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RESEARCH ARTICLE OPEN ACCESS

Environmental and energy issues in biodiesel production using palm oil from the interspecific hybrid OxG and Elaeis guineensis: a case study in Colombia☆

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Abstract – In Colombia, in the last decade, the *interspecific hybrid cultivar OxG*, generated by a cross between American palm and African palm, has increased due to its tolerance to bud rot caused by *Phytophthora palmivora*. This study aimed to evaluate and compare the energy balance and environmental indicators of biodiesel production chains for both cultivars in Colombia. For this, an energy analysis was carried out to determine how energy is used in each process, as well as the palm energy per hectare. Also, a comparative analysis "cradle-to-gate" was made to verify the environmental performance of the genotypes studied. The functional unit was defined as 1.0 MJ of energy produced, and impacts were modeled using SimaPro v.8.0.3 software and quantified using the Impact 2002+ method. The results showed biodiesel from hybrid OxG reduced 6.2% the overall efficiency indicator of the system compared to biodiesel from *E. guineensis*. Life cycle CO_2eq emissions of *E. guineensis* biodiesel were 12.5 g MJBD-1 (excluding carbon sequestration). In contrast, the CO_2eq emissions of OxG hybrid biodiesel were 13.8 g MJBD-1. The life cycle efficiency indicators for biodiesel produced from *OxG and E. guineensis* showed a reduction in the fossil energy index of 26.9% and 19.7%, respectively.

Keywords: Biodiesel production / *Interspecific hybrid OxG* / *Elaeis guineensis* / LCA

Highlights

- Biodiesel production through the interspecific hybrid OxG and Elaeis guineensis.
- Overall efficiency of 61.82 and 55.62 for E. guineensis and OxG hybrid, respectively.
- Energy productivity per hectare of 1086.90 GJ ha-1 and 1131.02 GJ ha-1 for E. guineensis and OxG hybrid, respectively.
- 12.5 g MJBD-1 and 13.8 g MJBD-1 are emitted in biodiesel from E. guineensis and OxG hybrid, respectively.

Abbreviations

CPO	Crude Palm Oil
ICE	Internal Combustion Engine
CPKO	Crude Palm Kernel Oil
LCA	Life Cycle Assessment
PKC	Palm Kernel Cake
LCI	Life Cycle Inventory
EFB	Empty Fruit Bunch
LHV	Lower Heating Value
POME	Palm Oil Mill Effluent
FER	Fossil Energy Ratio
POM	Palm Oil Mill
NER	Net Energy Ratio
FFB	Fresh Fruit Bunch
η_{gl}	Global efficiency of the system

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CHP	Combined heat and power
σ_{palm}	Energy productivity per hectare
LUC	Land-use change
η_O	Global thermal efficiency
W_L	Net electrical power generation
EUF	Energy Utilization Factor
Q_u	Useful thermal energy
CEST	Condensing extraction steam turbine
$\dot{m}$	Mass flow
BPT	Back pressure steam turbine
E.G.	Elaeis guineensis
E.O.	Elaeis oleifera

1 Introduction

Biofuel production is growing worldwide because its use contributes to the mitigation of greenhouse gas (GHG) emissions and reduces the consumption of fossil fuels (Leblanc *et al.*, 2022; Jeswani *et al.*, 2020). One biofuel feedstock is crude palm oil (CPO). Considering the increase in the demand for bio-based products (food, bioenergy, and materials), CPO production is also expected to increase supply of the required raw material (Dey *et al.*, 2020). CPO is one of the most important crops worldwide because of its versatility, high productivity (approximately 3.4 tons of CPO per hectare), and lower production cost compared to that of other vegetable oils (Ramirez–Contreras *et al.*, 2020). Globally, more than 23 million hectares are used for producing oil yielding palm (Fedepalma, 2021), which accounts for more than 76.2 million tons CPO produced (Salvi and Panwar, 2012; Blackshaw *et al.*, 2011; Issariyakul and Dalai, 2014; Rocha *et al.*, 2021; Sales *et al.*, 2022; Bajpai and Tyagi, 2006; Alexandre *et al.*, 2022; de Oliveira *et al.*, 2021; Balat, 2011). Malaysia and Indonesia are the main producer countries with approximately 84% of the total production (Fedepalma, 2021). Colombia ranks fifth, with 2% share of global production (Fedepalma, 2021). The source of the largest commercial production of palm oil is *Elais guieneensis* Jacq. (African oil palm) (Corley and Tinker, 2003). However, there are some crosses between the African oil palm and American oil palm (*Elaeis oleifera* Cortes) genotypes, resulting in interspecific hybrid OxG, commonly referred to as hybrid OxG (de Lima *et al.*, 2020). In Colombia, the interspecific OxG hybrid is a promising genotype because of its higher resistance to certain diseases (*e.g.*, bud rot disease caused by *Phytophthora palmivora*), high productivity, and oil quality (Daza *et al.*, 2021; Ayala, 2013; Johnson, 2017). Currently, the area planted in Colombia is approximately 600 thousand hectares, of which the OxG represents 13%, however an increase in production is expected in the coming years (Fedepalma, 2021).

Research on palm oil production has focused on *Elais guineensis* cultivar. For example, Ramirez-Contreras *et al.* (2020) described the GHG emissions generated in the Colombian palm oil production chain, in addition to reporting the economic performance of its production both for the current situation and for two production scenarios using all the biomass generated in the CPO production chain. The results showed 55% reduction emissions in an optimized production chain based on good management practices, 20% reduction in capital expenditure and operating costs, and a reduction in the fossil energy consumed in the life cycle compared to the renewable energy produced. Results of a study by (Rivera-Méndez *et al.*, 2017), which assessed the carbon footprint of fresh fruit bunch (FFB) production of *E guineensis*, showed that carbon storage in the plantation was greater than the emissions associated with the whole oil palm production chain. Both studies agree on the possibility of producing sustainable oil palms in terms of GHG emissions and the economy in Colombia. However, sustainability is a complex aspect to analyze, as both environmental and socioeconomic issues converge in it (Ray, 2019). Sustainable production requires the use of the total biomass produced to maximize the efficiency of the energy used in the supply chain and reduce potential environmental impacts. In this regard, some studies (Yáñez Angarita *et al.*, 2009; Ali *et al.*, 2015; Garcia-Nunez *et al.*, 2016; Ocampo Batlle *et al.*, 2020) have proposed implementing the concept of biorefinery to produce CPO in a palm oil mill (POM), using all the biomass produced as a feedstock for energy and other co-products such as compost, biochar, pellets, bioethanol, biobutanol, biohydrogen, bioplastics, biocomposites, and bio-adsorbers. Moreover, these studies showed that a fraction of pressed mesocarp fibers, generating the steam and electricity, can be used as fuel for combined production of heat and power (CHP) required to run the POM. Anaerobic digesters have been proposed for the degradation of palm oil mill effluent (POME) as well as to obtain biogas that can be converted into electricity. The energy balance and environmental impacts of palm oil biodiesel have also been evaluated by (Pleanjai and Gheewala, 2009; De Souza *et al.*, 2010; Mata *et al.*, 2011), who reported the environmental benefits of palm oil biodiesel (*E. guineensis*) compared with other vegetable oil feedstocks.

Although much research has been conducted on issues related to the OxG cultivar focusing on its plantation, pollination, and oil characteristics, very little or no information is available regarding the energy efficiency or environmental impacts related to this oil palm genotype. Furthermore, as the largest production of palm oil in Colombia still depends on *Elaeis guineensis* cultivar, a comparative life cycle assessment between the two most produced oil palm genotypes is needed. The analysis included (i) conducting the energy balance considering the thermodynamic principles, and calculating the global efficiency of the system, energy productivity per hectare, net energy ratio (NER), and fossil energy ratio (FER) using Gate Cycle v.6.1.2 and Simapro v.8 .0.3 software; and ii) determination of the environmental impacts, including carbon footprint and life cycle impact assessment (LCIA) of seven midpoint categories (non-renewable energy, global warming, aquatic eutrophication, aquatic acidification, terrestrial acidification, ozone layer depletion, and respiratory inorganics) using the *Impact 2002+* method.

When comparing studies similar to the one proposed here, it can be seen that in the last 10 years (2014–2024) at least 7,314 studies have been published on the Web of Science, which assess the life cycle of palm oil for biodiesel production. However, when we evaluate only the studies that carry out LCA of biodiesel production using only the interspecific hybrid OxG genotypes or *Elaeis guineensis*, we see that nine studies were carried out in the same period. Tab. 1 shows the five papers with the greatest impact, *i.e.*, the most cited. The methods and main results of each paper are also described.

Table 1. Main studies that carry out an LCA of the use of *interspecific hybrid OxG* and *Elaeis guineensis* genotypes for biodiesel production.

N°	Title	Methods	Main results	Year	Cited by	Ref.
1	"Current state and environmental impact assessment for utilizing oil palm empty fruit bunches for fuel, fiber and fertilizer – A case study of Malaysia"	Case study of the use of palm oil waste, the empty fruit bunches (EFB) left after palm oil extraction. The assessment consists of analyzing the environmental performance of recycling technologies being developed in Malaysia for fuel, fiber and fertilizer. The life cycle assessment (LCA) method is used to discuss the environmental impacts of these technologies to add value to this biomass.	Among the technologies for energy production, CHP plants have the best performance if the electricity generated is connected to the national grid, with superior benefits in most impact categories compared to briquette, methane, and ethanol production. Overall, methane recovery and composting are more environmentally friendly than other technologies, as measured by the reduction of greenhouse gas emissions.	2013	164	(Chiew and Shimada, 2013)
2	"The energy balance in the Palm Oil-Derived Methyl Ester (PME) life cycle for the cases in Brazil and Colombia"	Life cycle assessment focused on the energy balance of palm oil methyl ester (PME), taking into account practices in Brazil and Colombia.	The paper shows the differences between the results obtained in the two cases. The output/input energy ratio for the case studies evaluated ranged from 3.8 to 5.7, with an average value of 4.8.	2009	72	(Yáñez Angarita *et al.*, 2009)
3	"A Comparison of Life Cycle Assessment on Oil Palm (Elaeis guineensis Jacq.) and Physic Nut (Jatropha curcas Linn.) as Feedstock for Biodiesel Production in Indonesia"	The paper conducted a life cycle inventory analysis on biodiesel production from oil palm and Jatropha curcas, focusing on material and energy inputs, air emissions, waterborne emissions, and solid wastes.	The life cycle inventory analysis results showed the input-output mass and energy for both oil palm and Jatropha curcas-based biodiesel feedstock production. It was observed that the reduction in CO_2 emissions for BDF-CPO and BDF-CJCO was 37.83% and 63.61%, respectively, after stable productivity periods. The study highlighted the significant environmental impact of global warming potential in biodiesel production, with differences noted between palm oil and Jatropha curcas biodiesel production.	2015	56	(Siregar *et al.*, 2015)
4	"Life cycle environmental impacts of a prospective palm-based biorefinery in Pará State-Brazil"	The work discusses various allocation methods for biorefineries, highlighting the lack of a universally recognized best practice. The study also focuses on the production of ethanol from oil palm biomass, considering factors like feedstock composition and conversion processes.	The main results of the work include positive life cycle energy balance, greenhouse gas reductions, and carbon sequestration through oil palm reforestation in a prospective palm-based biorefinery in Pará State, Brazil. The study also found that establishing a palm-based biorefinery could have environmental advantages in terms of reducing greenhouse gas emissions compared to conventional fossil fuels.	2013	24	(Kami Delivand and Gnansounou, 2013)
5	"Environmental load assessment for an integrated design of microalgae system of palm oil mill in Indonesia"	This research was a case study based on average field measurement data from a major palm oil plantation located in Indonesia (Riau province, Sumatra Island).	The integrated system produced 26,471 tons of biodiesel that included 223 tons from microalgae and contribute to 39.90% of total GHG emission reduction from diesel fuel substitute. Additional co-product of 520.33 tons year−1 of animal feed from defatted biomass also possible to be produced and have potential for environmental benefits.	2018	18	(Sasongko *et al.*, 2018)

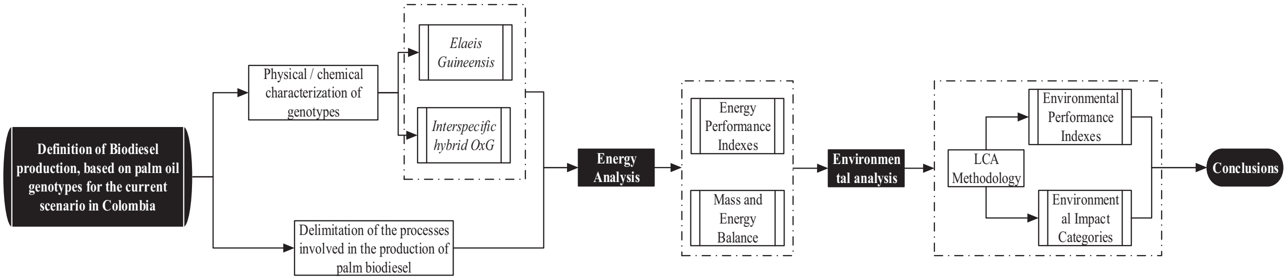

Fig. 1. Methodology flowchart for thermodynamic and environmental analysis of the different genotype considered.

Therefore, the novelty of this work is the evaluation and comparison of the environmental impacts of producing biodiesel from palm oil from *Elaeis guineensis* and the *interspecific hybrid OxG*. As well as all the energy required in the process from transporting the palm to producing biodiesel, based on a case study from Colombia.

2 Methodology

This study analyzes the energy and environmental performance of palm oil biodiesel from two oil palm genotypes planted commercially around the world, *Elaeis guineensis* and the interspecific hybrid OxG, as a case study in Colombia. The life cycle assessment of biodiesel production was analyzed in terms of energy efficiency, including the global system efficiency, energy productivity per hectare, NER, and FER. It was also analyzed in terms of potential environmental impacts, such as carbon footprint and LCIA of seven midpoint categories (non-renewable energy, global warming, aquatic eutrophication, aquatic acidification, terrestrial acidification, ozone layer depletion, and respiratory inorganics) using the *Impact 2002*+method. Fig. 1 shows an overview of the methodology.

2.1 Key characteristics between the two genotypes evaluated

The interspecific hybrid OxG is one of several palm genotypes developed in the Americas. It is the product of the crossing between two species that are economically important for the palm oil industry worldwide: *Elaeis oleifera* Cortes, native to the American continent, and *Elais guieneensis* Jacq., native to Central and West Africa (Daza *et al.*, 2021). The OxG genotype exhibited some specific characteristics different from those of *Elaeis guineensis*. Such characteristics includes a higher productivity of palm oil per hectare (>33 t of FFB ha^{-1} year^{-1}), a better response to bud rot disease, longer plant life (more than 25 years), and, in most of cases, a higher content of oleic acid (55%) in the palm oil produced (Rincón *et al.*, 2013; Barcelos *et al.*, 2015; Ayala and Romero, 2019).

In Colombia, the cultivation of OxG started in the 1980s in a few hectares of area that represented less than 0.5% of the total area of oil palm cultivation at that time. Due to the resistance of OxG against bud rot disease, the crop has reported continuous growth until it reached more than 80 thousand hectares in 2021 (SISPA, 2021). For the next few years, the cultivation area for OxG is expected to grow, especially in areas reporting the disease (Ayala and Romero, 2019). Having palm buds with a high tolerance to rot is extremely advantageous for agricultural production, especially in regions where this crop is economically significant. However, palm bud rot also presents considerable challenges. Here are the main advantages of rot-resistant palm buds: they tend to have a longer shelf life, reducing losses during storage and transportation (Rincón *et al.*, 2013). This is crucial for maintaining the quality and safety of the food until it reaches the end consumer. Resistance to rot can result in lower costs for chemical products to control diseases and fungi, as well as reducing the need for special handling to avoid damage during harvest and transportation. The reduction in the use of fungicides and other chemical treatments due to greater resistance to rot contributes to more sustainable agricultural practices, with less environmental impact and a lower risk of pathogen resistance development (Hassan *et al.*, 2024). One of the biggest challenges is to identify or develop palm varieties that are naturally resistant to rot. This may involve genetic improvement programs and plant selection. Many small producers may not have access to information or resources to implement effective management practices against rot. Agricultural extension and education programs are essential to spread best practices (Nurazah *et al.*, 2021). Tab. 2 shows the main characteristics of the OxG cultivars with respect to those of the *E guineensis* cultivar.

One of the major differences between OxG cultivars and African palm cultivars is the need for assisted pollination of female flowers because of the low viability and germinability of pollen. In absence of assisted pollination adequate bunches are not formed; therefore, the productivity of the fruit and the palm oil are affected (Rincón *et al.*, 2013). Adequate pollination of the inflorescences (time, quantity, season) can generate a 30% increase in the weight of the bunches compared to that of a non-pollinated fruit. It is possible to improve oilseed potential (disease resistance) by up to 5% and reduce the use of insecticides and pesticides (Osorio-Guarín *et al.*, 2019).

In contrast, studies conducted in Colombia by the Cenipalma Research Center (Nieto *et al.*, 2021), identified significant differences in the palm oil extraction rate in POM when processing OxG fruits compared to Guineensis fruits. The differences were directly correlated with the process variables in the digestion and fruit-pressing stages. These differences are mainly attributed to the pressure required in the screw press (higher), shell and kernel content (lower), palm oil per kg of fruit (higher), volume of press liquor (higher), distribution of volumetric phases (composition), and percentage of acidity of the oil (lower). In general, the processing of OxG fruit bunches reports a drop in capacity in the range of 8–10% with respect to

Table 2. Characteristics of the *Elaeis guineensis* palm and the *Interspecific hybrid (OxG)* palm.

Parameters	*Elaeis guineensis*	*Interspecific hybrid (OxG)*
Growth	46 cm year^{-1}	22 cm year^{-1}
Cultivation cycle	25 years	30 years
Seeding density	143 palms ha^{-1}	110–128 palms ha^{-1}
Pollination	Natural	Assisted
Harvest start	24–36 months	26–33 months
Harvest cycle	8–12 days	21–26 days
Percentage of extraction	20–24%	19–20%
Productivity	24–28 t ha year^{-1}	28–32 t ha year^{-1}
Oleic phase content	36–44%	49–58%

African palm fruit, causing the need to improve the industrial process for the extraction of OxG palm oil (Nieto, 2013).

2.2 Case study

To analyze the energy and environmental performance of Colombian palm oil biodiesel, a representative scenario of the biodiesel production chain that includes cultivation of oil palm, transport of FFB, oil extraction in the POM, transport of CPO, and refining and transesterification of the oil, was studied. The information used to build this scenario was collected through field visits to a POM located in eastern Colombia, one of the regions with the highest CPO production in the country (Fedepalma, 2021). The POM processes using the two types of fruits evaluated, that is, *E. guineensis* and interspecific hybrid OxG, with a production capacity of 70 t h^{-1} of FFB operating at 3583 h y^{-1}. In total, approximately 250 thousand tons of FFB are processed per year in the mill, obtained from approximately 10,000 ha of oil palm, with an average crop yield of 25.08 t FFB ha^{-1}y^{-1}. In order to harmonize the primary data collected for the interspecific hybrid OxG, we considered the same number of planted hectares as in the case of *E. guineensis* (10,000 ha y^{-1}). However, the OxG crop yield was 30.55 t FFB$_{\mathrm{OxG}}$ ha^{-1} y^{-1}, higher than that of *E. guineensis*, and the total FFB$_{\mathrm{OxG}}$ processed per year in the mill corresponded to 305,500 t FFB$_{\mathrm{OxG}}$. Considering the industrial conditions for processing FFB$_{\mathrm{OxG}}$ (*i.e.*, reduction in tons of FFB processed per hour), the production capacity in the mill is on average 62.7 t FFB$_{\mathrm{OxG}}$ h^{-1} in 4872 h y^{-1} working hours. For the two palm species, the same technical parameters of the cogeneration system were used, as described in Section 2.2.1. Furthermore, it is noteworthy that the POM's electrical consumption matrix is distributed as follows: 57% is supplied through an internal combustion engine that burns biogas (generated from POME), 37% is generated by back pressure steam turbine (BPT), and 6% through an internal combustion engine that burns diesel used mainly during start-up, failure, and maintenance periods. In contrast, the biodiesel plant (during refining and transesterification stages) consumes electricity from the Colombian electricity grid, and the thermal energy demand is fulfilled through a boiler (80% efficiency) that burns natural gas, which has an energy density of 39.3 MJ/kg.

For FFB, transporting 50 km from the plantation area to the mill was considered. The inputs to the processes in the mill include water, power energy, and diesel. After obtaining the CPO in the mill, it was transported to a biodiesel plant (refining, transesterification, and biodiesel). For CPO transport, trucks were considered to run for 200 km from the mill to the biodiesel plant. The inputs included in this process were steam, electricity, and diesel.

2.2.1 Combined heat and power system

In the Colombian oil palm sector, since the mid-1950s and 1960s, cogeneration systems with fibers and shells have been applied to meet the thermal demand of their industrial processes, as well as to achieve electrical self-sufficiency. In this study, the steam required to run the POM was assumed to be generated by the combustion of the fiber and shell in a high-pressure boiler (300 PSI). The saturated steam produced is used in a backpressure steam turbine (BPT) to generate electricity for the mill (Fig. 2).

Table 3 lists the yields, moisture content, and heating value of the fiber and shell used as fuel in the CHP system. The analyses of E. guineensis and Interspecific hybrid OxG were obtained in a laboratory. The samples were analyzed according to the ASTM D5291 standard and the mass balances carried out by the authors.

The CHP system shown in Fig. 2 was simulated in *GateCycle v.6.1.2* software, developed by General Electric, and corresponds to the current configuration of the POM process. A simulation was performed for each type of fruit. In the both cases, the isentropic efficiency of the turbine is 75%. The CHP system considers the use of two boilers to produce saturated steam (a 30-bar boiler with 70% efficiency and a 3.5-bar boiler with 62% efficiency) for cogeneration. The fuel for the boiler is palm biomass, which is a fiber-shell mixture. Based on the characteristics of each palm fruit evaluated, the percentage of each component of the mixture was established as follows: when processing *E. guineensis*, the mixture by weight was 70% fiber and 30% shell. When OxG was processed, the mixture contained 68% fiber and 32% shell. Two indicators were used for the CHP system efficiency evaluation: (a) global thermal efficiency (η_o), which considers the net electrical power (W_L) generated by the system (Eq. (2.1)), and (b) the energy utilization factor (EUF), a concept widely used in cogeneration systems as it includes the net generated electrical power and useful heat (Q_u) generated to meet the thermal demand of the system (Eq. (2.2)).

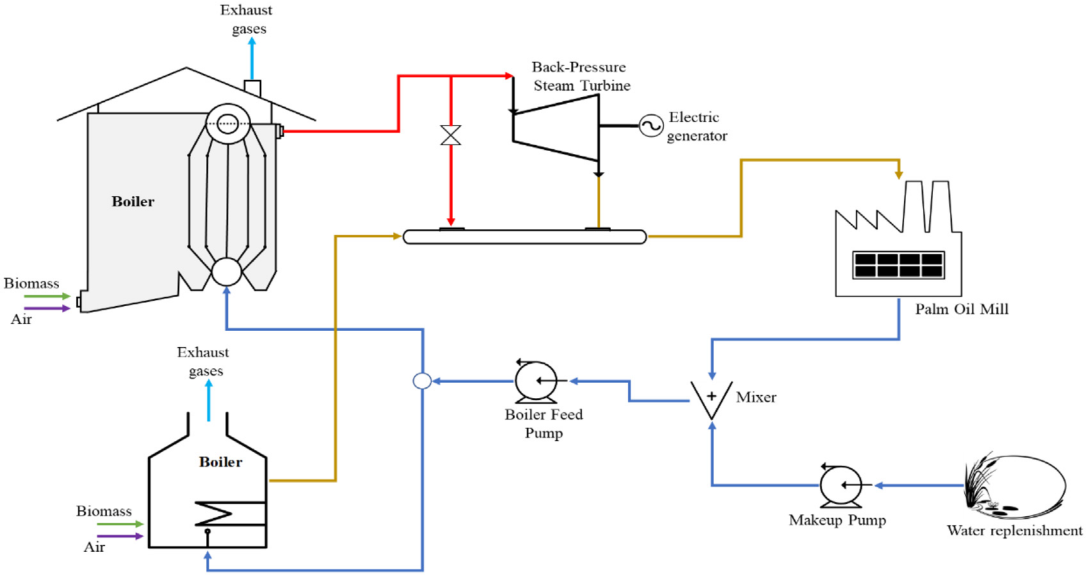

Fig. 2. Combined heat and power (CHP) system.

Table 3. Energy characteristic of the biomass used in the cogeneration system.

Parameters	E. *guineensis*	Interspecific hybrid OxG
Fiber yield [kg t FFB^{-1}]	134.2	152.2
Fiber moisture content [% wet]	30	38
Fiber LHV [MJ/kg]	19.2	16.9
Shell yield [kg t FFB^{-1}]	74.6	72.0
Shell moisture content [% wet]	10	13.2
Shell LHV [MJ/kg]	21.4	16.6

$$\eta_o = \frac{W_L}{\dot{m}_{fuel}}\left(LHV_{fuel}\right) \tag{2.1}$$

$$EUF = \frac{W_L + Q_u}{\dot{m}_{fuel}}\left(LHV_{fuel}\right) \tag{2.2}$$

2.3 Energy performance

The energy performance indicators include i) the global efficiency of the system (η_{gl}) and ii) energy productivity per hectare (σ_{palm}). The global efficiency of the system, which is defined as the ratio between the useful energy of the products (CPO, CPKO, PKC, methane, biodiesel, and glycerin) and the energy of the inputs of the process (FFB, fiber, and shell), was calculated according to Equation (2.3).

$$\eta_{gl} = \frac{\sum(\dot{m}_{prod} \times LHV_{prod})}{\dot{m}_{Ins} \times LHV_{Ins}} \tag{2.3}$$

where, $\dot{m}_{prod}$ = Energy of the manufactured products; LHV_{prod} = Low heating value of the products; $\dot{m}_{Ins}$ = Energy of the inputs; LHV_{Ins} = Low heating value of the inputs.

The indicator energy productivity per hectare shows the amount of energy converted into products, that is, CPO, CPKO, PKC, methane, biodiesel, and glycerin per hectare. It is determined by considering the production of one hectare of palm cultivation, according to Equation (2.4).

$$\sigma_{Palm} = \frac{\sum\left(\dot{m}_{produto}PCI_{produto}\right)}{\dot{m}_{Palm}}\psi_{Palm} \tag{2.4}$$

where Ψ represents the productivity of FFB per hectare for *Elaeis guineensis and Interspecific hybrid OxG* and corresponds to 25.08 t FFB ha^{-1} and 30.55 t FFB ha^{-1}, respectively). The σ_{palm} value is expressed as GJ ha^{-1}. The remaining parameters are listed in Tab. 4 (Yusniati Parinduri and Sulaiman, 2018).

2.4 Environmental analysis

LCA methodology was used to calculate the environmental performance of the conversion of palm oil from the two fruit genotypes (*Elaeis guineensis* and interspecific hybrid OxG) into biodiesel. The environmental analysis was carried out for each type of oil palm fruit, assuming a cradle-to-grave system boundary, *i.e.*, evaluating each process/technology required to produce biodiesel through the genotypes above and the environmental and energy costs to produce it. The functional unit (FU) was defined as 1.0 MJ of energy produced, *i.e.*, the unit of energy under which the number of pollutants and energy required or emitted in the process is calculated. The analysis included five sub-processes: crop cultivation (fertilizer application, pesticides), transportation (FFB and CPO), crude oil palm extraction, refining, and transesterification. The input data for calculating the environmental analysis for all cases were taken from i) data collected during the field visit to a

Table 4. Energy density of the analyzed products.

Product	Value (MJ kg^{-1})	References
FFB_G/FFB_H	19.0/18.1	Ramirez–Contreras *et al.*, 2020; Rivera-Méndez *et al.*, 2017; Yusniati Parinduri and Sulaiman, 2018; Archer *et al.*, 2018; Aziz *et al.*, 2019; Aziz and Hanafiah, 2020; Choong *et al.*, 2018; Corley and Tinker, 2021; Fabiani *et al.*, 2020; Garcia-Nunez *et al.*, 2016; Papilo *et al.*, 2018; Sasongko *et al.*, 2018; Sharvini *et al.*, 2020; Vaskan *et al.*, 2018; Zhang *et al.*, 2017; Lee and Ofori-Boateng, 2013
Glycerine	18.05	
Methane gas	20	
CPKO	39.4	
PKC	18.84	
Biodiesel	39,84	
PFAD	36	
Methanol	23	

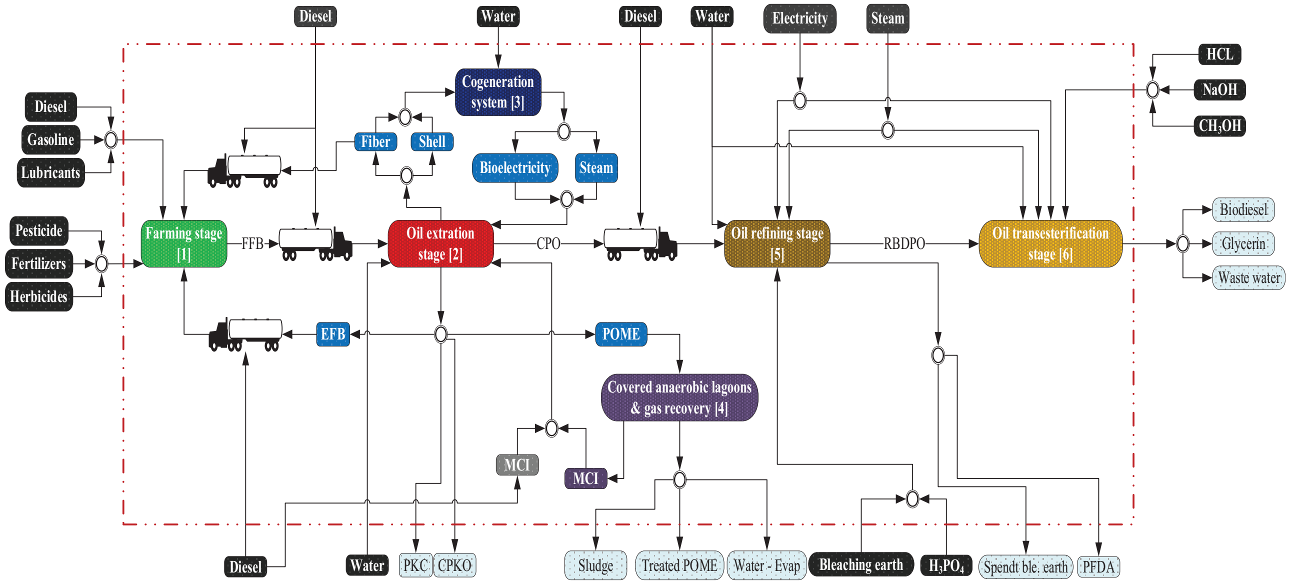

Fig. 3. System boundaries of the analyzed products.

POM, ii) *Ecoinvent* database (*Simapro v.8.0.3*), iii) information from a previous study by (Nieto, 2013), and iv) information from (Ramirez–Contreras *et al.*, 2020; Garcia-Nunez *et al.*, 2016; Nieto *et al.*, 2021; Garcia-Nunez *et al.*, 2016; Arrieta *et al.*, 2007; Yáñez Angarita *et al.*, 2009), Figure 3.

2.4.1 Life cycle inventory

The LCI data for crop cultivation for both fruit genotypes were obtained from a field visit to a POM in eastern Colombia. For this study, the crop lifespan for *E. guineensis* palm was estimated to be 25 years, and for interspecific hybrid OxG it was estimated to be 30 years. The main inputs for each stage of the biodiesel production chain, located in the annexes, are shown in Tables A.1, A.2, A.3, A.4 and A.5.

2.4.2 Life cycle impact assessment (LCIA)

In this phase of the LCA, the potential environmental and human impacts of biodiesel production were evaluated. These impacts were translated into indicators that consider a series of steps according to the ISO 14040 and ISO 14044 standards (selection, classification, and characterization) (Dongyan Mu and Xin, 2020; Zhichao and Fang, 2021). Of the three major endpoint categories (ecosystem impacts, human health, and resource depletion) with 15 midpoint categories, seven midpoint categories were considered: non-renewable energy, global warming, eutrophication, aquatic acidification, terrestrial acidification, ozone depletion, and respiratory inorganics. The impacts were quantified using the Impact 2002+ method, whereas GHG emissions were calculated using SimaPro v.8.0.3 software. Data inputs to estimate the carbon footprint were obtained from the Ecoinvent database, field studies, and literature. For land-use change (LUC), the percentage of areas converted to oil palm *E. guineensis* corresponded to 37.8% for rice, 25.9 % for replanted *E. guineensis,* and 36.4% for grazing areas. For LUC, the percentage of areas converted to interspecific hybrid OxG corresponded to 40.8% for rice, 18.8% for renovation of OxG plantations, and 40.4% for pasture areas. The carbon stock of the crop was calculated considering data from the previous study (Rivera-Méndez *et al.*, 2017) and the lifetime of the plantation for each type of fruit evaluated. It included both belowground and aboveground biomass. We assumed that CO_2 absorption in the palm crop occurred on the fronds and trunk of the plant. The products contained in the FFB, that is, CPO, fiber, kernel, shell, and empty fruit bunches, were considered carbon-neutral.

2.4.3 Life cycle efficiency

Several energy indicators are available for quantifying the net energy flow and assess the overall efficiency of the processes. The most commonly used ones are the net energy balance (NEB), net energy yield (NEY), and NER (Ocampo Batlle *et al.*, 2020; Rocha *et al.*, 2014). Nonetheless, NER, also called *Life Cycle Energy Efficiency* (LCEE), is the most used indicator for calculating the net energy produced from a system and can be considered an indicator of the sustainability of the life cycle energy balance (Zhang *et al.*, 2017; Mayer *et al.*, 2020; Brambilla *et al.*, 2018). In this study, NER_{Total} was used to comparatively evaluate palm genotypes. NER_{total} is expressed as the sum of the net energy production (biodiesel and co-products) divided by the net energy input, which includes the energy inputs in the cultivation stages (fertilizers, agrochemicals, lubricants, and fossil fuel), transport (fossil fuel), and industry (thermal/electric energy and fossil fuel), as presented in equation (2.5).

$$NER_{total} = \frac{\sum \text{Net energy production}(\text{MJ})}{\sum Net\ energy\ input(\text{MJ})} \tag{2.5}$$

As a complementary indicator of LCEE, we used the FER, also called the renewability factor (Mata *et al.*, 2011), which is defined as the ratio between the final energy of the fuel and the fossil energy required to produce it (Eq. (2.6)).

$$FER = \frac{\sum Fuel\ Energy_{Output}}{\sum Fossil\ Energy_{Input}} \tag{2.6}$$

3 Results and discussion

3.1 Energy performance

Figure 4 shows the mass and energy balance for *E. guineensis* genotype. When *E. guineensis* FFB is processed, POM has an energy consumption of 15.09 MWt (steam at 350 kPa) and 2.1 MW_{ele}. For the processing of palm oil of this genotype in the biodiesel plant (refining and transesterification), a demand of 18.33 MWt (steam at 350 kPa) and 1.95 MW_{ele} is reported. It should be noted that the energy demanded by the biodiesel plant is obtained from processes external to the evaluated system. The POME obtained in the POM was sent to a covered anaerobic lagoon, aiming to obtain biogas through anaerobic digestion producing 1981 m^3 biogas. Of the total biogas, 634.4 m^3 was used to generate 1.63 MW_{ele} using an internal combustion engine (ICM). Furthermore, 71.4% of fiber and 48.5% of shell generated by the extraction of CPO were burned in a cogeneration system that provided 37% of the electricity required by the POM and it fully supplied the thermal energy required by the POM.

In Figure 5, the mass and energy balance of the interspecific hybrid (OxG) genotype is presented. The amount of fruit processed in this case is less than that of *E. guineensis* as explained in Section 2.1. The energy (thermal and electric) required to process OxG fruit at the mill is higher (15.1 MWt and 2.2 MW_{ele}) compared to that needed in case of *E. guineensis* due to low or no nut content in the OxG FFBs, which are used as fuel for power generation. A decrease of 4.2% in the POME was also observed with respect to the processing of *E. guineensis* fruit, possibly due to the characteristics of the OxG fruit and the use of less water for its processing in the mill. A lower production of biogas (1774 m^3) and consumption of this biogas in the ICE_{biogas} system (858 m^3) are reported to generate the 1.6 MWel required to complement the energy required to run the POM. The biodiesel plant (refining and transesterification plant) demands 14.7 MWt (steam at 350 kPa) and 1.19 MW_{ele}. It should be noted that the energy demanded by the biodiesel plant was supplied through processes that were external to the evaluated system.

The net efficiency of electricity generation is low for those of the genotypes involving more than 5% for guineensis and OxG fruits in relation to the energy flow in the biomass fed in the boilers. This can be explained by the fact that the cogeneration cycle operates using 50% of the mass flow coming from the superheated steam boiler (30 bar and 70% efficiency), and with the remaining 50% of the steam is obtained from a saturated steam boiler (3.5 bar and 62% efficiency). The low net efficiency of the generation cycle refers to the low operating pressures of the boilers (30 bar and 3.5 bar) and the type of turbine used in this cycle (BPT with 75% efficiency) compared to those used in a conventional generation cycle, which operate with 60 bar boilers (90% efficiency) and condensation-extraction turbines (CEST) that have efficiencies greater than or equal to 85%.

Figure 6 shows the η_{glo} and palm for the fruit genotypes evaluated. For E. *guineensis*, the η_{glo} is greater than that for the interspecific hybrid OxG while considering the increase in the consumption of thermal (8.2%) and electric (10.2%) energy during the process the FFB of the OxG fruit. The σ_{palm} of the OxG fruit is higher than that of the guineensis fruit which is attributed to the higher productivity of OxG per hectare (30.55 t FFB ha $year^{-1}$). It means about 18% more FFB produced in OxG and about 4% more palm oil content per hectare per year (5.04 t CPO ha $year^{-1}$).

3.2 Environmental analysis

3.2.1 Carbon Footprint

Figure 7 shows CO_{2eq} emissions, carbon capture, and the carbon footprint for the biodiesel production cycle from palm oil. The value of emissions in the figure was reported above the zero line and removals as negative values under the zero line. The largest share of CO_{2eq} emissions in the evaluated cases come from the farming (217 and 180 kg CO_{2eq} t BD^{-1} for OxG and *E. guineensis* respectively) and transesterifications (131 kg CO_{2eq} t BD^{-1} for both genotypes) stages. These results are in line with the results reported in the studies by (Ramirez –Contreras *et al.*, 2020; Yáñez Angarita *et al.*, 2009; Pleanjai and Gheewala, 2009; De Souza *et al.*, 2010; Mata *et al.*, 2011). The main emission factors are related to the CO_2 released in combustion and chemical fertilization (use and application),

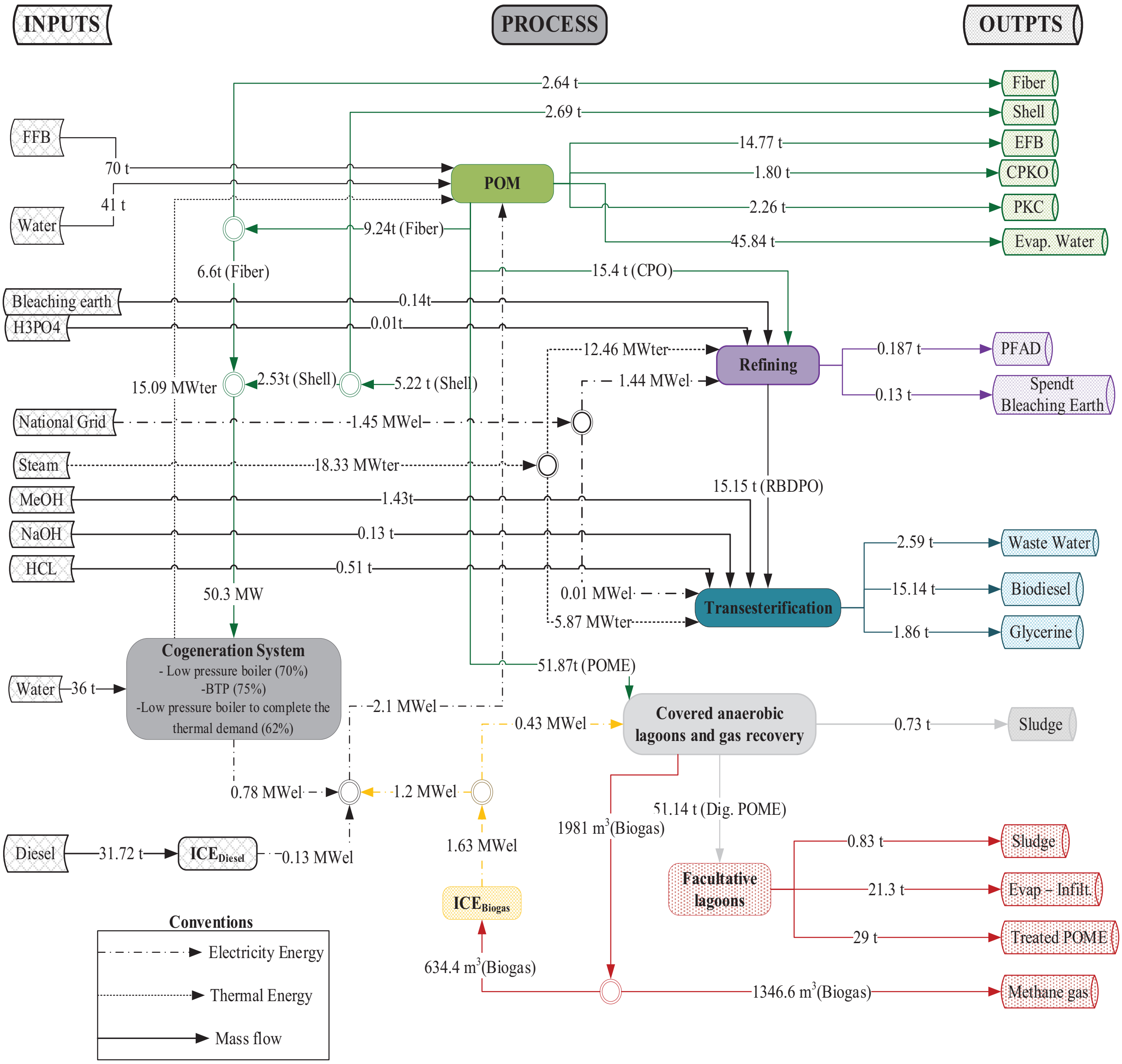

Fig. 4. Energy and mass balance of biodiesel production from *E. guineensis*. The colors in the lines represent the products and by-products of each phase: green line for the extraction phase; purple line for refining; blue line for transesterification; red line for POME and gray line for cogeneration.

where 39% of the total emissions correspond to the fertilization of *E. guineensis* and 42% of it correspond to the fertilization of interspecific hybrid OxG fruit. The total CO_2 emissions related to the plantation are 106.73 kg t^{-1} FFB for *E. guineensis* and 120.57 kg t^{-1} FFB for interspecific hybrid OxG. The carbon captured by FFBs due to photosynthesis is 1.45 t CO_2eq t^{-1} FFB (*E. guineensis*) and 1.3 t CO_2eq t^{-1} FFB (interspecific hybrid OxG). The carbon footprint of the biodiesel produced from *E. guineensis* is −960 kg CO_{2eq} t^{-1} FFB and −760 kg t^{-1} FFB for that produced from the interspecific hybrid OxG.

The production of palm oil biodiesel from the interspecific hybrid OxG report higher emissions than *E. guineensis* since it needs a greater consumption of fertilizers in the crop (13.2% N and 3.27% K_2O more) and diesel in transport (29.67% more). In addition, a greater energy demand (2.54% higher electric energy and 8.95% higher thermal energy) to produce one ton of palm oil is required. Nevertheless, the emissions from the use of pesticides and insecticides during OxG cultivation was 23.77% lower than that of *E. guineensis* (genotype with greater susceptibility to pests).

Figure 8 shows a comparative study on GHG emissions for palm oil biodiesel production, including our study. These emissions were reported to range from 4.34×10^{-2} kg CO_{2eq} MJ_{BD}^{-1} (Yáñez Angarita *et al.*, 2009) to 1.21×10^{-2} CO_{2eq} MJ_{BD}^{-1} (De Souza *et al.*, 2010). The palm oil biodiesel production system reported an average emission value of 7.1 g CO_{2eq} MJ_{BD}^{-1}) for an agricultural yield of 18.4 t FFB ha^{-1}. The emissions of the cultivation stage for the

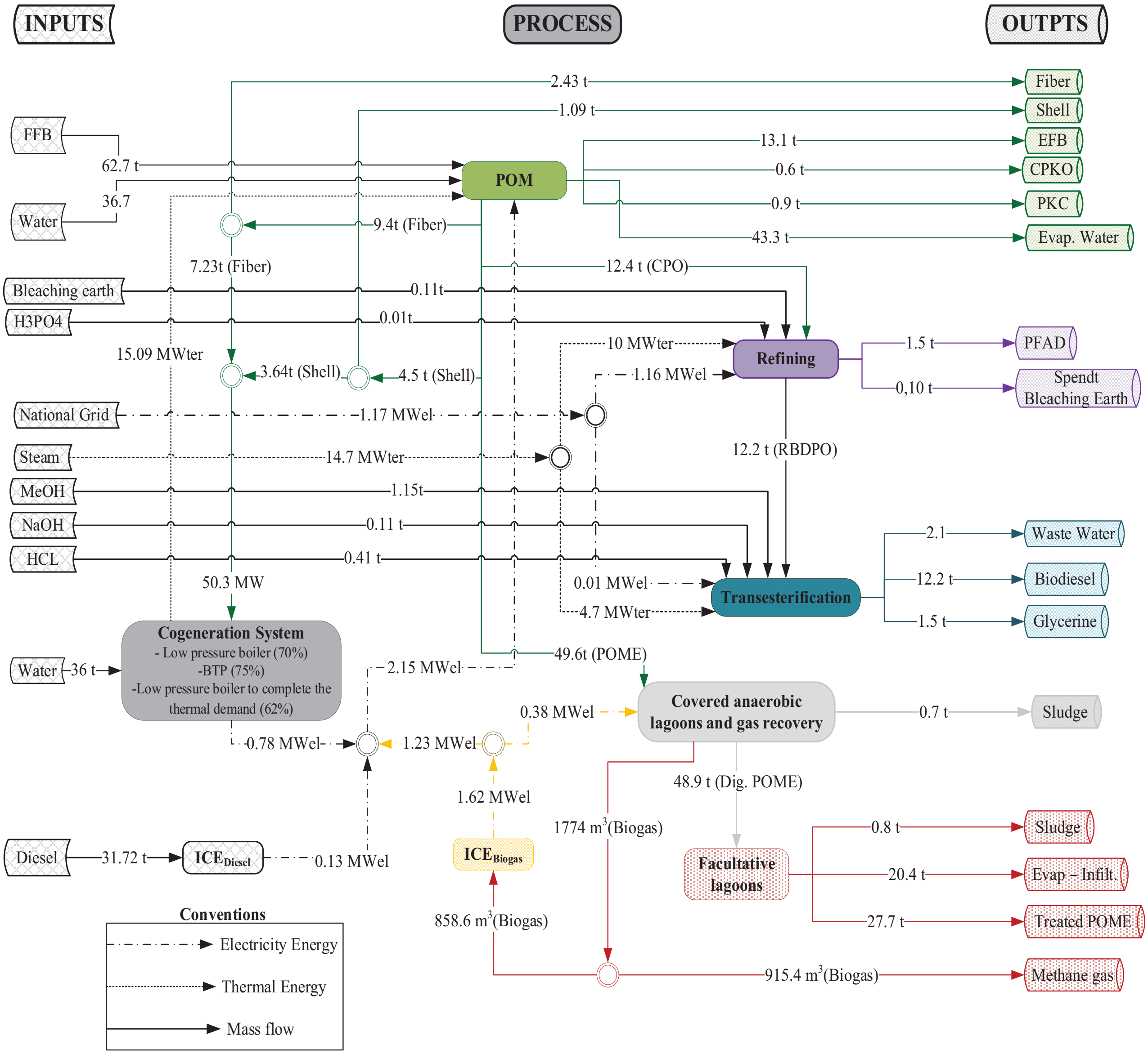

Fig. 5. Energy and mass balance of biodiesel production from *Interspecific hybrid (O × G)*. The colors in the lines represent the products and by-products of each phase: green line for the extraction phase; purple line for refining; blue line for transesterification; red line for POME and gray line for cogeneration.

two cultivars (4.45 and 5.45 g CO_{2eq} $MJ_{BD}{}^{-1}$ for *E. guineensis* and interspecific hybrid OxG, respectively) were lower than those reported in the literature. This could be is due to its use in the field of the biomass (28.6% of fiber and 100% of EFB) generated in the POM. Biomass degradation is a major contributor to CO_2 release, followed by emissions from the combustion of fibers and shells in steam boilers. These two emission sources are generally not considered in LCA studies of the palm oil process (Garcia-Nunez *et al.*, 2016) because the CO_2 released comes from carbon (C) stored in the FFB. However, in this study, all emissions associated with the return of the co-products to the field were considered.

3.2.2 Environmental impact assessment

Seven midpoint categories for biodiesel production from the two palm oil genotypes were evaluated, considering 1 MJ of biofuel produced as a FU, as mentioned previously. Table 5 and Figure 9 show the results by impact category. All categories showed higher values for the interspecific hybrid OxG genotype than that for *E. guineensis*. This is a consequence of the higher demand for nitrogen (13.2%) and potassium oxide (3.27%) during chemical fertilization. In addition to the higher consumption of diesel in the transport of the fruit to the POM (29.67%), thermal energy (26.1%), and electricity (29.3%) for the processing.

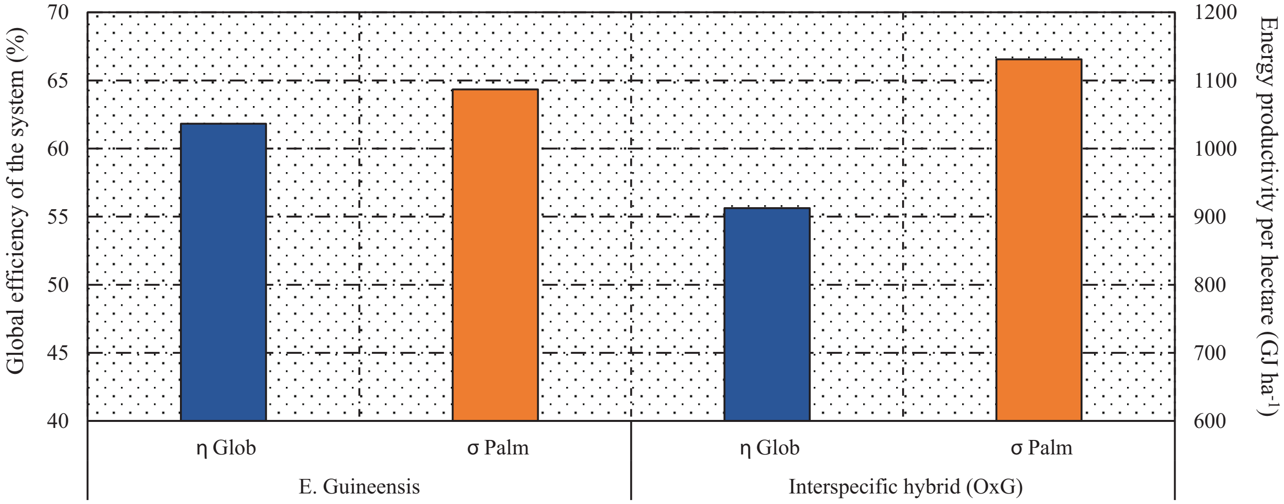

Fig. 6. Indicators of the first law of thermodynamics of total BD production from *E. guineensis* and *Interspecific hybrid (OxG)*.

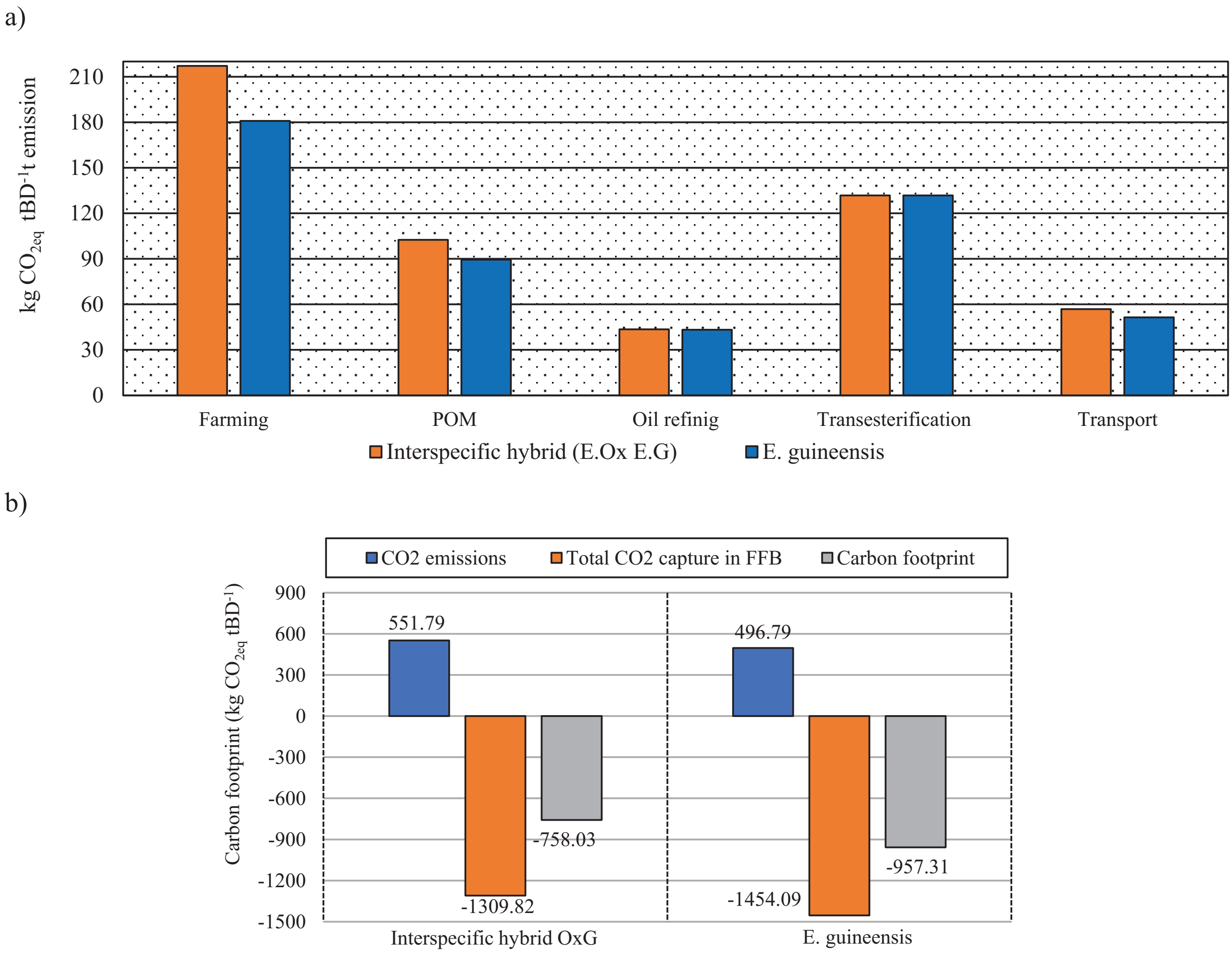

Fig. 7. GHG emissions: a) Share of emissions by life cycle stages. b) Carbon Footprint per each genotype.

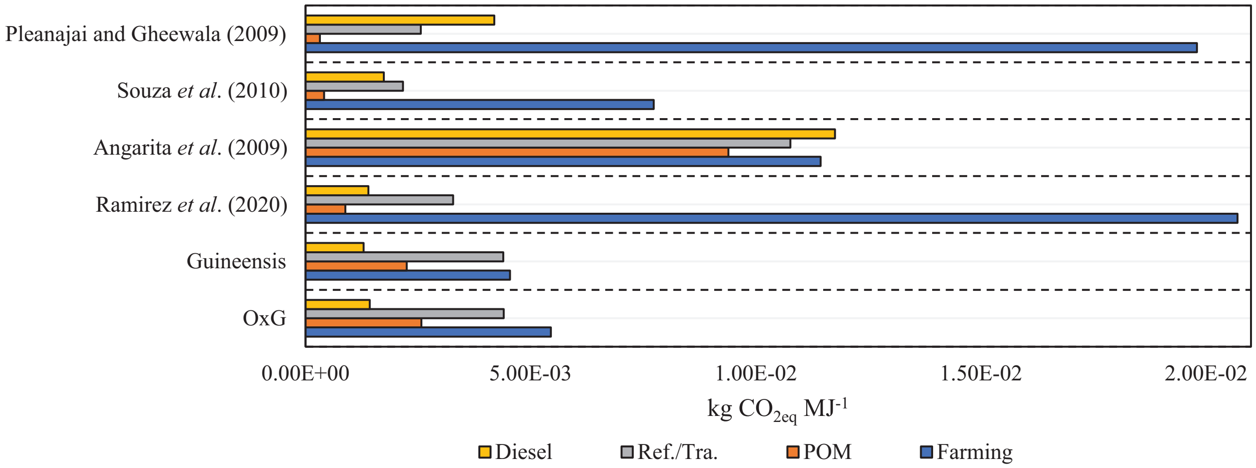

Fig. 8. GHG emissions in several studies of the palm oil sector.

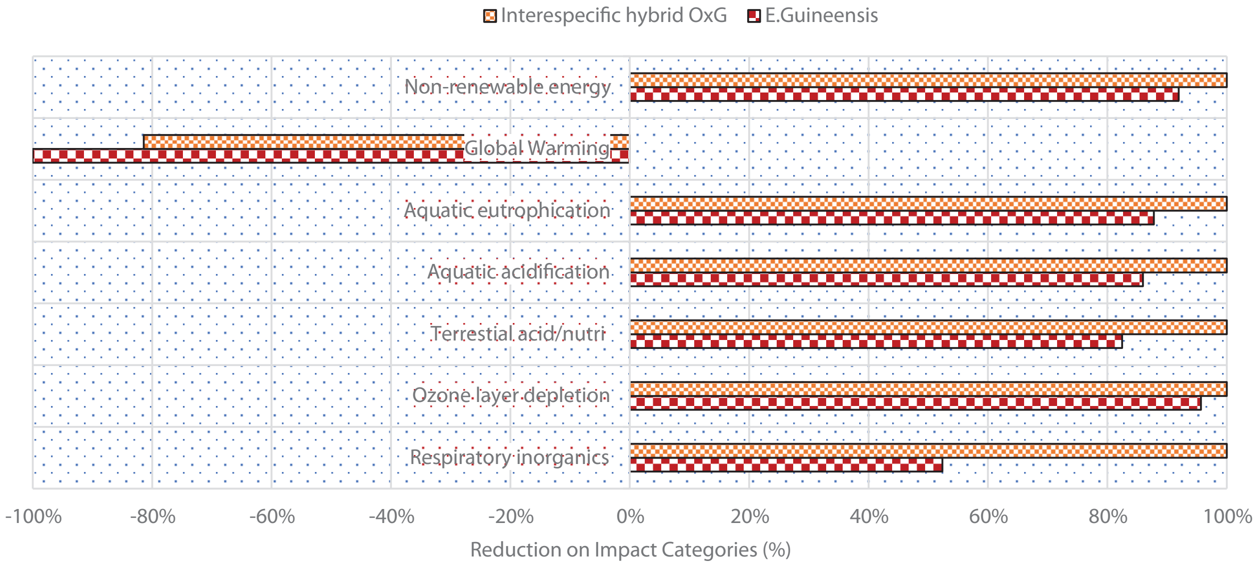

Fig. 9. Impact categories comparison for interspecific hybrid OxG and *E.Guineensis*.

Table 5. Impact categories for biodiesel production (1.0 MJ) from interspecific hybrid OxG and *E. Guineensis*.

Impact Categories	**Units**	**E. Guineensis**	interspecific hybrid OxG
Adverse health effect due to particles	g $PM_{2.5\ eq}$	2.05×10^{-2}	3.92×10^{-2}
Ozone layer depletion	g $CFC_{-11\ eq}$	4.08×10^{-06}	4.26×10^{-06}
Terrestrial acid/nutrition	g SO_{2eq}	0.62	0.75
Aquatic acidification	g SO_{2eq}	0.12	0.14
Aquatic eutrophication	g $PO_4\ P_{-lim}$	7.14×10^{-3}	8.14×10^{-3}
Global warming	g $CO_{2\ eq}$	-23.2	-18.9
Non-renewable energy	$MJ_{primary}$	0.22	0.24

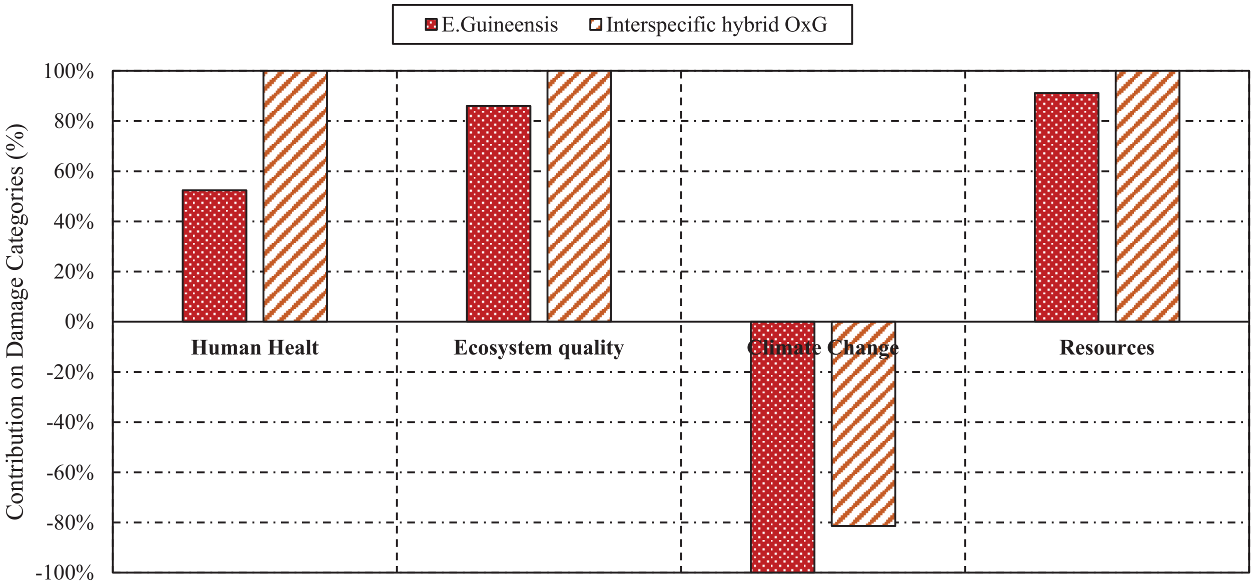

Fig. 10. Damage category impact share for BD production scenarios.

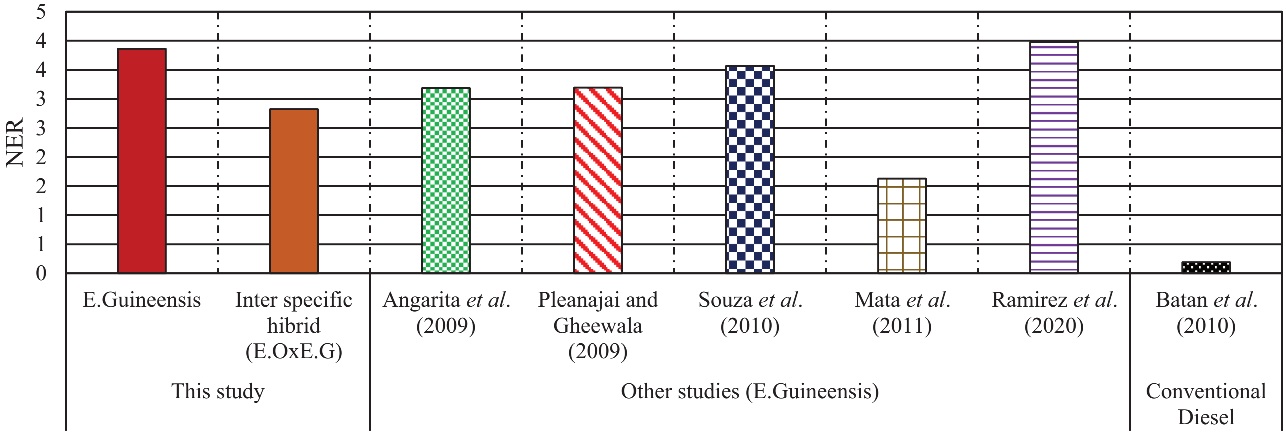

Fig. 11. Comparison of the NER obtained with values reported in the literature and conventional diesel, including the present study.

Overall, the impact categories (Fig. 9) related to the production of the interspecific hybrid OxG were higher than those reported for *E. guineensis* as the category's aquatic eutrophication, terrestrial acid, and aquatic acidification associated with the quality of the ecosystem increased by 12.2%, 17.5%, and 14.0%, respectively. These changes were related to the release of compounds, such as phosphate, NH_3, NO_x, SO_x, and P, into the soil and water bodies. Emissions of particulate matter ($PM_{2.5}$), sulfur (S), and nitrogen oxides (NO_x) related to diesel consumption had an impact on respiratory inorganics and the depletion of the ozone layer, representing an increase of approximately 47.6 % and 4.3%, respectively. Furthermore, the increase in diesel consumption for transporting the fruit to the mill directly leads to an increase in the indicator non-renewable energy use by 8.4% and to a decrease in carbon capture in the global warming category by 18.6%.

3.2.3 Assessment of damage categories and life cycle indicators

Figure 10 shows the results of the damage endpoint impact categories (resources, climate change, ecosystem quality, and human health) for biodiesel production. The contributions of these categories were higher for the interspecific hybrid OxG cultivar than in case of *E.guinenssis* cultivar, except for the climate change category. Human health impact category was the major contributor (47.57%), attributed to the emissions of PM, NO_x, SO_x during transport of FFB to the mill (diesel consumption is almost 30% more than in the case of *E. guinenssis*).

The NER_{Total} and FER indicators were estimated for two alternative productions of biofuel/bioproducts, and the results are shown in Figures 11 and 12. The assessment of NER_{Total} of the two genotypes (*E. Guineesis* and interspecific hybrid OxG)

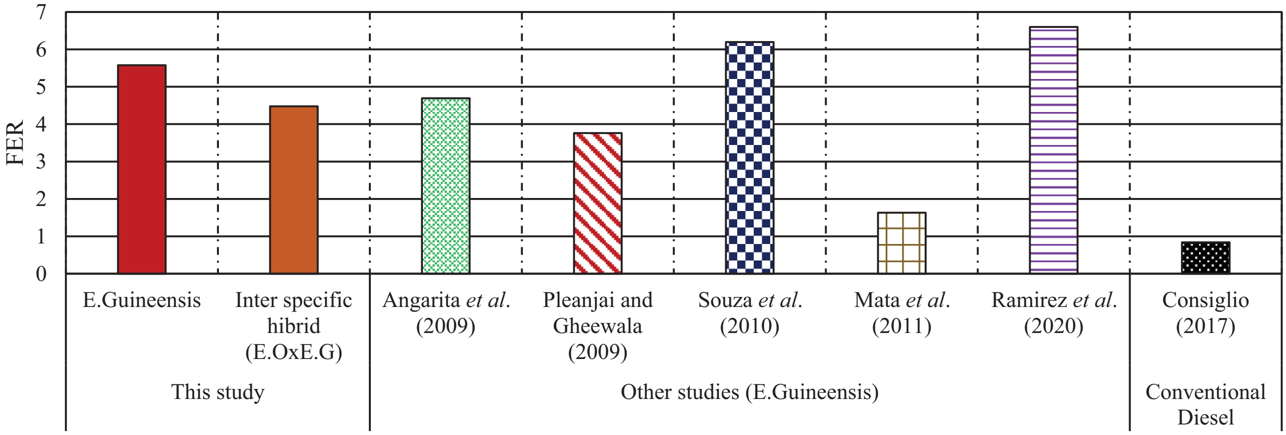

Fig. 12. Comparison of the FER obtained with values reported in the literature and conventional diesel, including the present study.

in our study demonstrated 3.86 energy units for *E. guineensis* and 2.82 energy units for interspecific hybrid OxG considering the stages BD, methane gas, glycerin, CPKO, PKC, and PFAD. The energy efficiency of biodiesel production is 4 and 3 times (in *E. guineensis* and interspecific hybrid OxG, respectively) greater than the energy input. The NER_{Total} values, reported in the literature that considered biofuels and bioproducts, for the BD chain in Thailand, Malaysia, Indonesia, Colombia, and Brazil were between 1.63 and 3.98 (Fig. 11). Nevertheless, a comparison of the energy balance, including all products and by-products, showed that the potential value of NER_{Total} was greater for *E. guineensis* than that for interspecific hybrid OxG. Some studies on bio-based palm oil products have also reported higher values of NER between 17.7 and 22.9 (Garcia-Nunez *et al.*, 2016; Ocampo Batlle *et al.*, 2020). The NER_{Total} for *E. guineensis* and interspecific hybrid OxG is higher than the NER_{Total} for the conventional fossil diesel production cycle (0.19), that is, the same energy unit consumed is produced in 1:4 and 1:3 energetic units from *E. guineensis* and interspecific hybrid OxG genotypes, respectively.

A total FER of 5.58 and 4.48 (MJ_{out}/MJ_{in}) was calculated for the *E. guineensis* and interspecific hybrid (OxG) genotypes, respectively (Fig. 12). These results are comparable to those of previous studies on the production of biodiesel from palm oil (1.6 6.6 MJ_{out}/MJ_{in}). The FER values reported by (Ramirez–Contreras *et al.*, 2020; De Souza *et al.*, 2010; Yáñez Angarita *et al.*, 2009) are greater than those obtained in this study, given that the cogeneration system operates with more efficient boilers, uses CEST (which have surplus electricity production), and the refining and transesterification plant is attached to the POM.

Notably, the interspecific hybrid (OxG) genotype has a higher consumption of fossil energy than that recorded in case of *E. guineensis* genotype. This is attributed to the greater demand for fertilizers, agrochemicals, and diesel during the agricultural and transportation stages. However, it was noticed that the interspecific hybrid (OxG) was one and three energy units more renewable than *E. guineensis* as evaluated in studies done by (Mata *et al.*, 2011; Pleanjai and Gheewala, 2009), respectively.

4 Future works

Due to the proposed work, its results and discussions, some topics that can be evaluated in future work are indicated below:

- The life cycle assessment applied does not consider or compare the economic aspects of the genotypes in question. Therefore, parameters such as the reduction or increase in production costs of the *interspecific hybrid OxG* and its biodiesel must be calculated. This is because when in the future we want to evaluate not only the life cycle, but also the sustainability of the life cycle, we need the economic values associated with each process.
- At the start of the proposed work, the main advantage of the OxG interspecific hybrid genotype was its greater resistance to rot compared to *Elaeis guineensis*. However, this work does not explore resistance to other diseases, pests or variations in climate, so that when compared to Elaeis guineensis we can have a better idea of the viability of replacing one type with another.
- The work shows that the genotype obtained from crossbreeding is less environmentally damaging when looking at life cycle indicators. On the other hand, replacing the existing genotype may have social implications in terms of the transfer of technology to produce the new genotype. Therefore, in future work it would be pertinent to evaluate the social impact of replacing the current genotype with another, for example, using the hierarchical analytical process method.

5 Conclusions

This study evaluated and compared the energy efficiency and environmental performance of the biodiesel production chain of two oil palm genotypes (*E. guineensis* Jacq and interspecific hybrid OxG) currently cultivated in Colombia. The energy balance showed that the production of biodiesel from the interspecific hybrid OxG resulted in a 6.2% reduction in the overall efficiency of the system when compared to the biodiesel from *E. guineensis*. This reduction could be associated with the inefficiency of the machinery currently used at the mills, because these machines were previously designed according to the characteristics of the *E. guineensis* fruit (mainly related to nut and shell content). Nonetheless, the interspecific hybrid OxG fruit showed a 4% higher potential in energy productivity per hectare (σ_{palm}), without any modification in the mechanical processes of the mill, what can be attributed to higher productivity (30.55 t FFB ha year^{-1}) compared to that of *E. guineensis.*

The LCA of biofuels produced from palm oil (whether conventional or hybrid) has the potential to reduce both global warming and the impacts generated by changes in land-use in Colombia. The GHG emissions of *E. guineensis* palm oil biodiesel were 12.5 g $MJ_{BD}{}^{-1}$ and the emissions from the interspecific hybrid OxG palm oil biodiesel was 13.8 g $MJ_{BD}{}^{-1}$. This 10.4% increase in emissions from the interspecific hybrid OxG was mainly due to the increase in diesel consumption in the transport of fruit from the crop to the POM, in addition to a greater demand for biomass to run the cogeneration system. However, carbon capture was slightly greater for *E. guineensis* than that for the OxG interspecific hybrid. Consequently, the carbon footprint reported for *E. guineensis* biodiesel is slightly higher (–957 kg CO_{2eq} t BD^{-1}) than that of the hybrid studied (–758 kg CO_{2eq} t BD^{-1}).

In Colombia, the growth and production of interspecific hybrid OxG are critical issues because of the resistance of this crop to bud rot disease. Moreover, other characteristics, such as the increase in palm oil yield per hectare and a longer lifetime for this cultivar compared to the other, make its use attractive. This novel study is the first to compare two chief oil palm cultivars planted in Colombia. Therefore, it is crucial to continue comprehensive analyses to evaluate the environmental, social, and economic significance of the production of these cultivars, considering the entire production chain.

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Conflicts of 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.

Data availability statement

The datasets used during the current study available from the corresponding author on reasonable request.

Author contribution statement

D-I.N.M.: Conceptualization, methodology, data analysis and curation, writing-original draft preparation, review &editing. **O.J.V.**: Data curation, organization, technical assistance, review &editing. **E. A.O.B.:** Software, methodology, technical assistance. **A.M.G.:** Technical assistance, review &editing & improved the language. **D.A.M.F.:** helped in revising the manuscript & Conceptualization, investigation, writing-reviewing and editing. **N.E.R.C.**: Methodology, technical assistance, data validation. **J.A.G.N.**: Software, technical assistance, review &editing. **P.T.B.**: data analysis and curation, review &editing. **E.E.S.L.**: Organization, technical assistance, review &editing. All authors have read and approved the final manuscript and agreed to the published version of the manuscript.

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Appendix

Source: (Nieto *et al.*, 2021; Nieto, 2013).

Table A.1. LCI of crop cultivation per hectare per year.

Farming stage	*Elaeis guineensis*	*Interspecific hybrid (OxG)*	Unit
Inputs			
Yield	25.08	30.55	kg
N	143.85	162.83	kg
P_2O_5	74.31	68.79	kg
K_2O	277.38	280.92	kg
S	23.42	21.40	kg
M_gO	104.02	88.43	kg
B_2O_3	3.03	0.89	kg
Ca	71.46	35.39	kg
Glyphosate	3.66	2.79	kg
Diesel	3.10	2.73	L
Gasoline	8.66×10^{-03}	5.40×10^{-03}	L
Lubricants	1.66×10^{-02}	1.26×10^{-02}	L

Table A.2. LCI of the oil extraction stage (t of crude palm oil).

Oil extraction stage	*Elaeis guineensis*	*Interspecific hybrid (OxG)*	Unit
Inputs			
FFB	4366.81	5056.11	kg
Diesel for FFB transport	35.48	46.01	kg
Electricity	130.98	169.35	kWh
Steam	2245.4	2831	kg
Outputs			
CPO	1,000	1,000	kg
CPKO	117	50	kg
PKC	147	0.076	kg
EFB	959	1.054	kg
Fiber	600	759	kg
Shell	339	364	kg
Oil extraction	22	19.78	%
Emissions to air and water			
CO_2	132	152.84	g
CO	62.3	72.14	g
NOx	4.82×10^{-1}	5.58×10^{-1}	g
SOx	1.87×10^{-1}	2.16×10^{-1}	g
Particulate matter	2.38×10^{-1}	2.75×10^{-1}	g

Table A.3. LCI for the cogeneration system (1 kWh of generated electricity).

Cogeneration system	*Elaeis guineensis*	*Interspecific hybrid (OxG)*	Unit
Inputs			
Fiber	1.05	1.15	kg
Shell	0.40	0.56	kg
Water consumption by boiler	6.94		kg
Electricity for Water Pumping	0.01		kWh
Outputs			
Bio-Electricity	1		kWh
Steam (3.5 bar, saturated)	6.94		kg
Emissions to air			
CO	34.41	40.58	g
NOx	3.91	4.61	g
SOx	0.12	0.14	g
Particulate matter	8.42	9.93	g
Total organic carbon (TOC)	0.31	0.36	g

Table A.4. LCI of palm oil refining stage (t of oil-refined).

Oil refining stage	*Elaeis guineensis*	*Interspecific hybrid (OxG)*	Unit
Inputs			
CPO	0.984		kg
Process water	0.105		kg
Phosphoric acid (H_3PO_4)	5.08×10^{-4}		kg
Bleaching earth	9.15×10^{-3}		kg
Diesel for CPO transport	68.21		kg
Electricity	94.76		kWh
Steam (3.5 bar, 310 °C)	0.981		kg
Outputs			
RBDPO	1,000		kg
PFAD	0.123		kg
Spent bleaching earth	8.25×10^{-3}		kg
Emissions to air and water			
CO_2	165		g
CO	85.6		g
NOx	4.11×10^{-1}		g
SOx	1.84×10^{-1}		g
Particulate matter	1.62×10^{-1}		g

Table A.5. LCI of the oil transesterification stage (t of biodiesel).

Oil transesterification stage	*Elaeis guineensis*	*Interspecific hybrid (OxG)*	Unit
Inputs			
RBDPO	0.999		kg
Process water	0.149		kg
Chloridric acid (HCL)	3.4×10^{-2}		kg
NaOH	8.63×10^{-3}		kg
Methanol (CH_3OH)	9.4×10^{-2}		kg
Electricity	0.416		kWh
Steam (3.5 bar, 310 °C)	0.462		kg
Outputs			
Biodiesel	1,000		kg
Glycerin ($C_3H_8O_3$)	0.124		kg
Waste water	0.171		kg
Emissions to air and water			
CO_2	172		g
CO	62.9		g
NOx	4.86×10^{-1}		g
SOx	1.84×10^{-1}		g
Particulate matter	2.33×10^{-1}		g

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