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Life Cycle Assessment of the valorization of rice straw for energy purposes. Rice production in Cuba

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Abstract: Due to the need to evaluate the sustainability of rice straw management during rice production in Cuba, the objective of this work was to analyze four possible alternatives for the valorization of rice straw for energy purposes in Cuba in two different scenarios. Life Cycle Assessment (LCA) methodology was used. The "*Sur del Jíbaro*" Grain Enterprise was assessed as a case study.
The environmental impacts generated from the intermediate impact categories and those associated with the three categories of final damages proposed by the methodology ReCiPe were assessed. The behavior of the ecological footprint was also assessed.
The impact category climate change is expressed in kg CO_2-Eq. The three proposed alternatives (Alternatives 2, 3 and 4), where valorization of rice straw for energy purposes are considered, presented better results. One of them (Alternative 4), where part of the biogas generated is used in the transportation of different products, has the lowest impact on climate change, with a difference of 4.09923 e + 7 kg of CO_2-Eq as compared to the alternative used at present (Alternative 1).
In the particle formation impact category expressed in kg PM10-Eq, Alternatives 2 and 3 have the most unfavorable results with emissions of 3.46561 e + 5 kg PM10-Eq. This value is higher than that of Alternative 1, which is associated with the necessary increase of diesel consumption for the transportation of different products in the process. However, in Alternative 4, the emissions are reduced in 1.86204e + 5 kg PM10-Eq when the biogas is used as fuel replacing a part of the diesel used in transportation.
In the categories of final damages, Alternatives 2, 3 and 4 have advantages with respect to Alternative 1. Alternatives 2 and 3 have a score of 9.11450e + 5 points

less than Alternative 1; and Alternative 4 reaches a score of 3.033540e + 6 points less than Alternative 1 and of 2.119390e + 6 points less than Alternatives 2 and 3, what makes Alternative 4 the one that damages the environment the least.

Keywords: Biogas, Life Cycle Assessment, ReCipe, Rice production

Novelty statement: The environmental contribution of the energetic valorization of rice straw by anaerobic digestion in Cuba is assessed for the first time and the most sustainable alternative is defined using LCA.

Introduction

Recent experimental studies have shown that the implementation of biomass as energy resource in Sancti Spiritus, Cuba, would provide around 98% of renewable energy and would help to increase from 6% to 55% the contribution of renewable sources to the electric generation matrix of the province. The biomass and wastewaters generated only in this province could provide a biogas potential of 7.37 x 106 m^3/year, which can be translated into 21.96 GWh/year of electrical energy and 30.02 GWh/year of thermal energy (Congress, 2017).

In Cuba, the biogas potential of several solid agricultural wastes (i.e. rice straw (crop residue) (Contreras *et al.*, 2012), cane straw (residues from cleaning centers), corn straw, banana straw (leaves), bean straw, coffee husks and parchments, and sugarcane bagasse (López-Dávila *et al.*, 2013)) have been studied. Their methane potentials total 1,258.26 x10^6 m^3/year, which is sufficient to generate 3,749.61 GWh of energy per year - equivalent to 19.6% of the country's annual electricity (López-Dávila *et al.*, 2013). On the other hand, industrial wastewater's (dairy industry, cannery, fish processing and coffee wet wastewater) have also shown considerable biogas potential.

Among them, the agro industrial wastes of rice production and the wastes from the sugar, agricultural and livestock industries are more relevant. The agro industrial wastes of rice production, specifically rice straw, are of the most problematic to eliminate during the rice harvest. Worldwide, more than 730 million tons of rice straws are produced per year (Zhao *et al.*, 2010). Given the problematically high cost of its removal and low utilization, the most frequent practice is to burn it, which generates a high concentration of air emissions of particles and gases resulting from the combustion (Abril *et al.*, 2009; Gadde *et al.*, 2009). This has been a widespread practice in rice fields around the world, as it favors the destruction of fungal and bacterial spores and weed seeds. However, on the other hand it facilitates the reincorporation of Nitrogen, Phosphorus, Potassium and Silica to the soil (Ram *et al.*, nd).

If the straw is not burned, there are mainly two disposal options: grinding and incorporating it to the soil; and removing it from the field for its use. The anaerobic digestion of rice straw has been studied in the past century, but its renewable energy potential is barely utilized (Mussoline *et al.*,2013). Furthermore, the Greenhouse gas emissions from rice fields can be substantially reduced if straw is removed. For all these, the valorization of rice straw for energy purposes using the anaerobic digestion (AD) technology has been very attractive in recent decades (Wang *et al.*, 2009) (Contreras *et al.*, 2014). Not only because it allows its ecological management, but also because it takes advantage of the biogas and effluent that result from the process, turning the rice straw into a source of renewable energy and bio fertilizer for the grain production itself.

The growing generation of solid waste worldwide requires management strategies that integrate concerns for environmental sustainability, by quantifying the environmental impacts of the systems. Life-cycle assessment (LCA) is a tool that can contribute to responding to this call (Laurent *et al.*, 2014). Besides, this very author in a review of 222 articles published on LCA shows that most of them were carried out in developed countries and the majority of them have been focused specially on domestic waste, this associated to the lack of data and the misrepresentation of lifecycle concepts in developing countries (Laurent *et al.*, 2014).

LCA is traditionally used to assess the environmental impacts of products, services and processes, through the life cycle in a "cradle to grave" approach (Heijungs *et al.*, 2009). There are several benefits of LCA, including the ability to assess the material and energy efficiency of a system, identifying pollution shifts between operations, and providing benchmarks for improvement (Huntzinger and Eatmon, 2009)

The existing standard to implement this tool is ISO 14040 (Standard, 2006), which defines four fundamental stages: I) definition of objectives and scope, II) life cycle inventory, III) environmental impact assessment, and IV) interpretation of results.

For the case of Cuba, two aspects should be observed. First, this country has projected its sustainable development until the year 2030 considering as an important element to increase the use of renewable energy sources, and within them, the use of waste for energy purposes. Second, at present LCA is increasingly being used in waste management to identify strategies that prevent or minimize negative impacts on ecosystems, human health or natural resources (Laurent *et al.*, 2014). Thus, it is necessary to introduce the concepts associated to LCA to all development projects and specifically to renewable energy development projects in Cuba.

The scope of this research is the analysis of four possible alternatives, in two different scenarios, for the valorization of rice straw for energy purposes in Cuba using LCA. The "*Sur del Jíbaro*" Grain Enterprise is assessed as a study case.

This research evaluates the environmental impacts generated from the intermediate impact categories and those associated with the three categories of final damages proposed by the methodology ReCiPe. In addition, the behavior of the ecological footprint of each of the proposed alternatives was assessed.

Materials and Methods

The present work is carried out from the hypothesis that any valorization of rice straw for energy purposes will reduce the environmental impacts throughout the productive system. To confirm this hypothesis, the LCA methodology is used.

OpenLCA

For this research, the Life Cycle analysis software OpenLCA was used. It was developed by "Green DeltaTC" and is an open source with a modular and flexible structure, making it possible to include various modules, which are applied as autonomous applications. OpenLCA proposes an improved user interface for Java applications, in addition to other interfaces, such as one to visualize the process inventory network. The format converter runs as a standalone application and can convert multiple data sets into queues. The open source nature of the software allows adjustments and adaptation to specific needs. Users can select different formats to store the data. By providing the converter, data availability and exchange with other programs and databases improve (Ciroth, 2007).

ReCiPe Methodology

The methodology used is ReCiPe and it is built on the basis of Eco-indicator 99 and CML (Centrum Milieukunde Leiden). It has 18 categories of impact and 3 categories of damage (Goedkoop *et al.*, 2009). ReCiPe attempts to harmonize two assessment methodologies, based on intermediate point and endpoint indicators. Like its predecessor Eco-Indicator 99, it raises three points of view: Equal, Hierarchical and Individualistic, which have the same conceptualization. Figure 1 shows the relationship between the impact categories and the environmental mechanisms. In addition, the ecological footprint methodology was used, also available in OpenLCA software.

System boundaries and Functional unit and Data base

At present, the enterprise has an area of 83,875 hectares. Of them, 15,282.7 ha are used only for rice cultivation. It is located in the southern region of the province of Sancti Spíritus. The main rice masses are located in three regions. The first is located at the southeast of ¨Mapo¨ and ¨Natividad¨; the second extends from ¨Peralejo¨ to ¨El Jíbaro¨, in the southern part; and the third is located in the southwest of ¨Las Nuevas¨. The units dedicated to the industrial production process are: ¨Los Españoles¨, having three discontinuous technology drying plants with a total daily capacity of 368 t of wet rice; and ¨Tamarindo¨, which has two drying plants, one of discontinuous technology, with a daily capacity of 128 t of wet rice, and another with continuous technology, with a capacity of 257 t of wet rice per day. It also has a rice mill capable of processing 240 t of dry paddy rice per day.

The aim of the assessment is the rice production system. The functional unit considered for the study was a production capacity of 40,000 tons of rice per year. For the definition of the boundaries, the system expansion method was used to obtain adequate information on the environmental consequences when manipulating production systems that are interconnected among themselves due to the interrelation that exists between the production of rice and the production of energy when the rice straw is energetically valorized. The geographical limits considered include all areas of the enterprise used for rice production in the agricultural and industrial phase; the time limits considered include all material and energy flows necessary for the production of rice in two stages of harvest for one year of production. Figure 2 shows the processes that are incorporated to the agricultural and industrial phases of rice production for the valorization of rice straw for energy purposes.

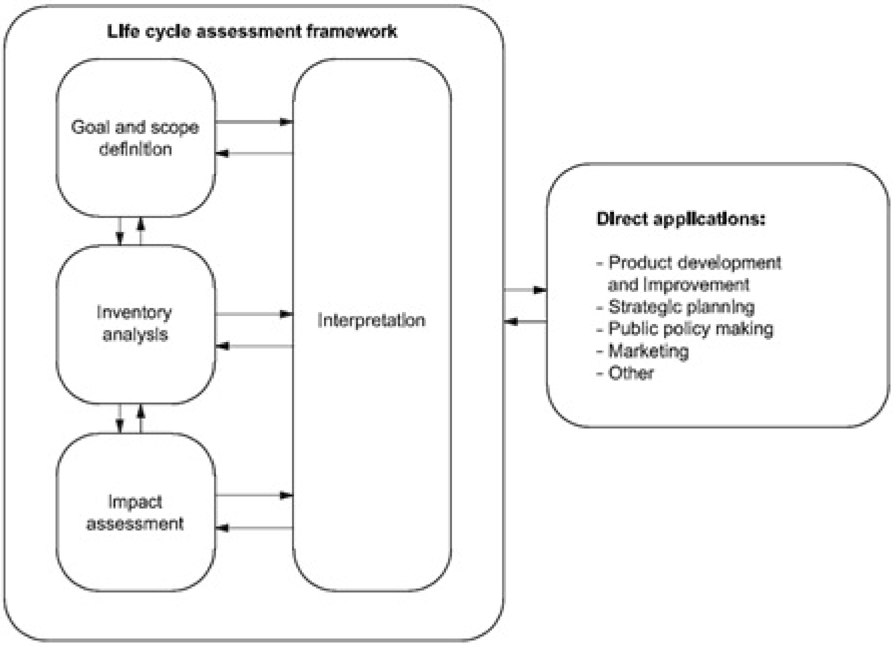

Fig. 1 - Relationship between Impact and Damage categories of ReCiPe (Goedkoop et al., 2009).

In the study, a prospective analysis is carried out from the perspective of the environmental impacts of the rice production life cycle to decide how to make rice production in Cuba more sustainable and to introduce the use of harvest residues to obtain energy via anaerobic digestion.

In the research, four alternatives are compared in two scenarios for the valorization of rice straw for energy purposes in Cuba, using LCA within the boundaries proposed. The two scenarios are the following:

First scenario: It considered the mass and energy flows within the proposed boundaries of the rice production system, including emissions of carbon dioxide generated in the two phases (agricultural and industrial) of the process.

Second scenario: It considered the mass and energy flows within the proposed boundaries, but also considered the difference between the CO_2 emissions in the rice production system (agricultural and industrial phases) and the emissions avoided by the non-generation of electricity in a thermal plant, when rice straw is valorized for energy purposes (Contreras *et al.*, 2014), using the following equation:

$$CO_2\text{system} = CO_2\text{generated} - CO_2\text{avoided}$$

Where:
CO_2system: CO_2 balance entering into the system
CO_2generated: CO_2 produced by diesel combustion in the agricultural and industrial phases of rice production.
CO_2avoided: CO_2 that is no longer emitted in a thermal generation plant if the same amount of energy considered in the study is generated via anaerobic digestion.

In three of the four alternatives evaluated, it is considered to use all the straw generated in the fields when harvesting for anaerobic digestion, according to the biogas plant projected by Luz M Contreras *et al.* (2014). There, a technology consisting of a completely stirred tank reactor (CSTR) was proposed, with a continuous feeding system, considering the following operating parameters: particle size, 1-3 cm; temperature, 55±2 °C; reactor configuration, CSTR; maximum volumetric organic load, 4 kgSVm-3d-1; and hydraulic retention time of approximately 21 days. The expected biogas yield under these conditions is 0.271 m3 kgMF-1.
Thee four alternatives are defined as follows:

Alternative 1:
It is the basic scenario and coincides with the rice (main product) production system that is currently used, where all the straw (by-product) generated in the harvest phase are incorporated into the soil.

Alternative 2:
The main product is rice. In this scenario it is evaluated the generation of electricity (5 MWh installed capacity) from the biogas produced (19.46 E + 6 m^3/year) by the anaerobic digestion of all the straw produced (by-product) and where all the electric energy generated is delivered to the national electro energetic system (SEN, Spanish acronym). For this purpose, it was necessary to determine the new mass and energy balances in the soil fertilization process since they are modified. On the one hand, the contribution of some components (Nitrogen (N), Phosphorus (P) and Potassium (K)) is limited because the natural decomposition of rice straw in the soil no longer occurs. On the other hand, in this scenario the digestate from the biogas plant is used as biofertilizer, so a new source of soil components appears. In this alternative, similarly to Alternative 1, the electric energy needed by the socio-productive system is imported from the SEN.

Alternative 3:
The main product is rice. It is evaluated the generation of electricity (5 MWh installed capacity) from the biogas produced (19.46 E + 6 m3/year) by the anaerobic digestion of all straw produced (by-product), but only 93% of the generated power is delivered to the SEN, and the rest is used for the self-sufficiency of the enterprise.

Alternative 4:
The main product is rice. It is evaluated the use of a part of the biogas produced by anaerobic digestion of all the straw (by-product) produced (31.49 E + 5 m^3/year), after being subjected to a process of purification and compression. The biomethane obtained is used for the internal combustion equipment in the harvesting processes and transportation of the product rice, compaction and transfer of the straw, and the transfer of the digestate to the rice fields as bio-fertilizers. For that, it was considered the substitution of 60% of the diesel used in Alternative 2, according to Cacua *et al.* (2011) and Canakci and Hosoz (2006) and the energy consumptions in the industrial stage were adjusted. By reducing the availability of biogas, electricity generation in this alternative is reduced to 4 MWh of installed generation capacity. As in this research it is assessed the behavior of the different environmental impacts in different rice production energy schemes where rice straw is valorized via anaerobic digestion, a detailed scaling of what is involved is not carried out. The reduction of the installed capacity in the electric generation stage does not significantly influence the results obtained. It could be taken into account for future studies.

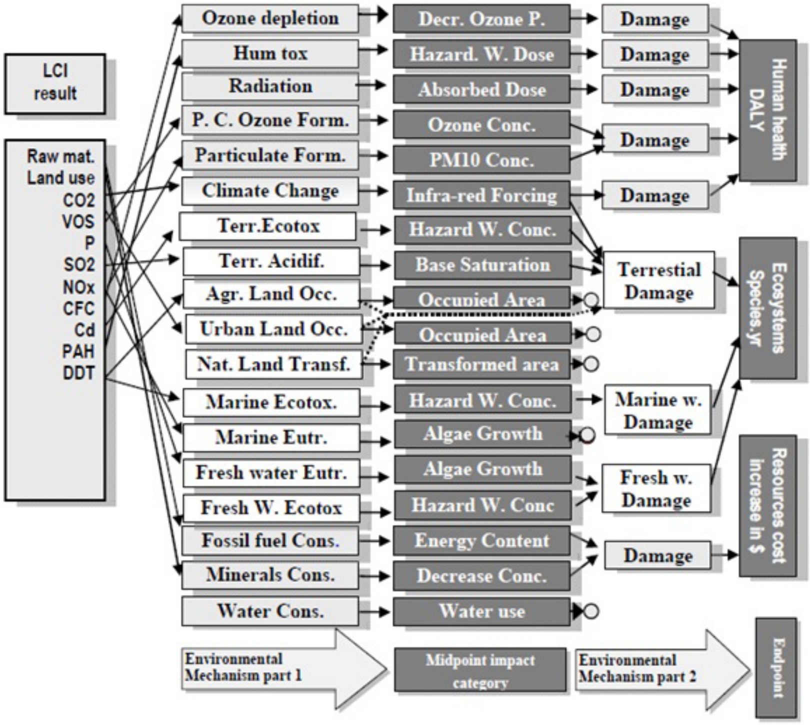

Fig. 2 - Processes that are incorporated to the agricultural and industrial phases of rice production for the valorization of rice straw for energy purposes

Table 1 - Elements considered for the environmental impact assessment in the case study of the enterprise "Sur del Jíbaro".

Parameter	Unit	Value
Available rice straw	ta^{-1}	74 400
Ratio water feed/straw	-	2:1
Annual Operating Days	d	365
Density of biomass	kgm^{-3}	74,50
Water Density	kgm^{-3}	1 000
Estimated retention time	d	45
Organic matter of food	$kgSV\ tMF^{-1}$	698,20

Table 1 - continued

Parameter	Unit	Value
Experimental biogas yield	m^3kgMF^{-1}	0,27
Index of electric power generation	$kWhm^{-3}$	2,23
Daily biomass feeding	td^{-1}	219,18
Daily water supply	td^{-1}	438,36
Daily total feeding	td^{-1}	657,53
Daily Volume Feed	m^3d^{-1}	657,53
Flow of daily organic matter to the digester	$kgSV\ d^{-1}$	153 030
Maximum volumetric organic load	$kgSV\ m^{-3}d^{-1}$	4,00
Minimum effective reactor volume	m^3	38 258
Daily biogas production	m^3d^{-1}	55 239
Daily production of electricity	kWh	120 000
Power of electric generation system	MW	5
Available daily thermal energy	kWh	197 199

The data base used for this research corresponds to the results of (Contreras *et al.*, 2012; Contreras et al., 2014) (Table 1), where the two main elements that make up a biogas plant for cogeneration of energy are the total volume of digestion and the power of the engine or electric generator.

Some other considerations were considered in this study, such as:

1. Daily water requirement for the digester: 4.38 m^3. It indicates that for Alternatives 2, 3 and 4 there is additional water consumption for the anaerobic digestion process.
2. Only the energy used by 33 agricultural machineries was considered.
3. Index of diesel consumption per harvest: 9.34 to 13 L t^{-1}. This index is used to calculate the total diesel value required in the compaction and transportation of the rice straw to the digester.
4. Specific density of diesel: 8.32E + 02 kg m^{-3}.
5. Specific density of water: 1.00E + 03 kg m^{-3}.
6. The organic matter supplied to the soil by the rice straw is calculated according to Table 2, which reflects the chemical composition of the agricultural residue, according to Jiménez (2015).

Table 2 - Chemical composition of rice straw. Source: (Sanchis et al.*, 2014).*

Composition	Nitrogen (N) (g kg-1)	Phosphorus (P) (mg kg-1)	Potasium (K) (mg kg-1)
Rice straw	8,96	2,95	1,55

The rice for consumption was the final product in Alternative 1; while rice for consumption and electric energy are the final products for the other three alternatives. The annual production is 40,000 tons of consumption rice in a year. The data used were collected through interviews with executives and technicians of the enterprise, bibliographical and standardized consultations on this topic. The main source was the data used by (Contreras *et al.*, 2014) with modifications made by the authors according to the production data for year 2015, related to the yields of rice production per hectare, and associated with it, the flows of water, rice straw, technological inputs, energy, etc. (Table 3).

Table 3 - Flows used for the life cycle analysis in the four alternatives evaluated. (Modified from Contreras, 2013).

Data base of rice production		Alternatives			
Flow		Nr.1	Nr.2	Nr.3	Nr.4
Input	Unit	Amount	Amount	Amount	Amount
Diesel of agricultural phase	kg	772709,85	6299089,8	6299089,8	6299089,8
Diesel of industrial phase	kg	3844689,8	662575	662575	662575
Electricity generation in Cuba	MJ	9971348,94	9971348,9		
Herbicides	kg	224080	224080	224080	224080
Lubricating oil (Agricultural phase)	kg	150000	450000	450000	450000
Lubricating oil (Industrial phase)	kg	450000	150000	150000	150000
Occupation, arable	m^{2}*a	152827000	152827000	152827000	152827000
Oxygen, in air	kg	16067300	24608300	24608300	11453700
Phosphorus	kg	338700	116100	116100	116100

Table 3 - continued

Data base of rice production		Alternatives			
Flow		Nr.1	Nr.2	Nr.3	Nr.4
Input	Unit	Amount	Amount	Amount	Amount
Potassium	kg	270900	270900	270900	270900
Rice seed	kg	2407000	2407000	2407000	2407000
Urea	kg	338700	116100	116100	116100
Water, lake	m^3	64260	64260	64260	64260
Zinc	kg	169350	169350	169350	169350
Output					
Biomass	kg	4503680	4503680	4503680	4503680
Rice husk, waste from dryer	MJ	24770240	24770240	24770240	24770240
Carbon dioxide, fossil fuel	kg	14329279,5	21947413	21947413	10214155
Electricity, at cogent with ignition biogas engine	MJ		157680000	157680000	157680000
Methane, biogenic	kg	8520105	3667848	3667848	3667848
Nitrogen oxides	kg	2879101	4409784	4409784	2052265,9
Oxygen, in air	kg	17324585	26535135	26535135	12349251
Rice production in Enterprise	kg	40000000	40000000	40000000	40000000
Rice ringleader	kg	11259200	11259200	11259200	11259200
Sulfur dioxide	kg	92272	141328	141328	65773
Water	kg	6350451	9726702	9726702	4526747

In addition, oxygen uptake and greenhouse gas emissions in the combustion of diesel and methane used throughout the process were considered, according to their stoichiometric composition (Cacua *et al.*, 2011), as well as biogenic methane emissions in the process of decomposition of rice straw in the field (Sanchez *et al.*, 2014; Lagomarsino *et al.*, 2016).

For the second scenario, the balance of carbon dioxide flows was modified, as shown in Table 4. In Alternative 1, the nitrogen balance was considered considering the nitrogen provided by the straw in its natural decomposition in the soil, which is characterized by being a slow process, and the nitrogen that is necessary to import for fertilization in form of Urea. In Alternatives 2, 3 and 4, the nitrogen balance was the content of nitrogen in the digestate, the nitrogen that is left to contribute for removing the rice straw, and the one that needs to be imported to supply the agronomic recommendations. In the latter case, the nitrogen in the digestate is quickly and highly available for the plants to grow in a short term (Alburquerque *et al.*, 2012), which is why the values that need to be imported into the urea production system are lower in Alternatives 2, 3 and 4. This is another advantage of the valorization of waste by anaerobic digestion with respect to the environmental damage caused.

Table 4 - Changes to flows used for the life cycle analysis in the four alternatives evaluated.

Flow		N 1	N 2	N 3	N 4
Input	Unit	Amount	Amount	Amount	Amount
Carbon dioxide, fossil fuel	kg	14329279,5	-269483113,5	-269483113	-292789855,7

Results and Discussion

Rice production depends on using a lot of water and its availability can generate significant changes in the results of this research. However, the authors considered not doing a specific sensitivity analysis related to the possible climatic variability for two reasons:

First: The information available in the Cuba Statistical Yearbook Edition 2016 reflects that there have been no significant variations in the rainfall in the last 5 years. In that region the average rainfall from 2011 to 2016 was 1439.8; 1138.1; 1756.8; 1062.7; 1576.1; and 1086.6 millimeters per year respectively. In addition, the productive system implemented by the enterprise is by flooding. For this, there are irrigation canals fed from an artificial lake upstream with a reservoir capacity of 1,020 million cubic meters of water.

Second: Complying with the objective of this work, the energy schemes from the evaluation of different scenarios for the consumption of electrical energy was modified for Alternatives 2, 3 and 4, as well as the consumption of energy diesel for Alternative 4. This enables to assess the behavior of the different environmental damages of rice production in different scenarios, constituting a sensitivity analysis.

ReCiPe Midpoint. First scenario

In this section, the results related to the evaluation of the impacts of the intermediate categories according to the methodology used are described. The results of the most significant impact categories among the four alternatives evaluated in the first scenario are studied.

Figure 3 shows the results in the climate change impact category expressed in kg CO_2-Eq. Alternatives 2, 3 and 4, where valorization of rice straw for energy purposes are considered, presented better results. Alternative 4, where part of the biogas generated is used in the transportation of the different products, has the lowest impact on climate change, with a difference from the currently used Alternative 1, of 4.09923 e + 7 kg of CO_2-Eq.

In the particle formation impact category expressed in kg PM10-Eq, Figure 4 shows that Alternatives 2 and 3 have the most unfavorable results with emissions of 3.46561 e + 5 kg PM10-Eq. This value is higher than that of Alternative 1, which is associated with the necessary increase of diesel consumption for the transfer of the different products in the process (Fuzzi *et al.*, 2015; Karagulian *et al.*, 2015). This also coincides with Shafie *et al.* (2014) in their study on "Life cycle assessment of rice straw-based power generation in Malaysia", where the increase in emissions is associated to the increase of primary energies, mainly to the distance to transport the substrate to the biogas plant. However, in Alternative 4, the emissions are reduced in 1.86204e + 5 kg PM10-Eq when the biogas is used as a fuel source for the replacement of a part of the diesel used in transportation. Thus, Alternative 4 has the lowest impacts in this category. Figure 5 shows all categories of intermediate impacts for the four alternatives evaluated.

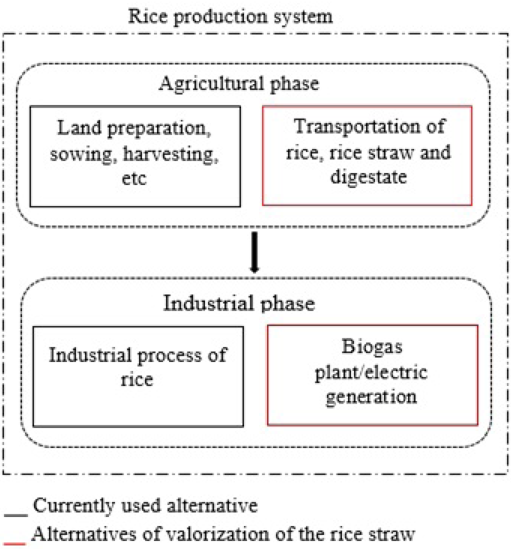

Fig. 3 - Impacts on the intermediate category: climate change (kg of CO2-Eq), according to ReCiPe Midpoint. Where the geographical limits considered include all areas of the enterprise used for rice production in the agricultural and industrial phases (First scenario).

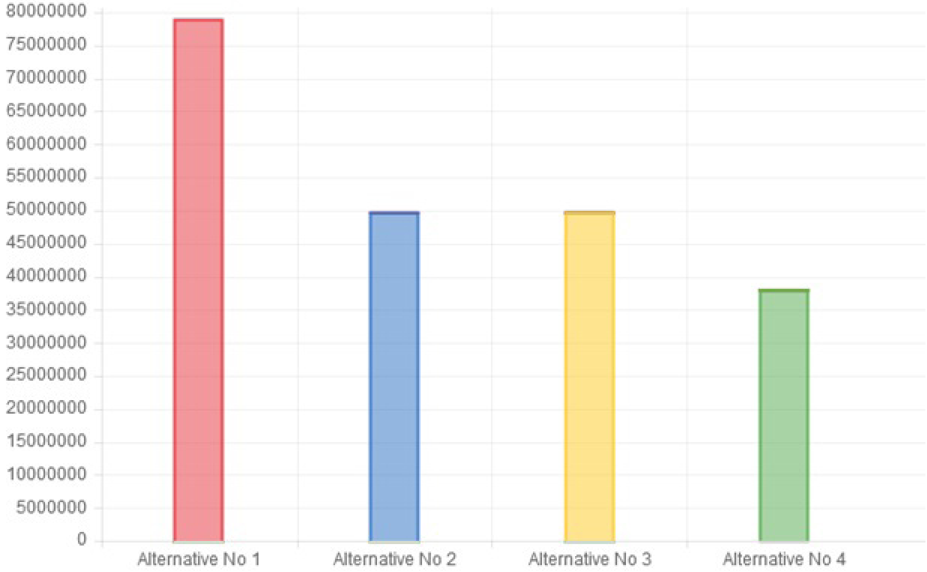

Fig. 4 Impacts on the intermediate category: formation of particles (kg PM10-Eq), according to ReCiPe Midpoint. Where the geographical limits considered include all areas of the enterprise used for rice production in the agricultural and industrial phases (First scenario).

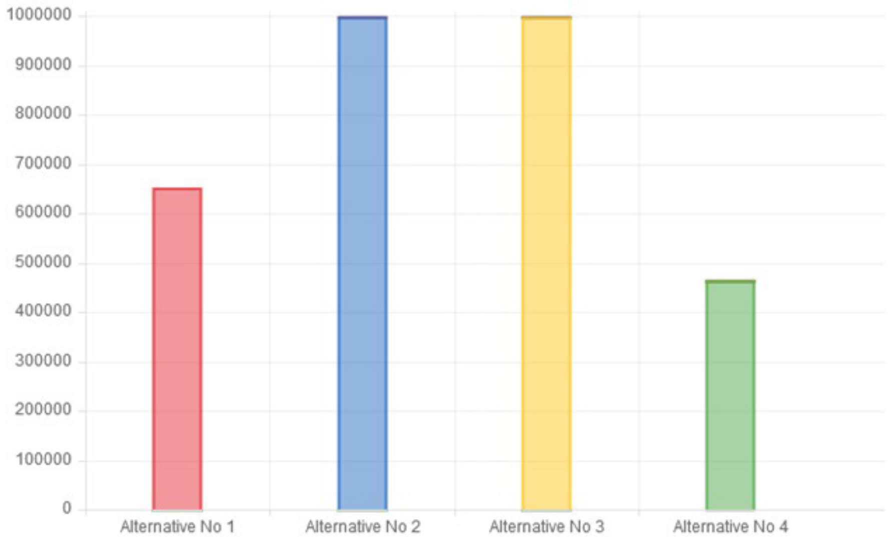

Fig. 5 Impacts on the intermediate categories, ReCiPe Midpoint (%). Where the geographical limits considered include all areas of the enterprise used for rice production in the agricultural and industrial phases (First scenario).

ReCiPe Midpoint. Second scenario

In this section, the results of the most significant impact categories among the four alternatives evaluated in the second scenario are depicted. As described above, the CO_2 balance resulting from the substitution in the generation of electricity in a thermal plant by a renewable energy source (biogas) is considered.

In Figure 6, 7 and 8 the significant difference between the results of the impacts caused by the current production alternative (1) and the three alternatives that energetically valorize the rice straw is shown. The most significant categories are climate change (kg CO_2-Eq) and the formation of particles (kg PM10-Eq). If the results of the two scenarios are compared, significant differences can be observed. From this analysis it can also be concluded that for this type of evaluation it is very important to select the boundaries for each specific study objectively, and depending on the objectives desired. The results obtained in the first scenario, when only the boundaries of the productive ecosystem are considered, demonstrate the feasibility of the use of rice production residues (rice straw) for energy purposes. However, all the advantages of this type of technology are not yet exploited. In the second scenario, with an extension of the boundaries related to CO_2 emissions to the atmosphere, it can be noticed the true benefits of renewable energy projects for sustainable development. This finding contrasts with Buitrago & Belalcázar (2013) who relate the null or marginal benefits that biofuels can represent in comparison to conventional fuels in some categories of impacts, only to the data collection and the area where the study is developed.

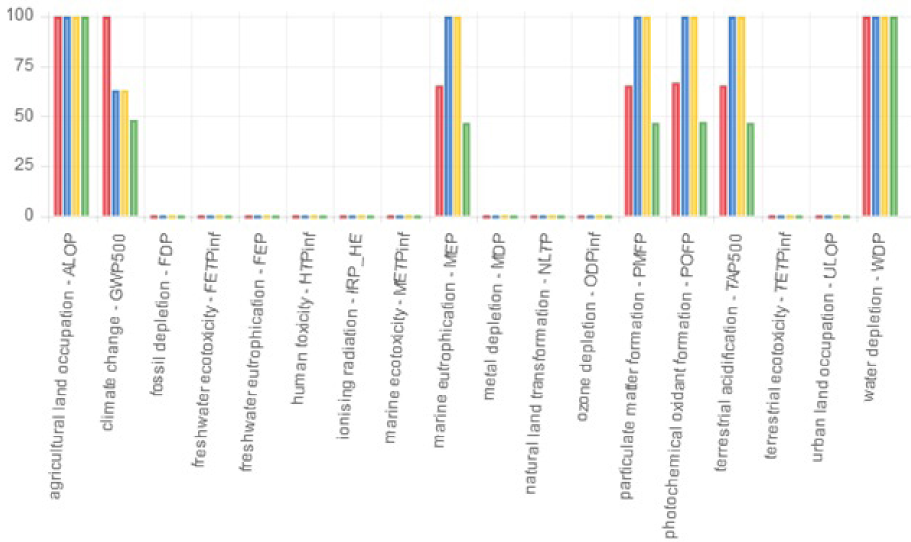

Fig. 6 - Impacts on the intermediate category: climate change (kg of CO_2-Eq), according to ReCiPe Midpoint. Where it is considered the difference between the CO_2 emissions in the rice production system (agricultural and industrial phases) and the emissions avoided by the non-generation of electricity in a thermal plant when valorizing rice straw for energy purposes (Second scenario).

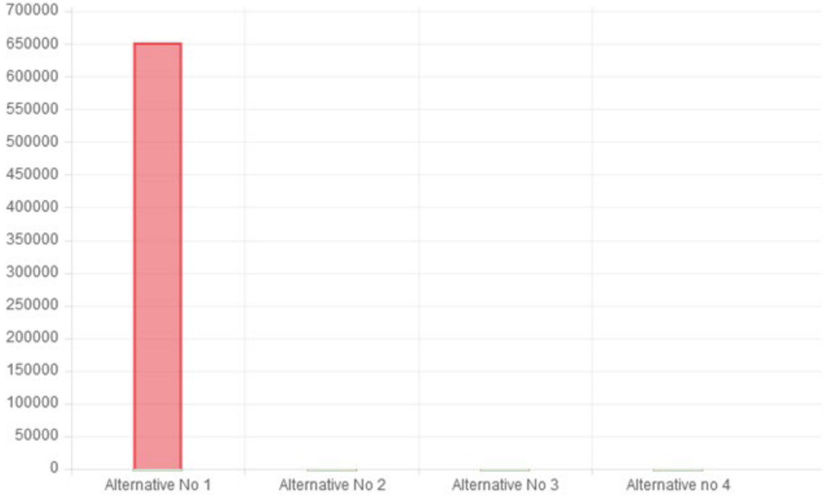

Fig. 7 - Impacts on the intermediate category: formation of particles (kg PM10-Eq), according to ReCiPe Midpoint. Where it is considered the difference between the CO2 emissions in the rice production system (agricultural and industrial phases) and the emissions avoided by the non-generation of electricity in a thermal plant when valorizing rice straw for energy purposes (Second scenario).

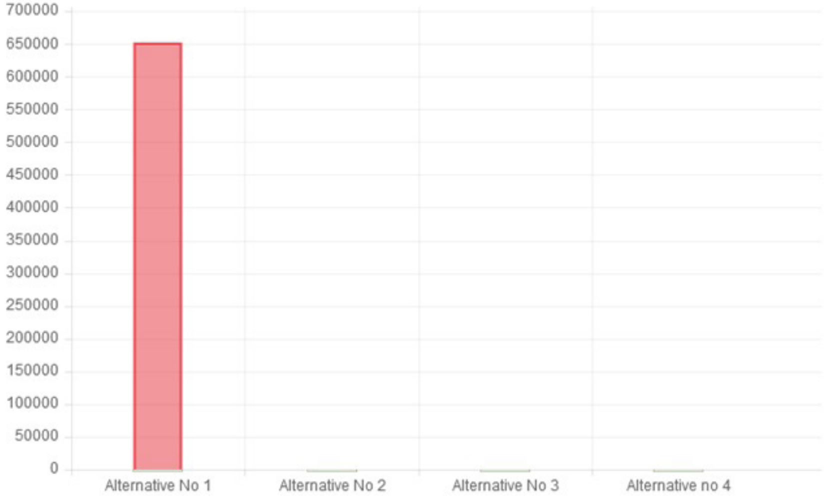

Fig. 8 - Impacts on the intermediate categories, ReCiPe Midpoint (%). Where it is considered the difference between the CO2 emissions in the rice production system (agricultural and industrial phases) and the emissions avoided by the non-generation of electricity in a thermal plant when valorizing rice straw for energy purposes (Second scenario).

ReCiPe Endpoint. First scenario.

Subsequently, the results associated to the categories of final damages are described for each scenario evaluated. The results for the final impact categories of the three damage categories proposed by the methodology (ecosystem quality, human health and resources) are evaluated in points.

In Figure 9, according to the categories of final damages proposed by the methodology, the three alternatives where it is proposed to valorize rice straw for energy purposes have advantages with respect to Alternative 1. Alternatives 2 and 3 have a score of 9.11450e + 5 points less than Alternative 1; and Alternative 4 reaches a score of 3.033540e + 6 points less than Alternative 1 and of 2.119390e + 6 points less than Alternatives 2 and 3. This makes Alternative 4 the one that damages the environment the least according to the three categories proposed by the methodology used.

Figure 10 shows the contribution of each category of intermediate impact in relation to the category of final damage evaluated, being the categories of climate change and human health those in which Alternative 4 presents better results when compared to the others studied. Despite the unfavorable results obtained when using the ReCiPe Midpoint tool in the categories of particle formation and terrestrial acidification (Figure 5), the results of the ReCiPe Endpoint tool for the same scenario shows that the three alternatives where rice straw is valorized are still the most environmentally viable. It also shows that Alternative 4 is the one that has the lowest impact on the environment. This result coincides with what was obtained by Roy *et al.* (2012) when they study rice straw to produce bioethanol in Japan. On the other hand, when the digestate is reincorporated into the soil, a more efficient form of nitrogen incorporation is achieved. This would reduce the consumption of resources and the direct emissions to the agricultural subsystem, as reported by Mingxin *et al.* (2010).

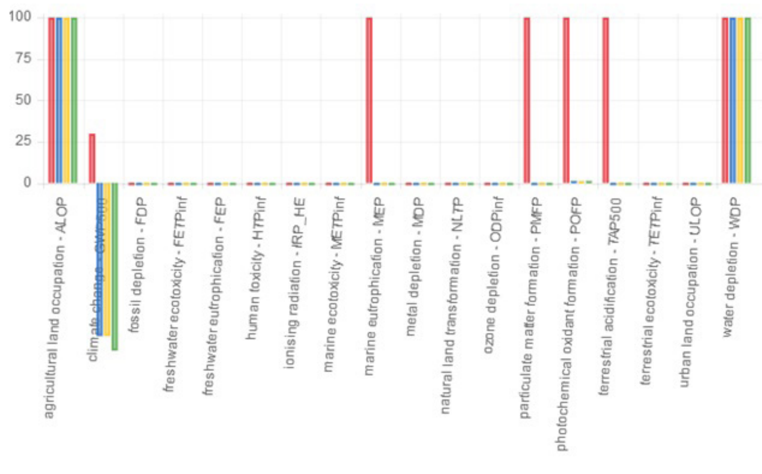

Fig. 9 - Impacts of final damage categories according to ReCiPe Endpoint (Points). Where the geographical limits considered include all areas of the enterprise used for rice production in the agricultural and industrial phases (First scenario).

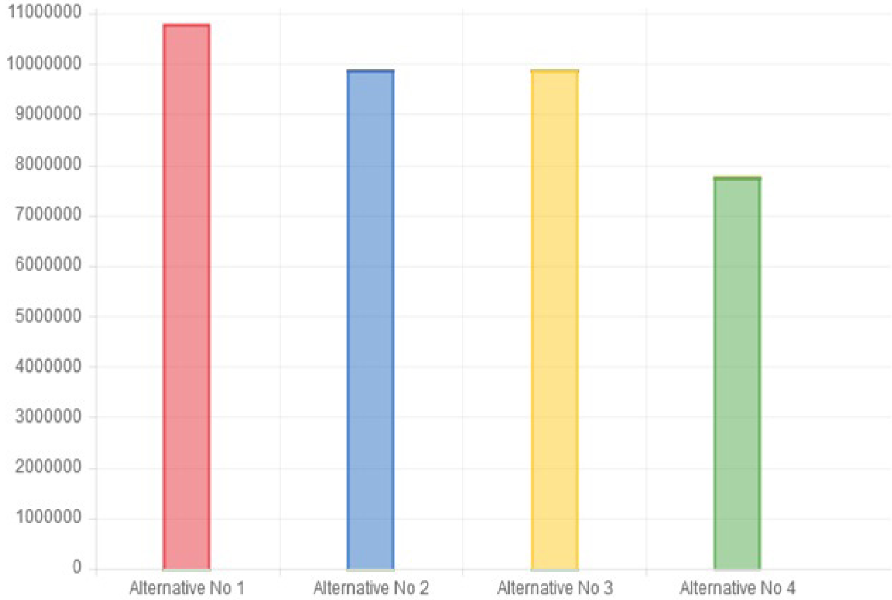

Fig. 10 - Contribution of intermediate impact categories to final damage categories according to ReCiPe Endpoint (%). Where the geographical limits considered include all areas of the enterprise used for rice production in the agricultural and industrial phases (First scenario).

ReCiPe Endpoint. Second scenario.

The results for the final impact categories of the three damage categories proposed by the methodology (ecosystem quality, human health and resources) in the second scenario studied are assessed (in points) in this section.

Figure 11 and 12 shows, as in the intermediate impact categories, a remarkable difference in the results of the final damages categories between Alternative 1 and the three alternatives that valorize rice straw for energy purposes. The damage categories that influence the most these outcomes are the category of damage to human health and the category of damage to ecosystem quality. This corroborates that it is strongly recommended to consider the boundaries depending on the goal of the research, if it is intended to demonstrate all the contributions of renewable energy projects.

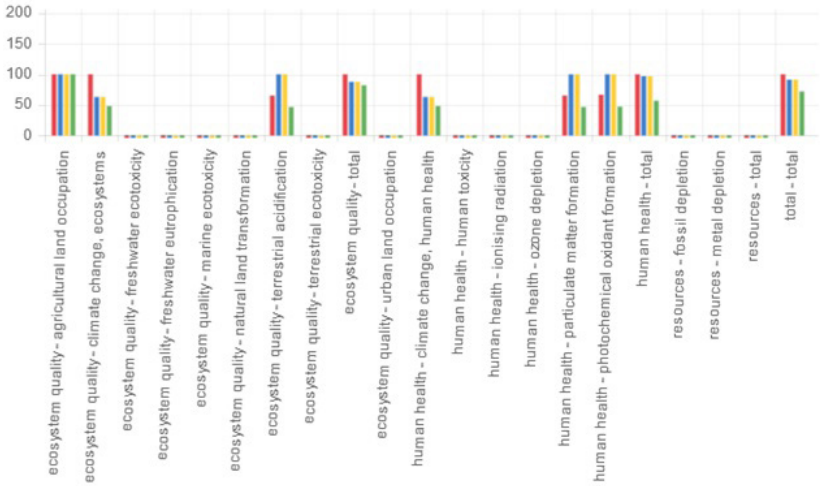

Fig. 11 - Impacts of the final damage categories according to ReCiPe Endpoint (Points). Where it is considered the difference between the CO2 emissions in the rice production system (agricultural and industrial phases) and the emissions avoided by the non-generation of electricity in a thermal plant when valorizing rice straw for energy purposes (Second scenario).

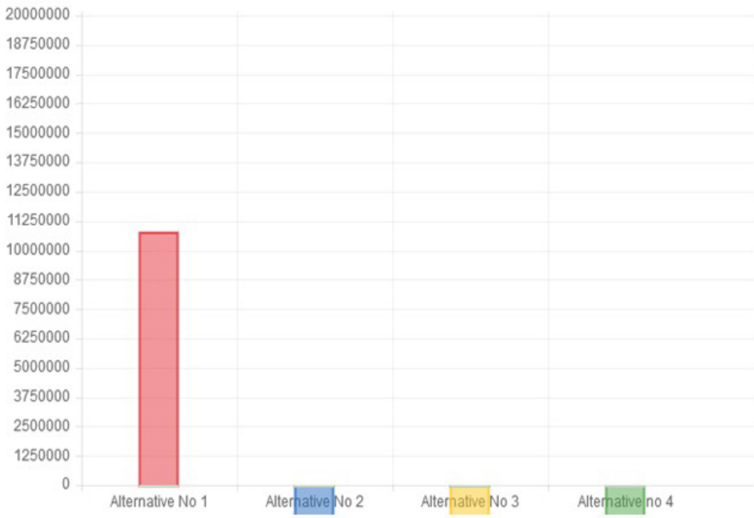

Fig. 12 - Contribution of intermediate impact categories to final damage categories according to ReCiPe Endpoint (%). Where it is considered the difference between the CO2 emissions in the rice production system (agricultural and industrial phases) and the emissions avoided by the non-generation of electricity in a thermal plant when valorizing rice straw for energy purposes (Second scenario).

Ecological footprint. First scenario.

In addition, the ecological footprints of each alternative proposed, considering both scenarios, were studied. The OpenLCA software also provides this outcome. The results showed that within the three aspects assessed by this methodology only the carbon footprints are the ones that mark a difference among the alternatives. The Alternatives 2 and 3 considering the limits of the first scenario presented a carbon footprint greater than Alternative 1 (Figure 13). This corresponds to the results obtained in the methodology ReCiPe Midpoint referring to the category of intermediate impact of climate changes, and could be associated to the increase in diesel consumption for transportation. Alternative 4 is also the most favorable for the valorization of rice straw for energy purposes. This coincides with a study by Xinhua *et al.* (2015) on lignocellulosic biomass.

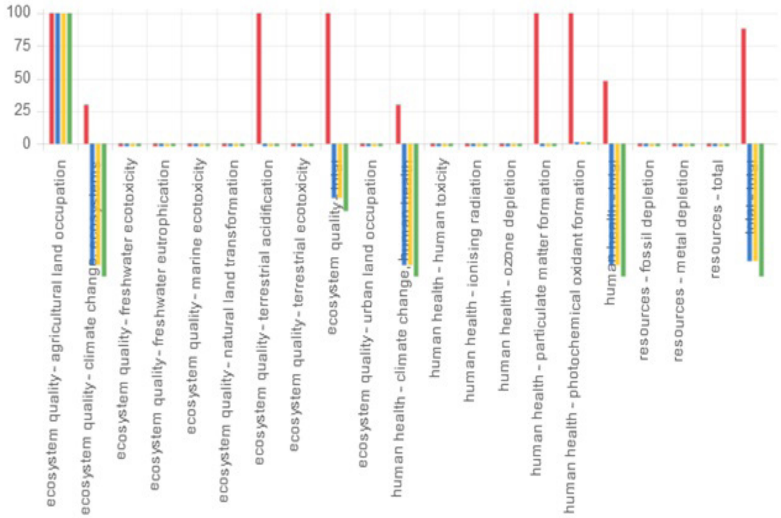

Fig. 13 - Ecological footprint (m2a). Where the geographical limits considered include all areas of the enterprise used for rice production in the agricultural and industrial phases (First scenario).

The results of the ecological footprint of the four alternatives in the second scenario are discussed in this section, where the CO_2 balance resulting from the substitution in the generation of electricity in a thermal plant by a renewable energy source (biogas) is considered. As it can be seen in Figure 14, any of the three alternatives to valorize rice straw for energy purposes has advantages over the alternative currently used in Cuba (1), with Alternative 4 being the most viable. These results corroborate those obtained by the ReCiPe methodology for this scenario, both for intermediate impact categories and for the final damage categories.

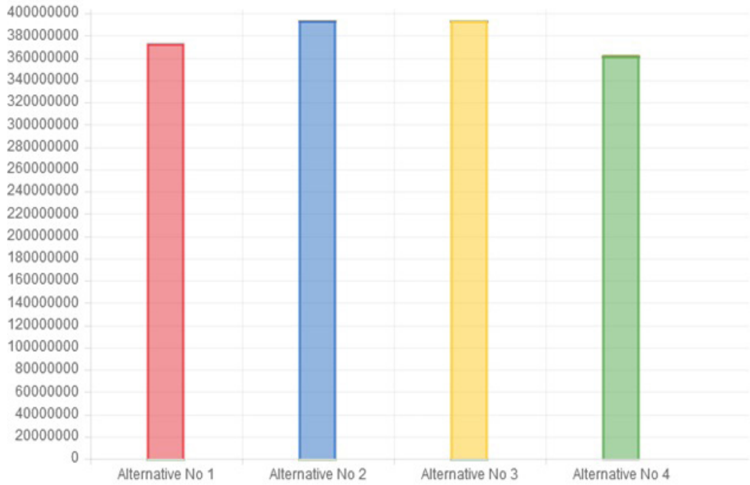

Fig. 14 - Ecological footprint (m2a). Where it is considered the difference between the CO2 emissions in the rice production system (agricultural and industrial phases) and the emissions avoided by the non-generation of electricity in a thermal plant when valorizing rice straw for energy purposes (Second scenario).

Conclusions

This study demonstrated that the three alternatives proposed for the valorization of rice straw for energy purposes in the rice production process in Cuba are not only technologically possible, but also more environmentally sustainable. Among the alternatives assessed, the alternative where part of the biogas generated is used to assume the increment and substitute part of the diesel used in the transportation of the different products in the process (Alternative 4) is the one with the lowest environmental impacts, what makes it the most viable.

The environmental impact assessment tools like Life Cycle Assessment and within it the ReCiPe methodologies and the Ecological Footprint, allowed to evaluate production processes where energy waste is to be valorized. Nevertheless, for this type of analysis in renewable energy projects it is strongly recommended to evaluate the boundaries objectively, for each specific study and depending on the objectives desired.

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