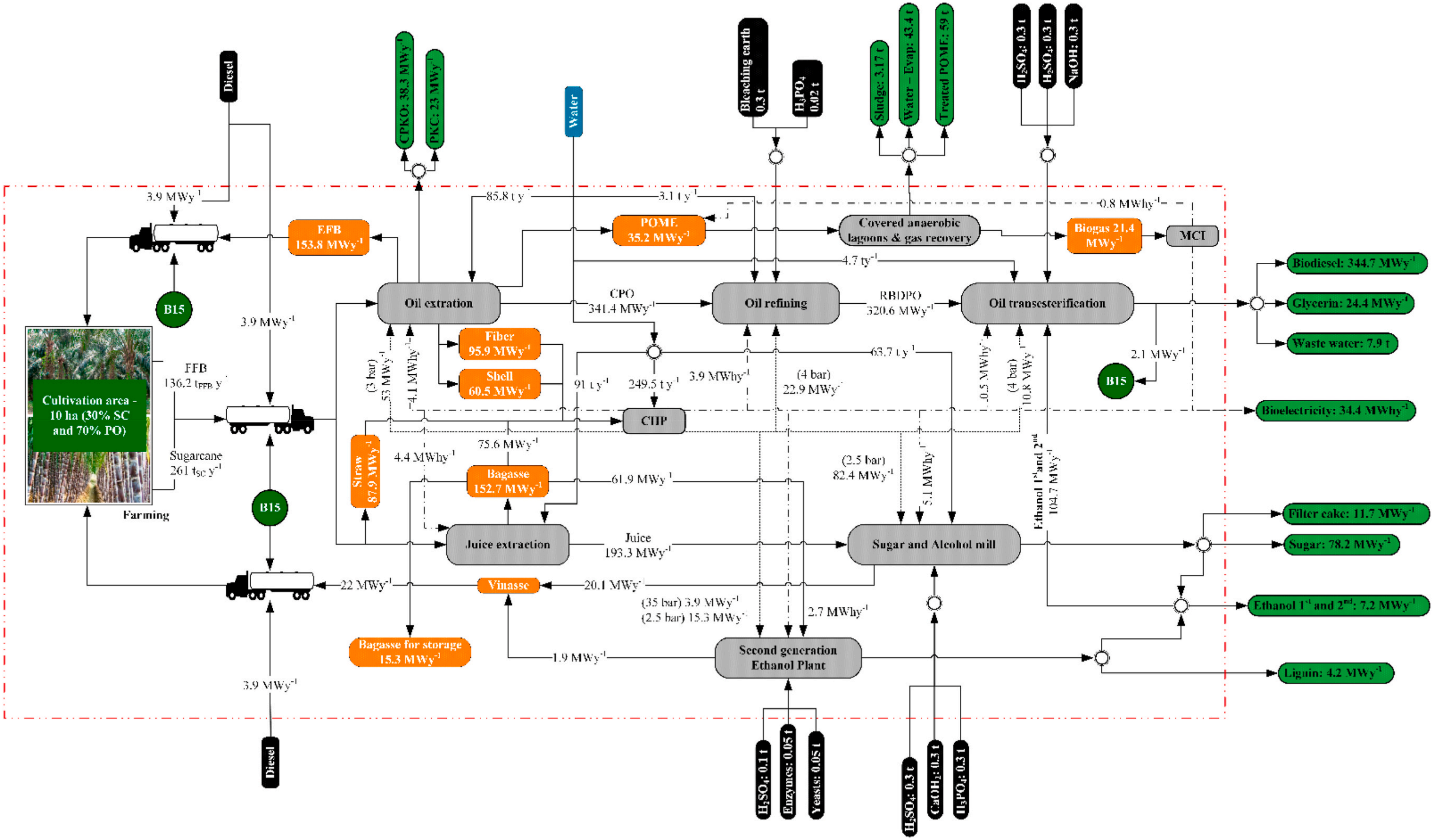

Fig. 7. Mass and energy balance of IBSc.

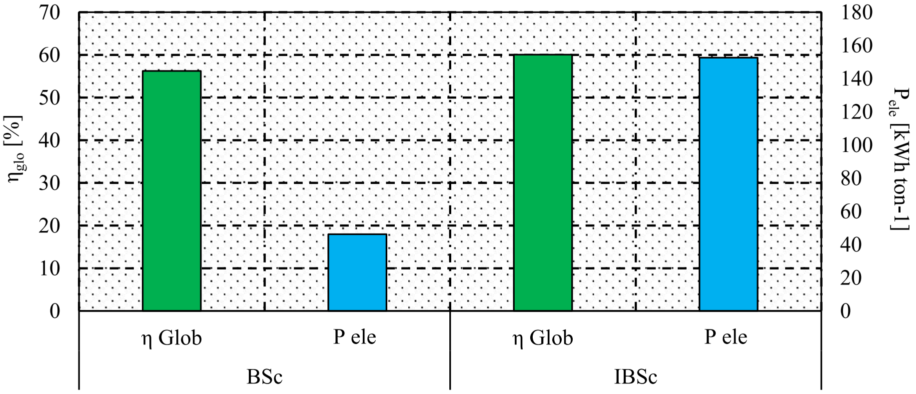

Fig. 8. Comparison of the energy indicators of the BSc and IBSc.

Table 6
Investment costs estimated for each plant of the multi-product system.

	BSc	IBSc
- Palm (M USD$)		
Palm Oil Extraction	73,780	73,780
Biodiesel plant	24,365	24,365
Open Lagoons	1961	–
Covered Lagoon and Gas recovery		4546
- Sugar Cane (M USD$)		
1G-Ethanol	32,304	32,304
2G-Ethanol	-	24,347
- Cogeneration (USD$/kW)		
CHP from palm biomass	1,980.44	3,649.25
CHP from sugarcane biomass	1,853.79	3,842.31
FCI (M USD$)	**165,585**	**358,138**

Table 7
Market costs and potential revenues of the products considered in the system.

	Practiced cost in Brazilian market		Unit	Reference
Ethanol	0.49		USD L^{-1}	CEPEA (2021)
Sugar	0.39		USD kg^{-1}	CEPEA (2021)
Biodiesel	0.79		USD L^{-1}	ANP (2021)
Glycerol	2.24		USD kg^{-1}	EPE (2019)
Electricity	40.52		USD MWh^{-1}	CCEE (2021)
	Potential revenue BSc (M USD$)	**Weighting factor (%)**	**Potential revenue IBSc (M USD$)**	**Weighting factor (%)**
Ethanol	16.30	9.06	21.96	11.43
Sugar	27.69	15.39	27.69	14.41
Biodiesel	90.50	50.30	90.50	47.11
Glycerol	45.42	25.25	45.42	23.64
Electricity	0.0001	0.00	6.54	3.41

Table 8
Minimum selling price the products produced in each scenario.

	MSP [BSc]	MSP [IBSc]	Unit
Ethanol	0.39	0.49	USD L^{-1}
Sugar	0.31	0.39	USD kg^{-1}
Biodiesel	0.63	0.78	USD L^{-1}
Glycerol	1.79	2.23	USD kg^{-1}
Electricity	32.23	40.19	USD MWh^{-1}

3.3. *Impact categories and Damage categories assessment*

According to section 2.4.3, seven mid-point categories were evaluated for the sustainable production of bioenergetics, considering 1 $MJ_{bioenergetic}$ as a functional unit. Table 9 shows the potential environmental impacts generated from the most prevalent bioenergetics in the comparative analysis between the BSc and IBSc scenarios, i.e., 1G ethanol, 2G ethanol, FAME, FAEE, and bioelectricity. The results reveal that the integration of palm oil and sugarcane bio-refining systems can make significant contributions to the sustainability of bioenergetics by integrating biomass waste and bioproducts processed along the entire bio-refining chain. In turn, they would help reduce various environmental impacts. For example, the global warming impact of 1G ethanol would be reduced from 6.92 to 4.88 g de CO_{2eq} MJ^{-1} of ethanol if all assumptions were applied. However, the combustion of biomass in the cogeneration system, the transportation (use of 15% of FAEE), along with the production of biodiesel by the ethylic route, led to an increase in the Respiratory inorganics category in ethanol from 0.08 g $PM_{2.5eq}$ MJ^{-1}.

Figs. 10, 11 and 12 show the relative potential environmental impacts per MJ of bioenergy produced from the comparative analysis between the BSc and IBSc scenarios, in the Global warning category, reductions of 44.50% for 1G+2G ethanol, 29.06% FAEE and 74.08% in bioelectricity were obtained. This is due to the suppression of 15% of diesel consumption (34.56 L_{diesel} ha y^{-1}) in the transport step and by the capture of CH_4 (550.72 m^3 ha y^{-1}) generated by POME. In the Non-renewable energy category, reductions of around 44.50%, 66.31% and 83.42% were achieved for 1G+2G ethanol, FAEE and bioelectricity, respectively. These reductions come from the replacement of 18,961.2 GJ y^{-1} of fossil methanol consumed in the transesterification step and 7.14 GJ y^{-1} of diesel consumed in the transport step. Consequently, such attenuations have a positive impact on the categories Ozone layer depletion (44.9% ethanol 1G + 2G, 47.11% FAEE and 84.13% bioelectricity), Terrestrial acid/nutri (37.95% ethanol 1G + 2G, 34.13% FAEE and 67.15% bioelectricity), Aquatic acidification (33.12% ethanol 1G + 2G, 35.93% FAEE and 68.27% bioelectricity) and Aquatic eutrophication (24.33% ethanol 1G + 2G, 1.15% FAEE and 70.92% bioelectricity). However, the Respiratory inorganics category showed an increase in $PM_{2.5\ eq}$ for 1G+2G ethanol (64.66%) and FAEE (27.86%) from the burning of residual biomass (mainly straw) and biogas while bioelectricity showed a 28.27% decrease in $PM_{2.5\ eq}$ due to the fact that a good surplus production was achieved (38.88 GWh y^{-1}).

On the other hand, in the Impact 2002 + method, the impact categories shown in Table 9 are related to four categories of damage (resources, climate change, ecosystem quality, and human health), and the results obtained in this analysis are presented in Fig. 13, Fig. 14, and Fig. 15. The results show that the significant benefits of integration between palm oil and sugarcane biorefinery for biofuels production are Ecosystem quality, Climate change, and Resources. Compared to the BSc, the reduction of these impacts would be 41.4%, 41.5%, and 36.2% for ethanol (1G + 2G) and 43.9%, 41.5%, and 25.2% for FAEE, respectively, if all the alternatives were implemented. In the case of the Human Health category, increases of 46.4% (ethanol (1G + 2G)) and 16% (FAEE) were obtained because this impact category is mainly

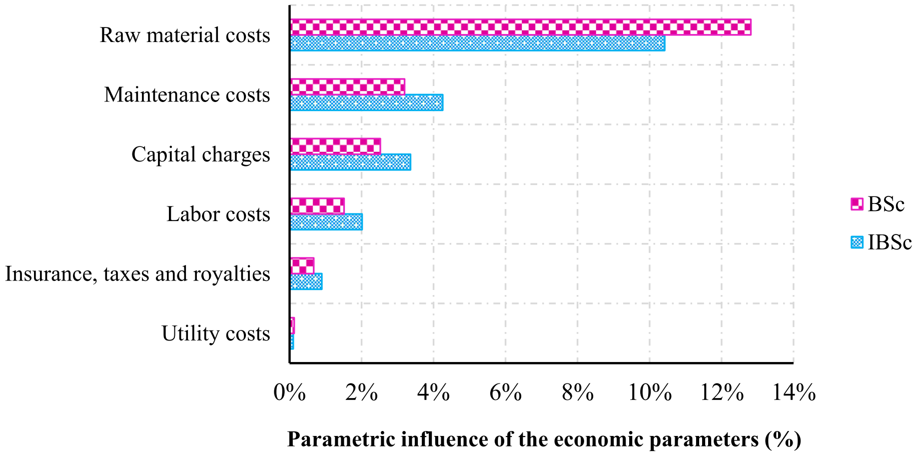

Fig. 9. Influence of the difference expenses on the minimum selling costs of the products.

Table 9
Potential environmental impact of final bioenergetics obtained from BSc and IBSc scenarios.

Impact Categories	Units	Ethanol [$MJ_{Ethanol}$]		Biodiesel [$MJ_{Biodiesel}$]		Bioelectricity [$MJ_{Electricity}$]	
		BSc (1G)	IBSc (1G+2G)	BSc (FAME)	IBSc (FAEE)	BSc (kWh)	IBSc (kWh)
Respiratory inorganics	G $PM_{2.5\ eq}$	0.05	0.13	3.25	4.50	296.07	212.38
Ozone layer depletion	g CFC-11 eq	8.15×10^{-7}	4.49×10^{-7}	7.14×10^{-7}	3.78×10^{-7}	2.60×10^{-5}	4.12×10^{-6}
Terrestrial acid/nutri	g SO_{2eq}	0.65	0.40	1.34	0.88	69.32	22.77
Aquatic acidification	g SO_{2eq}	0.14	0.09	0.22	0.14	9.96	3.16
Aquatic eutrophication	g PO_4 P-lim	0.04	0.03	0.05	0.05	1.79	0.52
Global warming	g $CO_{2\ eq}$	6.92	4.88	8.98	6.37	271.23	70.29
Non-renewable energy	$MJ_{primary}$	193.94	107.63	296.12	99.74	6444.72	1068.56

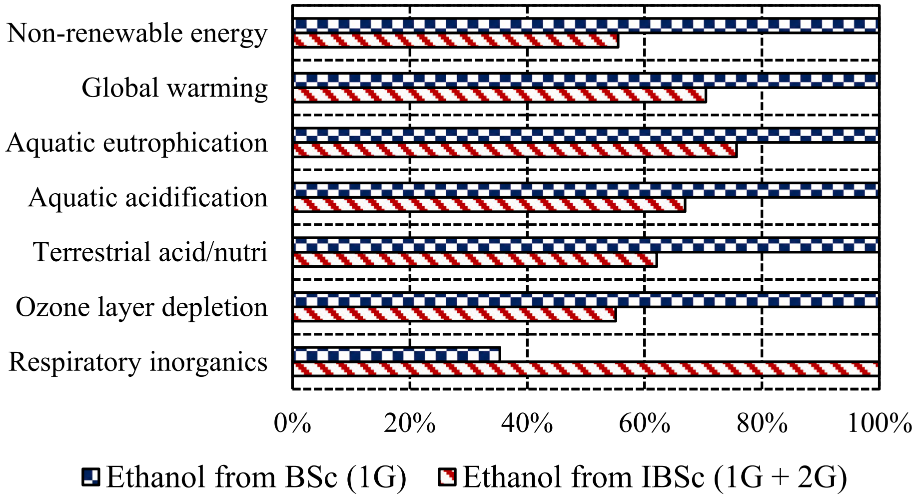

Fig. 10. Impact categories comparison of Ethanol BSc and IBSc scenarios.

contributed by the use of biomass (bagasse, straw, fiber, and bark) in the cogeneration system and biofuel (ethanol and FAEE) as an input in production processes (transport and ethyl transesterification), which increase $PM_{2.5}$ emissions. In contrast, the bioelectricity produced at IBSc shows reductions in all categories of damage of 16.2% (Human health), 53.2% (Ecosystem quality), 58.4% (Climate change), and 71.3% (Resources), coming from the best techniques in the cogeneration system and the use of biogas generated from treated POME.

3.4. Life cycle indicators

The NER and RF indicators were estimated for all alternative bioenergy production and the results are shown in Table 10. A total RF of 8.58 MJ_{out} MJ_{in}^{-1} was calculated for the BSc (Table 10), a result comparable with previous studies of biodiesel production from palm oil (9.9 and 10.1 MJ_{out} MJ_{in}^{-1}) (Ocampo Batlle et al., 2020; Souza et al., 2012) and ethanol from sugarcane (9.4 and 9.8 MJ_{out} MJ_{in}^{-1}) (Palacio et al., 2018; Renó et al., 2014). When BSc is compared to IBSc, the RF index increases 7.12 units of renewability energy, which is due to the significant reduction in fossil fuel consumption in the transport and transesterification stages, in addition to energy recovery from residual biomass in more efficient energy conversion systems.

In the analysis of the NER index, a value of 13.44 MJ_{out} MJ_{in}^{-1} was obtained for the IBSc scenario (Table 10). This represents an increase of

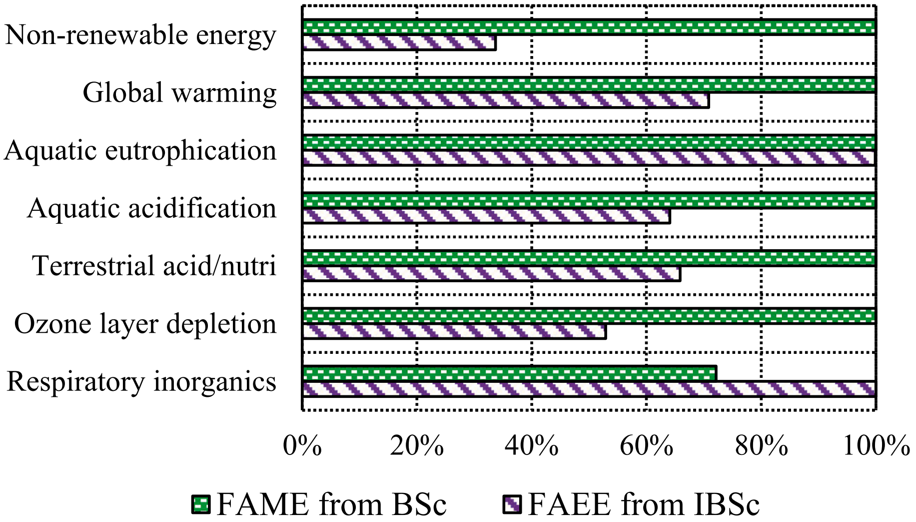

Fig. 11. Impact categories comparison of Biodiesel BSc and IBSc scenarios.

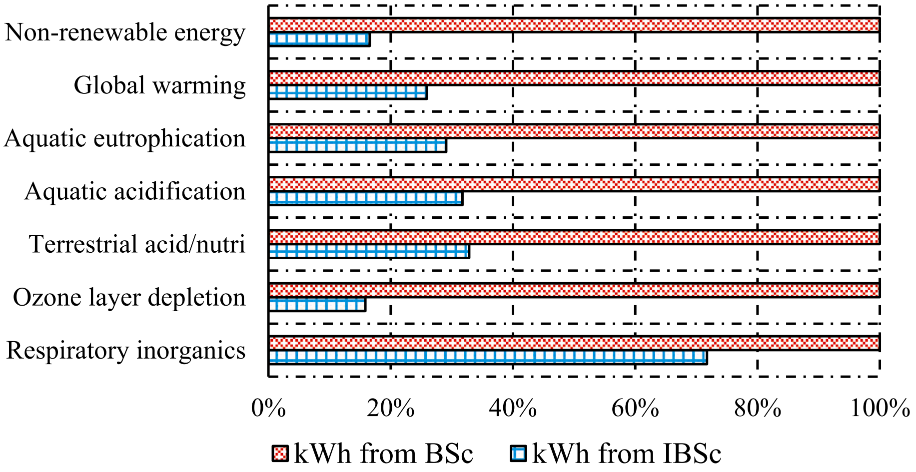

Fig. 12. Impact categories comparison of Bioelectricity BSc and IBSc scenarios.

83.1% in the production of energy when compared with the BSc. Therefore, the index has proved to be naturally advantageous both from an energy and environmental point of view since in the literature biofuels produced from palm and sugarcane have a plurality of values ranging from 8.10 a 9 MJ_{out} MJ_{in}^{-1} (Ocampo Batlle et al., 2020; Palacio et al., 2018; Renó et al., 2014; Souza et al., 2012). This is attributed to the fact that the characteristic assumptions of each work in which the consumption of fossil energy and improvements in the technical aspects of electricity and heat production systems can vary. Table 10 shows that the NER value calculated in the IBSc of this work, when compared with existing values in the literature on palm biodiesel and sugarcane ethanol, presented a growth potential of as much as 4.4 energy units, which translates into more efficient and sustainable use of raw materials. The potential energy gains and benefits could contribute to the improvement of integrated production in biorefining of palm oil and sugarcane, positively favoring Brazil's bioenergy sector.

It is important to note that the results presented in this survey are representative of the Brazilian case and consequently, changes can be expected under different geographical conditions. The reductions in fossil energy consumption in the evaluated scenarios of this work were determined by the premises adopted related to the limits of the system, inventory data, allocation method, and technological capabilities. The proposed production chains were based on the country's current conditions and depend on agricultural production and installed capacities. Also, the system boundary of this comparative LCA analysis excludes the use of the bioenergetics produced. Thus, the general analysis of the life cycle from cradle to grave of bioenergetics is beyond the scope of this study.

4. Conclusions

The multifunctional role of sugarcane and oil palm (dendezeiro) makes them medullar raw materials for the production of a wide portfolio of bioenergetics and other bioproducts. In this context, this research aimed to analyze the possibility of diversifying and integrating the products of the sugarcane and palm industry within the concept of biorefinery. This would encourage a reduction in dependence on fossil fuels (consequently reducing CO_2 emissions) and improve the energy performance of the system. Consequently, the proposal evaluated and calculated the potential environmental impacts, energy, and efficiency indicators related to integrated bioenergy production from palm oil and sugarcane through an LCA comparative study.

The integrated system evaluated showed a potential increase in the overall system efficiency of 3.82%, and an excess electricity production of 106.32 kWh ton_{PRM}^{-1}. Furthermore, the LCA of the integrated system demonstrates that such alternatives focusing on sustainable biofuels can reduce fossil energy consumption by 9.6 kJ MJ_{FAEE}^{-1} and 8.11 kJ $MJ_{ethanol1G2G}^{-1}$. As a result, substantial GHG reductions of 2.3 g CO_{2eq}

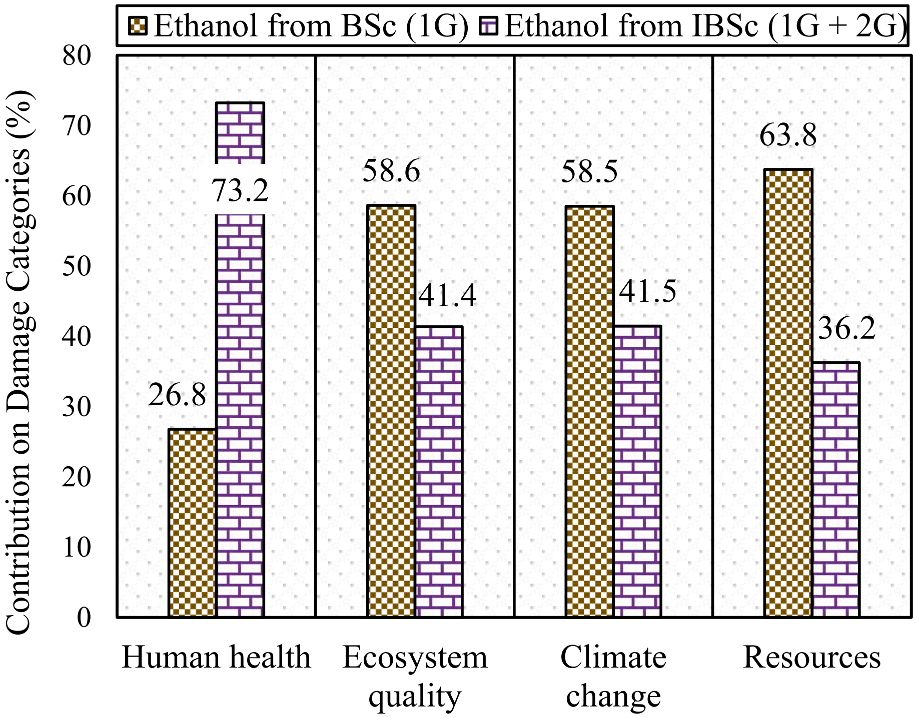

Fig. 13. Damage categories comparison of Ethanol BSc and IBSc scenarios.

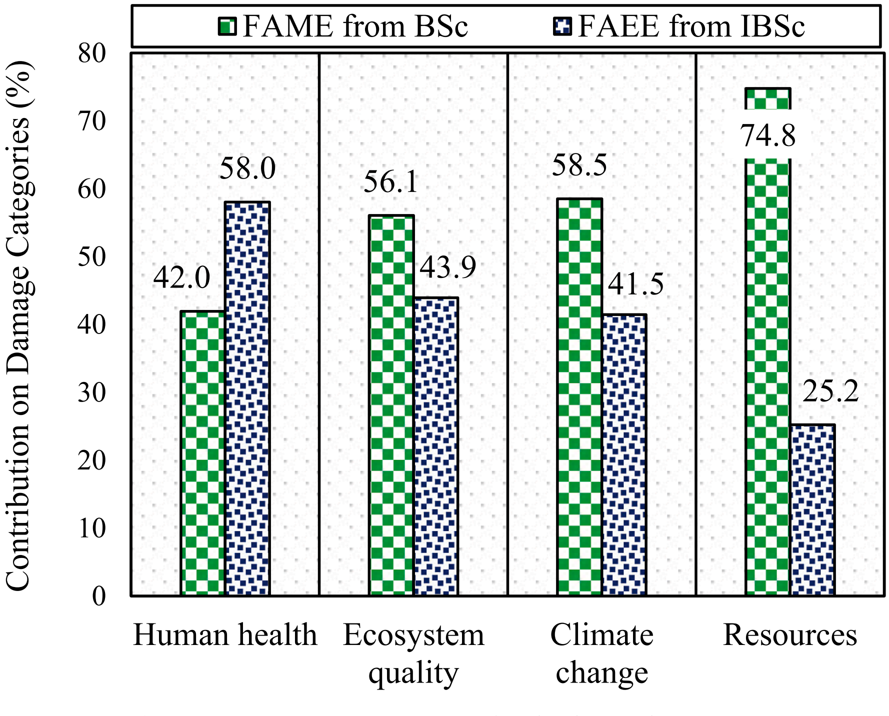

Fig. 14. Damage categories comparison of Biodiesel BSc and IBSc scenarios.

$MJ_{ethanol1G2G}^{-1}$ and 2.6 g CO_{2eq} MJ_{FAEE}^{-1} were seen. Therefore, the RF and NER indicated the potential environmental and energy benefits of integrated biorefining of palm and cane since they present an increase in renewability of 7.12 MJ_{out} MJ_{in}^{-1} and an energy utilization of up to 50% more. In light of the aforementioned details, it is evident that the proposed integrated biorefinery concept, in the context of an agro-industrial economy, can mitigate emissions to air, soil, and water from its cycles in addition to offering an attractive portfolio of bioenergy and coproducts. From an economic point of view, integration is also economically feasible; however, economic performance could be enhanced through governmental incentives founded on fossil energy use, enhanced conversion yielding, and improvements in conversion technologies.

Results outlined in this paper are based on the integration of technological and logistical considerations adopted in each scenario. Therefore, limitations of the present research can be described as: economic and logistical feasibility; geographic conditions that could affect agricultural performance; and technical aspects regarding biodiesel-ethanol integrated production. Once these technological and

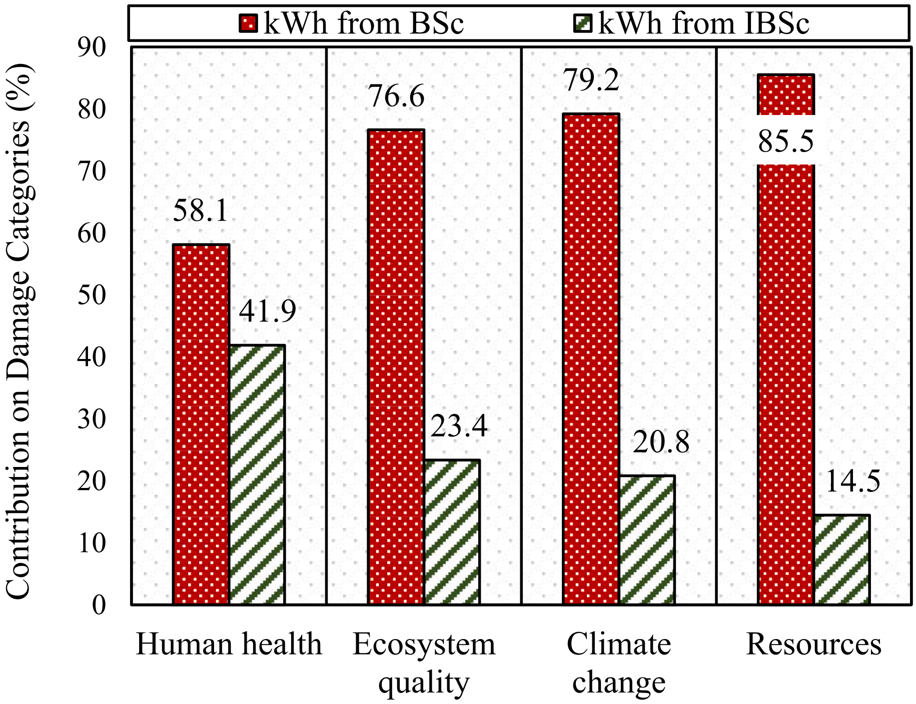

Fig. 15. Damage categories comparison of Bioelectricity BSc and IBSc scenarios.

Table 10
Comparisons of the NER and RF index obtained in this study with others reported in the literature.

Index	This study		Other studies			
	BSc	IBSc	Ocampo Batlle et al. (2020)	Palacio et al. (2018)	Renó et al. (2014)	Souza et al. (2012)
NER [MJ_{out} MJ_{in}^{-1}]	7.34	13.44	8.50	8.80	8.10	9.00
RF [MJ_{out} MJ_{in}^{-1}]	8.50	15.70	9.93	9.85	9.40	10.1

commercial disadvantages have been overcome, plants like the one proposed in this study might reach a feasible economic stage and likewise play an important role in the transition towards a circular economy that promotes sustainability. Thus, it is recommended that a socio-economic analysis with more detail should as well considered in a future study.

CRediT authorship contribution statement

Eric Alberto Ocampo Batlle: Writing – original draft, Conceptualization, Methodology, and, Software. **José Carlos Escobar Palacio:** Conceptualization, Investigation, Writing – review & editing. **Electo Eduardo Silva Lora:** Supervision, and, Resources. **Edson Da Costa Bortoni:** Project administration, Writing – review & editing. **Luiz Augusto Horta Nogueira:** Project administration, and, Supervision. **Gaylord Enrique Carrillo Caballero:** Investigation, and, Writing – review & editing. **Alisson Aparecido Vitoriano Julio:** Formal analysis, and, Investigation. **Yulineth Cárdenas Escorcia:** Visualization, and, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.127638.

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