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RESEARCH ARTICLE

Life cycle assessment of power generation using cocoa pod husk in Côte d'Ivoire

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Abstract

Objectives: This study assesses the environmental performance of cocoa pod husk as a fuel for a biomass power plant in Côte d'Ivoire. **Methods:** In this study, a life cycle assessment (LCA) is applied to identify four environmental impacts generated during the production of electrical energy. LCA assesses the environmental impact on the global warming potential of electricity production from a biomass power plant using a cocoa pod husk in Côte d'Ivoire. The greenhouse gas emissions of this electricity production are compared with those of other energy sources. **Findings:** The results show that the production of one kilowatt-hour results in the emission of 1.12 g SO_2eq,0.28 g PO_4eq., 9.91 g 1.4 DBeq. and 328.22 g CO_2eq. These emissions involve acidification, eutrophication, human toxicity and global warming respectively. The sensitivity analysis showed that the transport distance has an effect on the greenhouse gas (GHG) emissions of the chain. The sensitivity analysis showed that the transport distance has an effect on the GHG emissions of the sector. Thus, GHG emissions increase with the distance travelled by the transport vehicle. The analysis identified power plant locations that would reduce GHG emissions for the production of 1 kWh of electricity. **Novelty:** The life cycle assessment was used to evaluate the environmental impact of various processes using crop residues for energy purposes.

Keywords: Bioenergy; Crop residues; Cocoa pod husk; LCA; Thermal power plant

1 Introduction

To meet the ever-increasing electricity needs of its population, Cote d'Ivoire regularly invests in production infrastructure. Thus, its electricity production capacity has increased from 1391 MW in 2010 to 2214 MW in 2019. These electricity facilities are mainly composed of thermal and hydroelectric power plants. Thermal power plants, whose contribution to the electricity mix is estimated at 67% in 2019, remain dependent on natural gas. However, despite the many efforts made by the country, the electrical energy produced does not cover its energy needs. Indeed, about 31% of its 8513 localities are not yet connected to the national grid[1]. As a result, since 2021, the connected areas have been facing an electricity crisis. As the electricity produced is insufficient to supply them, they are facing a rotating rationing programme.

With the aim of increasing its production capacity, the country plans to introduce renewable energies into electricity production. This desire is expressed through an action plan, the implementation of which should make it possible to achieve a contribution of 42% of these energies in the energy mix by 2030. The estimated amount for the implementation of this plan for the period 2021-2030 is approximately USD 1,549.91 million. This amount should enable the realisation of several projects developed by the ministry in charge of the country's energy resources. These projects include the construction and operation of six biomass power plants for a total of USD 425.2 million[2]. The fuels used to power these plants will be mainly agricultural and agro-industrial residues available in the country. Given its agricultural potential, Côte d'Ivoire has enormous deposits of agricultural biomass residues. In 2018, the agricultural sector accounted for 28% of its GDP and 40% of its exports. In the world rankings, the country is the leading producer of cocoa and cashew nuts, the fifth largest producer of palm oil, and the seventh largest producer of robusta coffee. Côte d'Ivoire is also Africa's fourth largest cotton producer[3].

However, the present study evaluates the environmental performance of cocoa pod husk used as fuel for a biomass power plant. In a previous study, Zinla et al.[4] showed that this cocoa crop residue has a good energy performance. Indeed, the study of these authors revealed that Ivorian cocoa pod husk has a higher calorific value of 13.7 MJ/kg. Also, the dry pod husk of Ivorian cocoa has a humidity of 12.3% and an ash content of 10.8 %. However, this residue has not yet been reliably recovered for energy purposes in Côte d'Ivoire.

For the environmental assessment, the study calculates the environmental impacts of the electricity generation process using cocoa pod husk. According to Chauhan et al.[5], the application of the LCA method is useful to analyse the environmental impacts of a product or process. Also, in the literature, several authors have used life cycle assessment (LCA) to evaluate the environmental impact of various processes using crop residues for energy purposes. Shafie et al.[6] used it to assess the environmental impact of electricity generation using rice straw in Malaysia. It was used by Mohammadi et al.[7] to assess the environmental impact of energy recovery from bagasse in the Iranian sugar industry. Prasad et al.[8] also used LCA to assess the sustainable use of crop residues for energy production.

According to these authors, life cycle assessment (LCA) is a comprehensive method to assess the environmental performance of a biofuel. For Chauhan et al.[5], LCA is useful for analysing and helping to reduce the environmental effects of biomass use. It assesses the environmental impact of biomass use over its entire life cycle.

In this study, we use LCA to assess the global warming potential of electricity production from a biomass power plant using cocoa pod husk in Côte d'Ivoire. Greenhouse gas emissions of this electricity production are compared with those of other energy sources. The environmental analysis is important to define a better framework for technological investments for the energy valorization of Ivorian cocoa pod husk. The findings will provide guidance for the development of biomass thermal power plants using cocoa pod husk for electricity generation in Côte d'Ivoire.

2 Materials and Methods

2.1 Global approach

LCA is an iterative method structured around a functional unit. It is generally conducted in four stages: definition of objectives and scope, inventory analysis, impact assessment, and interpretation of results. These are both distinct and interdependent[9]. The definition of the objectives and scope of the study allows the objectives of the LCA to be defined, specifying its application: eco-design, comparison or environmental declaration. The scope of the study must also specify the functions of the product studied, the functional unit chosen, the boundaries of the system studied and the limits of the study. The functional unit is the unit of measurement used to assess the service provided by the product. The inventory analysis allows the assessment of material and energy flows in and out, associated with the life cycle stages. The inventory is therefore an analytical accounting of flows. For this purpose, two types of data are collected: activity factors and emission factors. The inventory is generally carried out using LCA software, but it can also be done by hand, using a spreadsheet. Based on the material and energy flows identified, and according to the indicators and the selected characterization method, the potential impacts are assessed[10]. Finally, the results obtained are interpreted.

2.2. Definition of the objectives and scope of the study

2.2.1. *Objective of the study*

This study conducts a life cycle assessment of electricity generation from a biomass power plant using cocoa pod husk in Côte d'Ivoire. It assesses the environmental performance of cocoa pod husk and compares it to other energy sources used for electricity production. Thus, the objectives of the study are: (a) to calculate the environmental impact of electricity production using cocoa pod husk, (b) to compare the environmental performance of cocoa pod husk with that of renewable and conventional sources of electricity production and (c) to analyse the sensitivity of the parameter that most affects the life cycle emissions of cocoa pod husk.

The functional unit used in this study is 1 kWh of electricity produced by the different energy sources. This functional unit is used in most LCA studies of electricity generation [11]. Although the objective is the same as in other studies, the result can be obtained in different ways due to the different choices and approaches applied during the study [12].

2.2.2 Scope of the study

If the boundaries are set too narrowly, some important impacts may not be detected; conversely, if they are set too broadly, other impacts than those of interest may be included [13]. Most researchers define the boundaries of bioenergy LCA starting with crop production and ending with energy production [14–16].

The process boundaries of this study start from the process of producing the mature cocoa pods from the cocoa farm to the process of burning the dry cocoa pod husk in the biomass boiler of the power plant. Thus, the boundaries of the power generation process include: the production of the mature cocoa pods (The establishment of cocoa farms is not taken into account in this step), the collection of the cocoa pod husk, the transportation of the cocoa pod husk, and the combustion of the cocoa pod husk. These different processes can be grouped into two main steps, namely, biomass preparation and cocoa pod husk burning. Biomass preparation includes: the process of producing mature cocoa pods, and the collection and transport of cocoa pod husk. Figure 1 shows a schematic representation of the boundaries of the electricity generation process in this study. The environmental impact is taken into account for each sub-process in the process.

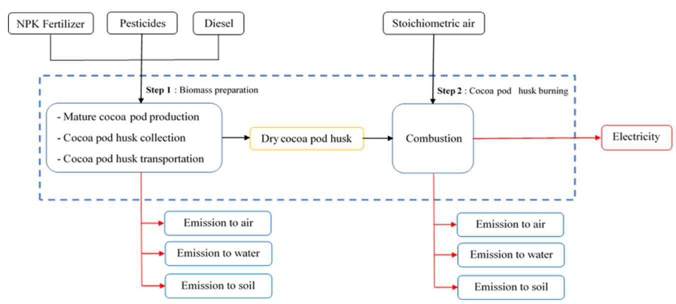

Fig 1. Schematic representation of the boundaries of the electricity generation proces

2.3 Life Cycle Inventory (LCI)

The study is carried out in the Bas-Sassandra district located on the southwest coast of Côte d'Ivoire. This district covers an area of 2,095 km^2. It includes the regions of San-Pedro, Gbôklè and Nawa. Figure 2 shows the administrative subdivisions of Bas-Sassandra District. Agricultural activities in the district are dominated by cocoa cultivation. The area of cocoa farms in the district represents about 30% of the country's cocoa area, estimated in 2019 at about 477,6874 hectares. This crop remains mainly concentrated in the Nawa region [17–19].

The production of mature cocoa pods require the use of fertilisers and pesticides. Data on fertilisers and pesticides come from CNRA (Centre National de Recherche Agronomique) literature [20] and from questionnaires sent to some farmers in the Bas-Sassandra district. At maturity, the cocoa pods are picked to extract the beans, after shelling. The wet pod husk is dried in the open air on platforms set up in the plantations. Harvesting, shelling and drying are done manually. According to Adzimah and Asiam [21], the cocoa pod husk and dry beans represent 14.7% and 10.9% of the mass of the mature cocoa pod respectively. Thus, for each kilogram of dry beans produced, about 1.35 kilograms of cocoa pod husk are generated. Given the diversity of cocoa varieties in the district, the yield of 500 kg of dry beans produced per hectare, obtained from farmers, is used for the various production input calculations.

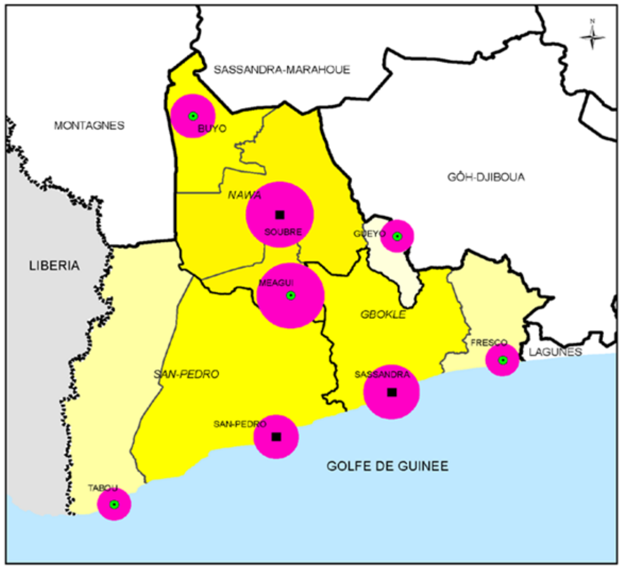

Fig 2. Administrative subdivisions of Bas-Sassandra district

The collection of cocoa pod husk in this study consists of conveying the dry cocoa pod husk in bulk from the plantations to the local collection centre, located near the village. Each village that produces dry cocoa beans will have a collection centre. The collection process requires the use of light vehicles. In general, in the district, the vehicles used to transport agricultural products from the farms to the village have a capacity of 3 tons per load. Thus, the vehicles used for the collection of dry cocoa pod husk are tractor-trailers with a capacity of 3 tonnes per load. The maximum distance between the collection centre and the cocoa farms is estimated at 10 km. In general, in the district, the furthest cocoa fields are located about 10 km from the village.

The cocoa pod husk is then transported from the local collection centre to the thermal power plant. The trucks used for transport have a loading capacity of 20 tonnes. For economic reasons and availability of residues, the study assumes that the power plant is located in the department of Soubré. This department is the heart of the new cocoa loop in Côte d'Ivoire. Soubré's cocoa production represents 59% of the cocoa production of the Bas-Sassandra district [18]. To estimate the distance to transport one unit of cocoa pod husk, the study assumes that the cocoa pod husk is evenly distributed throughout the district. Table 1 shows the distances between Soubré and the other departments of the district.

Table 1. Distances betweenSoubré and the other departments of the district

Departements	Transport (km)
San-Pedro	133
Tabou	229
Buyo	84
Méagui	52
Gueyo	67
Sassandra	161
Fresco	223

According to the study by Shafie et al. [6], the energy used by vehicles for the collection and transport of cocoa pod husk can be calculated from the energy unit of diesel (43.1 MJ/L), the specific fuel consumption, the average distance and the quantity of cocoa pod husk. However, the fuel consumption of a vehicle varies considerably depending on the type of traffic, roads, driving behaviour, etc. It is therefore advisable to base the fuel consumption of a vehicle on the average distance (100 km). So the calculations should be based on the actual fuel consumption of the vehicle [22].However, some authors suggest the use of indicative values, if no data are available, as the average fuel consumption for vehicles. For example, collection and transport vehicles have average fuel consumptions of 5.5 km/L and 4 km/L respectively for a distance of 100 km [6].

Electricity generation using cocoa pod husk is a new system in Côte d'Ivoire. The country does not currently have a biomass power plant using cocoa pod husk. This means that data sources are limited. Therefore, data on boiler emissions are taken from the USEPA report. The emission factors taken in this reference are those for dry wood burning in a biomass boiler. Table 2 shows the emission factors for a cocoa pod husk boiler[23]. LCA data for infrastructure construction and power plants are not included in this study.

The electrical power produced by the cocoa cortex is calculated from equation 1[24]. The HHV and LHV are 13.7 MJ/kg and 12.1 MJ/kg respectively[4]. Table 3 presents the total energy potential and availability of cocoa pod husk in Bas-Sassandra district in 2014[17].

$P = (m \times \eta \times LHV) / (3.6 \times T)$ (1)

m: Amount of crop residue used to produce 1kWh of electricity in kg ;

P: Electrical power produced by the biomass power plant in MW;

T: Operating time of the thermal power plant in hours;

η: Electrical efficiency of the biomass power plant; for this study the thermal power plant model has an electrical efficiency of 24.3 %. This was calculated from boiler combustion efficiency equal to 80 %[25]

LHV: Lower heating value of crop residue in MJ/kg.

2.4 Impact assessment

An environmental impact is understood as a change in the environment, whether beneficial or detrimental, due to a human activity. This change can cover very different environmental aspects. In LCA, these different aspects are called impact categories[26]. Thus, each resource withdrawal or substance emission, i.e. each elementary flow resulting from the inventory, can act on the environment through these different impact categories[26]. Impact assessment therefore consists of transforming an inventory of substance flows emitted and resources consumed into a series of clearly identifiable impacts[27].

There are no standard methods for assessing environmental impact categories[28]. However, in order to facilitate the use of the LCA method, different assessment methods have been developed over the years[29].

To assess the environmental impacts of bioenergy, the majority of LCA studies have used the midpoint impact categories of the CML method[30]. Developed in 2001 by the University of Leiden in the Netherlands, this method contains over 1700 different streams. It consists of the CML-baseline and the CML-non-baseline[31].

Of the eight impact categories of the CML-baseline, only four categories considered to be very robust for the purposes of this study were taken into account. Table 4 lists these impact categories of the CML Baseline method[11]. Several authors have defined these different categories of impacts, but the study retained the definitions from Aceroet al.[31]. According to these authors, acidification is an increase in the acidity of a soil, river or air due to human activities. Eutrophication is the accumulation of a concentration of chemical nutrients in an ecosystem that leads to abnormal productivity. While, human toxicity reflects the potential harm to humans of a chemical substance released into the environment. It is based on both the inherent toxicity and the potential dose of the substance. Finaly, global warming can be defined as an increase in the Earth's average surface temperature caused by the emission of greenhouse gases[32].

Table 2. Emission factors for a cocoapod husk boiler

Particulates emitted	NOx	CO	SO_2	VOC	CO_2	Particulate matter
Emission factors (g/kWh)	0.76	0.93	0.039	0.06	1750.03	0.62

Table 3. Energy potential and availability of cocoa cortex in the district in 2014

Region	Departement	Cocoa beans (Tonnes)	Cocoa podhusk (Tonnes)	Energy potential (MW)
San-Pedro	Tabou San-Pedro	171164	231071.4	20.62
Nawa	Soubré Buyo Méagui Gueyo	272265	367557.75	32.78
Gbôklè	Sassandra Fresco	21426	28925.1	2.58

Table 4. Environmental impact categories of CML-baseline

Environmental impact category	Relevant emissions	Unit
Acidification	SulfurdioxideSO_2	kg SO_2 equivalents
	Nitrogen oxides NOx	
	Hydrochloricacid HCL	
	Hydrofluoricacid HF	
	AmmoniaNH_3	
Eutrophication	Phosphate PO_4^{3-}	kg PO_4^{3-}equivalents
	Nitrogen oxides NOx	
	Nitrogen	
	Nitrates NO_3	
	AmmoniaNH_3	
Toxicity	Arsenic	kg 1,4- DB équivalents
	Chromiumequivalents VI	
	Benzene	
	Hexachlorobenzene	
Climate change	Carbon dioxideCO_2	kg CO_2equivalents
	Nitrous oxide N_2O	
	Methane CH4	
	Chlorofluorocarbon CFC	
	Hydrochlorofluorocarbon HCFC	

3 Results and Discussion

3.1 Environmental impacts

Figure 3 shows the results of the impact assessment of the electricity generation process using cocoa pod husk in Côte d'Ivoire. Figure 3 shows the contribution of the processes to theselected impact categories.

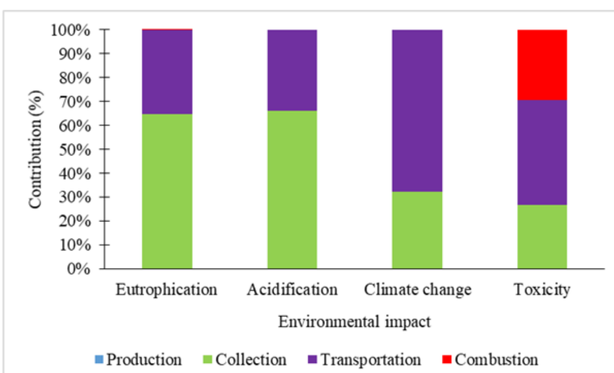

Fig 3. Contribution of processes to environmental impacts

These results reveal that electricity production using cocoa pod husk in the Bas-Sassandra district is accompanied by emissions of environmental pollutants involving climate change, acidification, eutrophication, and human toxicity.

The acidification is attributable to the emission of about 1.12 g SO_2eq./kWh of electricity produced. This phenomenon can alter chemical and biological balances and seriously affect the district's ecosystems. This will be noticeable by an increase in the acidity of the soil, waterways or air. These acidifying pollutants are emitted during the collection and transport processes of the cocoa pod husk. The collection process contributes about 65%. However, the study by Hajjaji et al.[33] reveals that the acidification generated by the electricity production process using natural gas in Tunisia is lower than that of the process using cocoa pod husk in Côte d'Ivoire. The Tunisian process emits about 0.065 g SO_2 eq/kWh of electricity. Also, the pollutants emitted involving eutrophication in Tunisia by the use of natural gas are lower than those of the process using cocoa pod husk in Côte d'Ivoire. The Tunisian process emits about 0.16 g PO_4 eq./kWh while the process using cocoa cortex in Côte d'Ivoire emits 0.28 g PO_4 eq/kWh of electricity produced. The eutrophication generated by the process using cocoa pod husk is attributable to the processes of collection, transport and combustion of cocoa pod husk. The contribution of the collection of the cocoa pod husk to this impact is about 65%, while the combustion contributes less than 1%. This phenomenon, resulting in an excess of nutrients in the aquatic environments of the district, can lead to the proliferation of aquatic plants.

Human toxicity is attributable to the emission of approximately 9.91 g 1,4 DBeq/kWh of electricity. This impact is implied by the pollutants emitted during the collection, transport and combustion processes of the cocoa pod husk. The contribution of collection to toxicity is about 27%; that of combustion is about 30%. Electricity generation using rice straw in Malaysia emits about 1.41 g 1,4DB/kWh of electricity[(6)]; while that using natural gas in Tunisia emits about 14.62 g 1,4 DB/kWh of electricity[(33)].

Finally, the process using cocoa pod husk in Côte d'Ivoire emits about 328.22 g CO_2 eq/kWh of electricity produced. These GHG emissions are mainly attributed to the collection and transport processes of the cocoa pod husk. The collection process contributes about 31%. Figure 4 shows the comparison of GHG emissions between electricity generation technologies using renewable sources including cocoa pod husk and those using conventional sources[(34,35)]. The data used represent the maximum emission values for renewable electricity technologies and the average values for conventional sources. The greenhouse gas emission factors are comparatively higher for conventional sources than for renewable sources. Electricity generation using nuclear energy generates fewer greenhouse gas emissions into the environment. But the disposal of radioactive materials has a greater impact on the environment[(36)]. The wide variety of biomass power generation technologies leads to a wide variation in carbon footprints. Some studies have shown that the carbon footprint of biomass electricity is generally lower than that of fossil fuel technologies[(37,38)]. The results of the present study show that the GHG emissions of electricity generation using cocoa pod husk are lower than those of generation using fossil fuels.

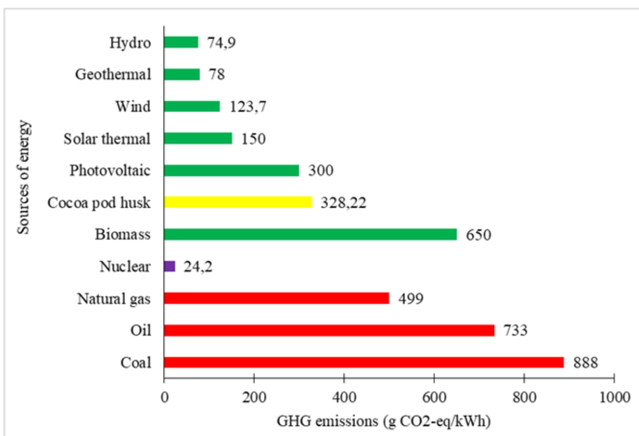

Fig 4. GHG emission levels ofelectricity generation technologies

Table 5. Results of the environmental impact assessment

Environmental impacts	Values	Units
Eutrophication	$28\ 10^{-2}$	g PO_4^{3-} équivalent
Climate change	328.22	g CO_2 équivalent
Toxicity	9.91	g 1,4 DB équivalent
Acidification	$11.2\ 10^{-1}$	g SO_2 équivalent

3.2 Sensitivity analysis

In order to take into account possible changes in the fuel supply circuit of the thermal plant, the study proposes to vary the transport distances in a sensitivity study to see their effects on the greenhouse gas emissions of the process. Figure 5 shows the effect of transport distance on the GHG emissions of the power generation system. Thus, the GHG emissions vary in an increasing and linear way with the transport distance. According to Cusenza et al.[39], if the transport distance is increased by 30%, the environmental impacts increase at percentages ranging from 1% (for water resource depletion) to 20% (for mineral fossil and renewable resource depletion).The study therefore recommends the installation of two production units. One unit could be installed in Soubré. The fuel for the latter will come from the departments of Gueyo, Méagui, Soubré and Buyo. In this case, the maximum transport distance is 84 km and the maximum GHG emissions are about 292.54 g CO_2 eq/kWh.

The second unit can be installed in San-Pedro, and supplied with fuel from the departments of Tabou, Sassandra and San-Pedro. The maximum transport distance in this case is 100 km for a maximum GHG emission of 328.22 g CO_2 eq/kWh. pod husk.

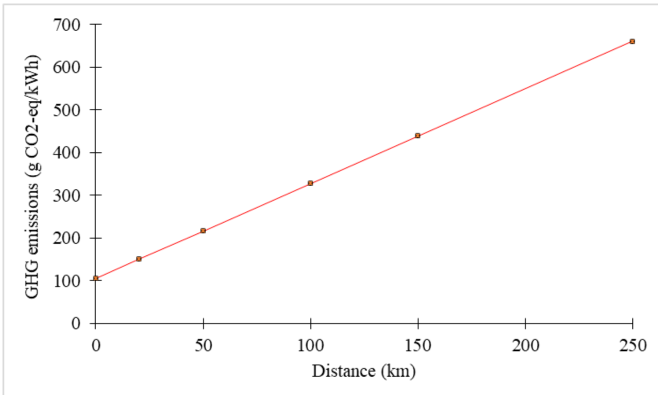

Fig 5. Variation of GHG Emissions with Transport Distance

4 Conclusion

The environmental impacts of the electricity generation process using cocoa cortex in the Bas-Sassandra district of Côte d'Ivoire were calculated for the processes of cocoa pod production, collection, transport and combustion of the cocoa pod husk to produce 1 kWh of electricity. This electricity production is accompanied by emissions of pollutants involving acidification, eutrophication, global warming and human toxicity.

Acidification is implied by the emission of 1.12 g SO_2 eq./kWh during the collection and transportof the cocoapod husk. However, the processes of transport, collection and combustion also emit 0.28 g PO_4 eq/kWh involving eutrophication. The study also found that the cocoa pod husk collection and transport processes emit 328.22 gCO_2 eq/kWh involving global warming. Finally, the collection, transport and combustion processes emit 9.91 g 1,4 DBD eq./kWh involving human toxicity.

The sensitivity analysis showed that the transport distance has an effect on the GHG emissions of the sector. Thus, GHG emissions increase with the distance travelled by the transport vehicle. The analysis identified power plant locations that would reduce GHG emissions for the production of 1 kWh of electricity.

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