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EVALUATION OF ENVIRONMENTAL IMPACTS OF CHARCOAL PRODUCTION: USE OF WOOD CARBONIZATION BY-PRODUCTS

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Abstract. *Brazil is the world's leading producer of charcoal, mainly used as a source of carbon in the steel and pig iron industry. Despite its vast production, an important amount part of the Brazilian charcoal production is still rudimentary and inefficient, and there is little use of the by-products generated during the wood carbonization. Charcoal is produced through slow pyrolysis, which also produces condensable gases and non-condensable gases. Usually, carbonization gases are released directly into the atmosphere, causing health and environmental impacts, in addition to energy waste, since the non-condensable gas has about 30-50% of the energy contained in the wood. Much progress can still be made in the sector and, seeking to contribute to reducing Greenhouse Gases (GHG) and improving the efficiency of the charcoal production chain, this work presents the benefits arising from the use of wood carbonization by-products, through a Life Cycle Analysis (LCA). Therefore, a Life Cycle Inventory (LCI) was built for a Charcoal Production Unit (CHPU) in Minas Gerais and its forestry unit. The environmental impacts were evaluated by comparing 3 scenarios: i) Current wood carbonization scenario; (ii) Wood carbonization with non-condensable burning gases; iii) Wood carbonization with the recovering of non-condensable gases energy for electricity generation. The results show that throughout the life cycle, the majority of GHG emissions occurs inside the Carbonization Plant, due to the carbonization gases emitted. Within the forestry unit, the emissions with the greatest contribution to the global warming impact were those from burning diesel in forestry operations. The use of nitrogen fertilizers affects other impact categories such as Depletion of the Ozone Layer and Potential for Acidification and Eutrophication. Regarding the Global Warming category of impact (GWP 100a), combustion of carbonization gases is a good option for reducing GHG emissions, however the scenarios considering electricity generation have led to the best result for the category, as the electricity generated and sent to the grid avoids emissions that would be generated in the production of electricity in Brazil.*

Keywords*: LCA, Charcoal production, Combustion of gases, Electricity.*

1. INTRODUCTION

Brazil is the largest charcoal producer in the world, producing about 6.19 million tons in 2019, which represents 12% of the world's charcoal production. Millions of tons of charcoal are consumed per year, mainly as raw material in the steel industry (EPE, 2020; IBÁ, 2020). Brazil is one of the only countries that uses charcoal in the steel and pig iron industries, rather than coal, which makes the production process more sustainable when the emissions balance of the two production routes are compared (Paula, 2014). Therefore, charcoal is very important for the Brazilian economy, especially in the state of Minas Gerais, where the largest consumption and production of charcoal in the country is concentrated (IBÁ, 2020).

Charcoal is produced through a slow pyrolysis process - biomass is subjected to slow heating, reaching temperatures between 400 ºC and 500 °C, in an environment with little or no amount of oxygen. Biomass undergoes a thermal decomposition process and the main product is charcoal. In addition to charcoal, there is also the production of Condensable Gases - CGs (Pyroligneous acid and insoluble tar) and Non-Condensable Gases - NCGs (Carbon dioxide, Carbon Monoxide, Hydrogen and Methane) (Pinheiro *et al*., 2006; Alves, 2003). The quantity and composition of each of the carbonization products depends on some operating variables, such as biomass, heating rate, final temperature and type of kiln (Antal & Grønli, 2003).

Although Brazil is the largest charcoal producer in the world, much of its production is still rudimentary and inefficient, around 70% of charcoal production occurs in low-tech kilns by small and medium producers (CGEE, 2015), and it is very common for the gases produced to be released directly into the atmosphere, causing social and environmental impacts. Furthermore, the eliminated gases have about 30 to 50% of the energy initially contained in the wood, and this energy is wasted when released into the atmosphere in the form of carbonization gases (Leme *et al*., 2018).

The Non-Condensable Gases (NCG) produced during wood carbonization have flammable gases (CH_4, H_2 and CO) in their composition; therefore, they can be burned to mitigate the environmental impacts of their emissions into the atmosphere. However, there is a technical challenge associated with the combustion of the NCGs: the fact the gas composition is highly variable during carbonization process. Especially in the early stages of carbonization, there is a greater presence of water vapor, due to the moisture of biomass, and the amount of combustible gases released is low, making the combustion of gases almost impossible. Over the course of carbonization, with the temperature increase, the amount of water vapor decreases, and the amount of combustible gases increases. Some measures that can be adopted to facilitate the combustion of gases are: to reduce the biomass moisture content, through pre-heating; charcoal kilns can be operated in synchrony, forming a cluster, what ensures less gas composition variation and smooth out the inconstancy of the gases energy content; or, semi-continuous or continuous kilns can be implemented at the Charcoal Production Unit (CHPU) (Vilela *et al*, 2014; Miranda *et al*, 2013). The thermal energy generated in the combustion process can be used for preheating the wood to be carbonized or for electricity generation.

Much development can still be promoted in the charcoal sector, and it is clear that the continuous study and development of new technologies and improvements in current carbonization processes are essential for the environment and forest sustainability, and are also essential for the industry. Therefore, seeking to introduce improvements in a CHPU to reduce Greenhouse Gases (GHG) emissions and to improve the efficiency of the charcoal production chain, this work presents the benefits arising from the use of wood carbonization of by-products, through a Life Cycle Assessment (LCA). This paper proceeds as follows: Section 2 characterizes the Charcoal Production Unit (CHPU) and reviews the LCA theory and methodology used in the analysis; Section 3 presents the results of the Life Cycle Impact Assessment (LCIA) and Section 4 summarizes the main points in the conclusions.

2. THEORY AND METHODS

Life Cycle Assessment (LCA) is carried out based on data retrieved from a Charcoal Production Unit (CHPU) located in the city of Curvelo, Minas Gerais state, which belongs to Plantar Siderúrgica S.A. The CHPU uses the technology of rectangular masonry kilns in its eucalyptus wood carbonization process. These kilns allow the mechanization of the operation and have higher gravimetric yield in charcoal, when compared to the kilns mostly used in Brazil (Hot tail kilns and surface kilns). The CHPU currently has 60 rectangular kilns, with an average monthly charcoal production in 2020 of 6,677.88 cubic meters of charcoal. The carbonization cycle lasts on average 12 days, the carbonization itself requires 4 days, kiln cooling takes about 7 days and 1 day is required for loading/unloading the kiln.

Currently, the gases produced in carbonization are eliminated into the atmosphere, although the CHPU has plans to build a gas burner and plans to use the thermal energy from the gases for electricity generation. CHPU is located within its forestry unit, which has approximately 23 thousand hectares of planted eucalyptus forest. Hybrid clones of eucalyptus species *Eucalyptus Urograndis* are used, and planting is done with a spacing of 3 m x 3 m (9 m²), with an average of 1,110 seedlings planted per hectare.

2.1 Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a methodology that aims to assess the environmental impacts of a product, process or activity throughout its life cycle. LCA can assist in identifying opportunities to improve the environmental aspects of products or services, at various points in their life cycle, and in decision-making and selecting relevant environmental performance indicators, including measurement techniques (ISO, 2006). To perform LCA, it is necessary to define the objective and scope of the study; carry out an inventory of inputs and outputs from a product system; assess the potential environmental impacts associated with these inputs and outputs in order to understand the magnitude and significance of potential environmental impacts and interpret the results to obtain conclusions and recommendations and, thereby, introduce improvements in production processes (ISO, 2006).

2.1.1 System objectives and scope

The objective of this LCA is to evaluate the environmental impacts of charcoal production, through the study of different scenarios, the first evaluates the current carbonization process, with the elimination of all gases generated directly into the atmosphere (Scenario 1); the second assesses the impacts of the combustion of Non-Condensable Gases produced during carbonization (Scenario 2), and the third assesses the use of thermal energy generated in combustion for electricity generation (Scenario 3). Therefore, it will be possible to identify the environmental gains that can be obtained in a Charcoal Producing Unit, by undertaking improvements in its production process.

The function of the studied system is to produce charcoal, using wood from planted eucalyptus forests. The functional unit is one ton of charcoal produced, and the input and output values of the Life Cycle Inventory (LCI) and the results of the Life Cycle Impact Assessment (LCIA) are calculated based on this functional unit. This LCA is a cradle-to-gate system, since the transport of the final product (charcoal) and its consumption are not included, therefore, the impacts will be assessed from the forest production stage up to the production of 1 ton of charcoal. Figure 1 illustrates the system boundaries to be studied.

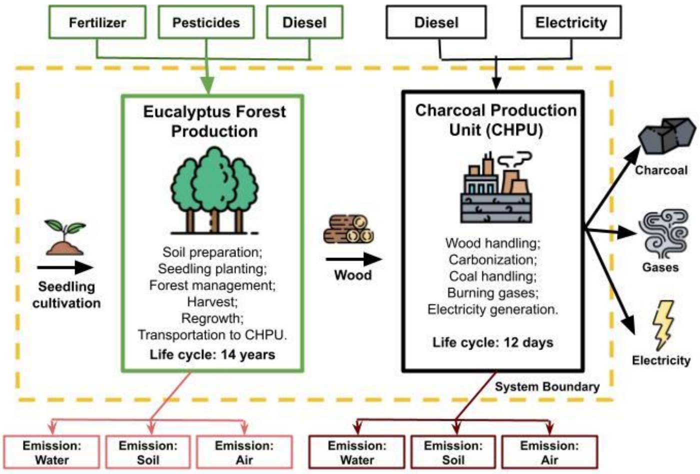

Figure1. System boundary

Life Cycle Assessment (LCA) is performed in SimaPro® software (v. 8.0.3.14). The Life Cycle Impact Assessment methodology adopted for this work is the CML-IA Baseline v.3.01 - Chain Management by Life Cycle Assessment - which is a software tool that is intended to support the technical steps of the life cycle evaluation procedure, whose method emphasizes the problem-oriented approach (mid-point) (CML, 2020). For this work, the impact categories selected for evaluation are presented in Table 1.

Table 1. Impact Categories selected for assessment

Category	Unit	Description
Depletion of Abiotic Resources	kg Sb eq/fossil abiotic depletion in MJ	It represents the decrease in the resources available in the world due to human activity.
Global Warming (GWP 100a)	kg of CO_2 eq	Global climate change over time, bringing consequences to the balance of systems and ecosystems. Occurs due to the increase in GHG concentration in the atmosphere, caused by human activities
Depletion of the Ozone Layer	kg of CFC_{-11} eq	Depletion or reduction of the stratospheric ozone layer, allows an increase in the flow of ultraviolet (UV) radiation, reaching the Earth's atmosphere.
Human toxicity	1.4-dB kg eq	This category is related to the effects that toxic substances can cause on humans.
Photochemical oxidation	kg C_2H_4 eq	Photochemical oxidants are formed as a result of chemical reactions that occur in the atmosphere, involving organic compounds, nitrogen oxides, oxygen and solar radiation, and ozone is an example of this pollutant.
Acidification	kg SO_2 eq	Acidic substances cause a number of impacts on soil, groundwater and surface water, organisms and ecosystems, even on buildings.
Eutrophication	in kg PO_4 eq	It occurs due to excessive levels of macronutrients, such as phosphorus and nitrogen, in the environment, caused by emissions to air, water and soil, and can cause an ecological imbalance of aquatic ecosystems.

This Life Cycle Assessment has some limitations, one of which is the absence of data from the Brazilian production chain of fertilizers and pesticides. Therefore, the production chain present in the Ecoinvent v.3 database is included. Furthermore, other products, marked in Table 2 and Table 3 as "*not found*", are not included in the study, as they are not present in the Ecoinvent v.3 database, and their respective inventories were not found in the literature. Another limiting factor is that, due to the complexity of the composition of Condensable Gases, during data entry into SimaPro®, a small fraction of their components (about 9.9% by mass) were not found in the software database, thus a simplification had to be made and these compounds were included as "*hydrocarbons, non-specified*".

3.1.2 Life Cycle Inventory (LCI)

Eucalyptus Forest Production

Eucalyptus forest production includes seedling production, soil preparation, seedling planting and development, forest maintenance, first harvest in year 7, regrowth management and development, forest maintenance, second harvest in year 14, and wood transportation. All the data were provided by the CHPU.

- **Input data:**

Production of eucalyptus seedlings: The production of seedlings is the first phase of eucalyptus forest production; the seedlings are cultivated by the company itself in its nursery. The input data for the production of 1,000 eucalyptus seedlings are presented in Table 2.

Table 2. Input data: production of 1,000 eucalyptus seedlings

Input data	Quantity	Inventory source
Single Superphosphate (SSP)	0.8 kg	Monteiro (2008)
PG mix (Fertilizer NPK)	0.06 kg	Ecoinvent V.3
Oscomote (NPK)	0.12 kg	Ecoinvent V.3
Calcium Nitrate	5.3 kg	Ecoinvent V.3
Potassium Chloride (KCL)	3.4 kg	Ecoinvent V.3
Purified MAP	1.75 kg	Ecoinvent V.3
Magnesium sulfate	3.1 kg	Ecoinvent V.3
Urea	3 kg	Ribeiro (2009)
Ammonium sulfate	0.5 kg	Ribeiro (2009)
Kellus Iron	0.2 kg	Not found
Manganese sulfate	0.035 kg	Not found
Zinc sulfate	0.01 kg	Not found
Copper sulfate	0.05 kg	Not found
Boric acid	0.035 kg	Ecoinvent V.3
Diesel	0.0916 kg[1]	Diesel production chain obtained in Sugawara (2012) and emissions from diesel burning in Nemecek and Kagi (2007)
Water	540.54 kg[1]	Ecoinvent V.3

[1] data were not provided by the company and was estimated based on Silva (2012)

Production of eucalyptus wood: The first activity that occurs is the soil preparation, prior to the seedlings planting, so that better conditions are provided for its development. The seedlings arrive through tractors to the planting site, the marking of the pits is carried out manually, as well as planting, and approximately 1,110 seedlings per hectare are planted. The failure rate considered in this study is the average index from Plantar’s CHPU at Curvelo of 1.5%; replanting is only performed when the index exceeds 2%. The seedling development phase occurs until, approximately, 180 days after planting, and then the longer lasting stage begins, the forest maintenance, which occurs until year 7. The first harvest occurs in year 7, where approximately 201,06 m³/ha of wood are harvested, in a mechanized way. Harvesting is carried out by a third-party company, so diesel consumption had to be estimated. After cutting, the trees are accumulated on the ground, tree’s tip, branches and leaves are removed and left in the forest ground. The logs are carried to a drying place, and are stacked for natural drying and, later, a truck transports the wood to the CHPU. After the first harvest, eucalyptus trees can sprout again, a maximum of 3 regrowth may occur. The use of the new sprouts of eucalyptus strains is very advantageous, as the planting area is already ready and the seedlings are used. According to Leme (2016) it is expected a decrease in crop productivity of about 10% for the second and 20% for the third crop, compared to the first one at 7 years. In this work, two harvests (14-year cycle) are considered and the activities previously carried out are basically repeated. In year 14, the harvest is performed again and, approximately, 180,96 m³ of wood/ha are harvested.

Other input data for the inventory are carbon dioxide absorption by eucalyptus trees and land occupation. Eucalyptus forests, through photosynthesis, sequester carbon dioxide present in the atmosphere and store it, accumulating carbon in their biomass. The calculation of the amount of carbon dioxide sequestered is based on the methodology adopted by Silva (2012), Reis *et al*. (1994) and on the Forest Absorbing Carbon Dioxide Emission report (1993). Land occupation considers the time and amount of land that is occupied for current use, being prevented from switching to its more natural state (without human action) (Weidema *et al*, 2013). According to Weidema *et al*. (2013), forests with extractive purposes, with less than three species in plantation and with an average age of the settlement <30 years fit into the classification "forest, intensive". For the calculation of land occupation, 1 hectare is divided by the total produced in 14 years and finally multiplied by the years of the cycle. Table 3 gathers all input data for the production of 1 m³ of eucalyptus wood.

Table 3. Input data: production of 1 m³ of eucalyptus wood

Input data	Quantity	Inventory source
Seedlings	0.1509 kg	Authors
MAP	0.00039 kg	Ecoinvent V.3
Single Superphosphate (SSP)	1.047 kg	Monteiro (2008)
Potassium Chloride (KCL)	1.047 kg	Ecoinvent V.3
Touchdown (Glyphosate)	0.0735 l (or 0.0455 kg Glyphosate)	Ecoinvent V.3
Isca Attamex-S (Sulfluramide)	0.22 kg	Ecoinvent V.3
Sulfurgran	0.26 kg	Not found
Actara (Thiamethoxam)	0.00013 kg	Ecoinvent V.3
K-otrine (Deltamethrin)	0.0000014 kg	Added as Pyrethroid-compound, from Ecoinvent v.3
Fordor (Isoxaflutole)	0.00094 kg	Ecoinvent V.3
Missil (Haloxifope-P-methyl)	0.00169 kg	Ecoinvent V.3
Joint Oil	0.01413 l	Not found
Agrosilicio S	8,37 kg	Not found
Boron	0.2617 kg	Not found
Diesel	1,67 kg	Diesel production chain obtained in Sugawara (2012) and emissions from diesel burning in Nemecek and Kagi (2007)
Water	15,26 l	Ecoinvent V.3
Carbon Dioxide	970.81 kg	
Land Occupation, Forest, Intensive	0.0366 ha.year	

- **Output data:**

Fertilizer and pesticide emissions: Nitrogen fertilizers applied in agriculture are not 100% used by plants, only a portion is assimilated, resulting in losses and environmental damage. Leaching, for example, is a common process that occurs when nitrogen that is not absorbed by plants is transported to deeper layers of the soil, in the form of nitrate (NO_{3^-}), reaching groundwater. Other common processes are the transformation of nitrates into nitrous oxide (N_2O), produced in the soil during the nitrogen cycle and the volatilization process, when nitrogen is lost in the form of ammonia (NH_3) into the atmosphere (Vieira, 2017). Therefore, the consumption of nitrogen fertilizers contributes to emissions of N_2O, NH_3 and NO_3-, and their emission rates are based on IPCC (2006) and Nemecek and Schnetzer (2012). There are also emissions, in the form of phosphorus pentoxide, to surface water due to the use of phosphorus-based fertilizers, and for this case, the emission rate suggested by Shigaki (2006) is used. The use of pesticides also results in emissions to the system and, according to Ecoinvent calculation, 100% of the pesticide used remains in the soil. However, a single exception was adopted for emissions resulting from the application of the herbicide Glyphosate, which is considered that 0.28% of the applied amount is sent to water by leaching, and this rate is based on Jabbar *et al*. (2008).

Table 4. Output data: Fertilizers and pesticides emissions

	Emissions into the air		*Emissions into the water*		
Stage	Ammonia (NH_3)	Nitrous oxide (N_2O)	Nitrate (NO_3-)	Phosphorus Pentoxide (P_2O_5)	Glyphosate
Seedling production (1,000 seedlings)	0.240486 kg	2.50865 kg	0.73572 kg	0.122715 kg	-
Eucalyptus forest production (1 m³ of wood)	0.00000376 kg	0.0000047 kg	0.0000141 kg	0.01939 kg	0.0001276 kg

Charcoal Production Unit (CHPU)

This stage includes all activities that occur within the CHPU, from the movement of wood, its carbonization, the movement of charcoal, to the combustion of gases and electricity generation.

- **Input data:**

Charcoal Production Unit (CHPU): Within the CHPU, machinery is needed to transport wood and charcoal, so there is diesel consumption. Carbonization occurs in rectangular kilns and, according to available data, the CHPU's rectangular kiln has an internal useful volume of 45 m³, with a capacity to store approximately 27,436 tons of wood (density 524,24 kg/m³ and 18% humidity). In addition to wood and diesel, there is also electricity consumption, in general lighting and in the CHPU's offices. Table 5 gathers all input data for the production of 1 ton of charcoal.

Table 5. Input data: production of 1 ton of charcoal

Input data	Quantity	Inventory source
Eucalyptus wood	5,635 m³	Authors
Diesel	0.06 kg	Diesel production chain obtained in Sugawara (2012) and emissions from diesel burning in Nemecek and Kagi (2007)
Electricity	1.39 kwh	Ecoinvent V.3

- **Output data:**

Carbonization kilns: The main output of a rectangular kiln is, on average, 9.28 tons of charcoal, with moisture of 7.3% and density (wet base) of 257.96 kg/m³. For each ton of charcoal produced, the carbonization kiln emits 72.19 kg of particulate material, according to Cardoso (2010), who measured the emission of particulate material in a rectangular kiln, based on a brazilian standard (NBR 12019). There is also an output of 60,931 kg of NCGs and 17,186 kg of CGs. Carbonization gases (NCGs and GCs) were measured and characterized through analyses carried out at Plantar's CHPU in 2019. In Scenario 1, all gases produced (CNG + GC) are released into the atmosphere. The composition of NCGs (mass base) is: 60.67% nitrogen, 14.31% oxygen, 17.03% carbon dioxide, 7.06% carbon monoxide, 0.16% hydrogen and 0.77% methane. To produce 1 ton of charcoal, 6,561.2 kg of NCGs and 1,850,63 kg of CGs are eliminated into the atmosphere (Scenario 1) and, with combustion (Scenarios 2 and 3), emissions are reduced. Therefore, Table 6 shows the atmospheric emissions for the 3 scenarios evaluated.

Table 6. Output data: Atmospheric emissions of NCGs, referring to the production of 1 ton of charcoal

Scenario	Nitrogen (N_2)	Oxygen (O_2)	Carbon Dioxide (CO_2)	Carbon Monoxide (CO)	Methane (CH_4)	Hydrogen (H_2)
Scenario 1	3981.3 kg	939.0 kg	1117.0 kg	463.1 kg	50.52 kg	10.3 kg
Scenario 2	398.1 kg	93.9 kg	111.7 kg	46.3 kg	5.05 kg	1.03 kg
Scenario 3	398.1 kg	93.9 kg	111.7 kg	46.3 kg	5.05 kg	1.03 kg

The composition of the GCs is much more complex and can be seen in Table 7. In the 3 scenarios the GCs are being completely emitted into the atmosphere.

Table 7. Output data: Atmospheric emissions of GCs, referring to the production of 1 ton of charcoal

GC composition	Emission	GC composition	Emission	GC composition	Emission
Isobutanol	4.78 kg	2-Butene	1.61 kg	Isobutyric Acid	4.11 kg
Ethyl format	4.16 kg	Furfuril	5.69 kg	Phenol	5.87 kg
4-methylpentanoic acid	1.07 kg	1-4 Butanediol	0.78 kg	Oxalic acid	0.88 kg
O-Cresol	2.76 kg	M-Cresol	4.7 kg	Methoxybenzene	1.77 kg
Sorbic acid	12.87 kg	4-aminophenol	10.94 kg	Vanillin	1.66 kg
Vanilic acid	24.85 kg	Resorcinol	1.22 kg	Hydrocarbons (Not Specified)	170.19 kg
Tar	25.53 kg	Water	1565.08 kg		

Gases combustion: Scenarios 2 and 3 include the combustion of NCGs and, in this process, it is considered that part of the NCGs generated in the carbonization kiln ends up being lost due to leaks in the system. Therefore, it is estimated that 90% of the NCGs are burned and the remainder, i.e., 10% are emitted into the atmosphere (As shown in Table 6). However, it is known that the combustion of carbonization gases releases CO_2, H_2O and N_2 into the atmosphere and, as there is no burner at the CHPU to perform a direct measurement of gases released during combustion, these values were estimated by the reaction balance of the combustion. Table 8 presents the emissions from the combustion process of non-condensable carbonization gases.

Table 8. Output data: Emissions from the combustion of NCGs

Emissions from the combustion of NCGs	Quantity
CO_2	1988.27 kg/t charcoal[a]
N_2	2353.53 kg/t charcoal[a]
Water	402.53 kg/t charcoal[a]
NMVOCs	0.082 kg/t charcoal[b]
NO_X	0.45 kg/t charcoal[b]
Particulates	2,03 kg/t charcoal[c]

[a] calculated by the author, through stoichiometric calculation; [b] based on Barcellos et al. (2004); [c] based on Cardoso (2010).

The stoichiometric calculation considers complete combustion of the carbonization gases, however, the real combustion (incomplete) of fuels emits other pollutants such as Carbon Monoxide (CO), Nitrogen Oxides (NOx), particulates and non-methane volatile organic compounds (NMVOCs), and these pollutants are also calculated, through emission factors obtained in the literature. NO_X and NMVOCs emissions factors are based on Barcellos *et al*. (2004) and particulate emission is based on Cardoso (2010).

Electricity generation: For constant and efficient electricity generation, it is recommended that the Curvelo Unit operates in a clustered system. Therefore, the simulation of the cluster system was made following the methodology proposed by Leme *et al*., (2018), so the thermal power available in the cluster system was obtained. It was determined that the best kiln operation sequence is 29 hours between each kiln's activation, thus the gases will have greater energy potential. The maximum and minimum thermal available power in the cluster system for this Δt is, respectively, 5,486 kWt and 3,382 kWt. To ensure energy security and to guarantee that the power conversion equipment will perform constantly, without interruptions, the minimum thermal power available of 3,382 kWt should be used. To calculate the electricity generation potential, it is considered a prime mover (ex: an Organic Rankine Cycle) with efficiency of 12%. Thus, the equipment's electricity generation capacity is 0.365 MWe and the electricity productivity per ton of charcoal produced is 0.19 MWh/t.

3. RESULTS

In this section, the results of the Life Cycle Impact Assessment for the production of 1 ton of charcoal (Functional Unit) will be presented, through the CML-IA method. Observing Figure 2, when comparing the 3 evaluated scenarios, it is possible to identify that Scenario 3 (in which NCGs combustion and electricity generation occurs) has the best performance in almost all evaluated categories compared to the current scenario (Scenario 1).

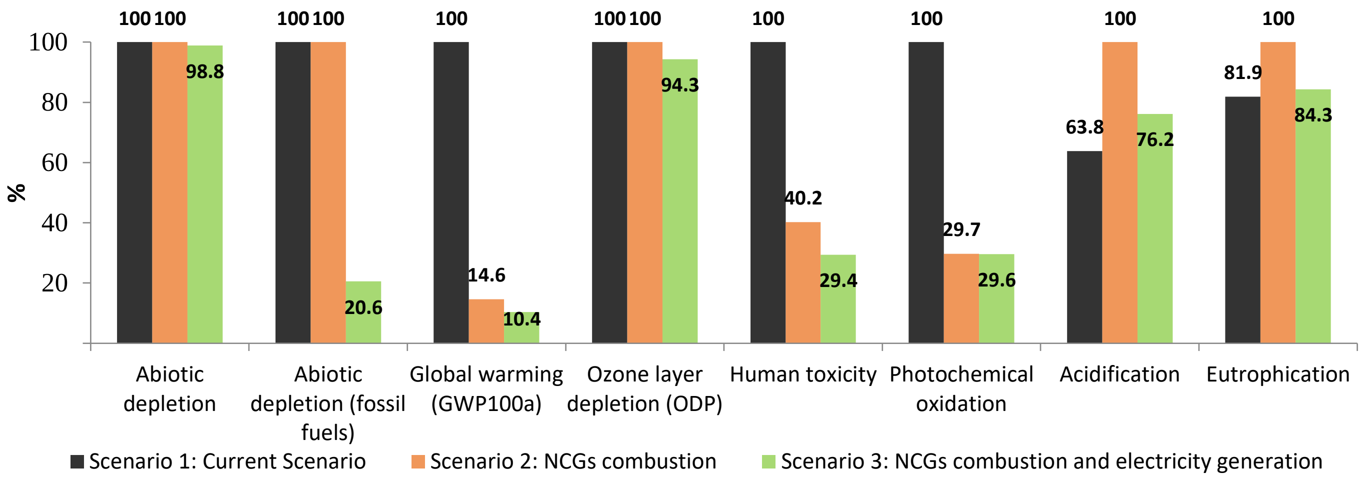

Figure 2. LCIA: General Characterization

Scenario 1 obtained the worst overall performance, with emphasis on the categories of Global Warming (GWP 100a), Human Toxicity and Photochemical Oxidation, due to the emissions of, especially, Methane (CH_4), Carbon Monoxide (CO) and particulate emissions, emitted in the carbonization kilns. NCGs combustion (Scenario 2) is a good option when considering those impacts categories, since the combustion reduces emissions of CH_4, CO and particulates in the atmosphere. However, in terms of Acidification and Eutrophication, the emission of nitrogen oxides contributes to the potential for Acidification and Eutrophication, making NCGs combustion the worst-case scenario.

Regarding the Abiotic Depletion, it is possible to notice that there are no changes between Scenarios 1 and 2, this occurs because most of the extracted resources occur during eucalyptus forest production. Electricity generation (Scenario 3) presents a better result for the Fossil Depletion category, which means that the electricity generated in the CHPU avoids the extraction of fossil resources for electricity generation in Brazil. For the compensation calculation, the approximate contribution of each source to electricity generation in Brazil is considered, which for this case was according to the Ecoinvent database (Ecoinvent v3; 2013). Something similar occurs for the Abiotic Depletion, Ozone Layer Depletion, Global Warming and Human Toxicity categories, in which scenario 3 had the best performance.

In respect of Photochemical Oxidation category, throughout charcoal's life cycle, 16.4 kg of C_2H_4 eq. are emitted (Scenario 1), these emissions occur almost completely within the CHPU, due to the emission of CO. In addition to CO, emission of CH_4 and two other components present in the CGs (Isobutanol and 2-Butene) also affect this category, but with less relevance. The benefits of NCGs combustion are remarkable when observing the reduction of impact between

Scenarios 1 and 2. Since combustion reduces emissions in the Photochemical Oxidation category by more than 70%. Emissions are not fully neutralized because in Scenario 2 and 3 the CGs are still being emitted into the atmosphere.

Regarding the categories Acidification and Eutrophication, most emissions that affects both categories occur within eucalyptus forest production. The main source of emission that causes Acidification is the burning of diesel in agricultural machinery, which emits nitrogen oxides and sulfur dioxide. In respect of the category of Eutrophication, the main source of the emissions is derived from the application of phosphate fertilizers, which emits phosphorus pentoxide for water.

Throughout charcoal's life cycle, the majority of GHG emissions, about 94%, occur due to the gases emitted in the carbonization kilns. When the current scenario of wood carbonization is considered (Scenario 1), 1,180 kg of CO_2 eq. are emitted to produce 1 ton of charcoal (Figure 3).

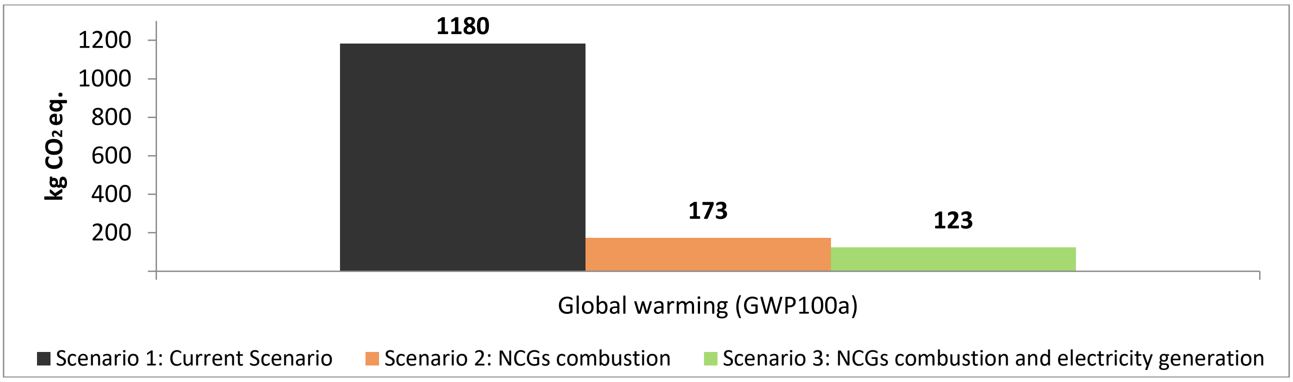

Figure 3. LCIA: Global Warming (GWP 100a), in kg CO2 eq./ton charcoal

Methane (CH_4), a gas with a global warming potential 25 times greater than CO_2, is the main responsible for GHG emissions in Scenario 1. With NCGs combustion in Scenario 2, CH_4 is converted into CO_2, which reduces CO_2 eq. emissions by 85.33%. Scenario 3 has the best environmental performance for the Global Warming category, reducing GHG emissions by 89.57% when compared to Scenario 1, as electricity generation within the CHPU avoids GHG emissions for Brazilian electricity production by approximately 49,9 kg of CO_2 eq. to generate 0.1923 MWh.

Besides the emissions that occur in carbonization kilns, 5,12% of emissions occur within eucalyptus forest production, and the remainder, less than 1%, comes from the consumption of diesel and electricity within the CHPU. Looking at the eucalyptus forest production stage, CO_2 is absorbed by trees through photosynthesis, which decreases the total emissions of charcoal's life cycle. However, CO_2 absorption is not sufficient to neutralize emissions at the stage, totaling 60.5 kg CO_2 eq. As can be seen in Figure 4, the largest share of emissions, 49,13% of them, comes from the burning of diesel in agricultural machinery, which emits CO_2, CH_4 and CO into the atmosphere. Followed by the burning of diesel, the second most GHG emitter is the production chain of the pesticide Sulfluramide, responsible for 22,96% of emissions and, thirdly, the activity of seedling production, responsible for 20.8% of emissions. During the production of seedlings, different types of nitrogen fertilizers are consumed, which emit nitrous oxide (N_2O) into the atmosphere, a gas with a high Global Warming Potential, about 300 times greater than CO_2.

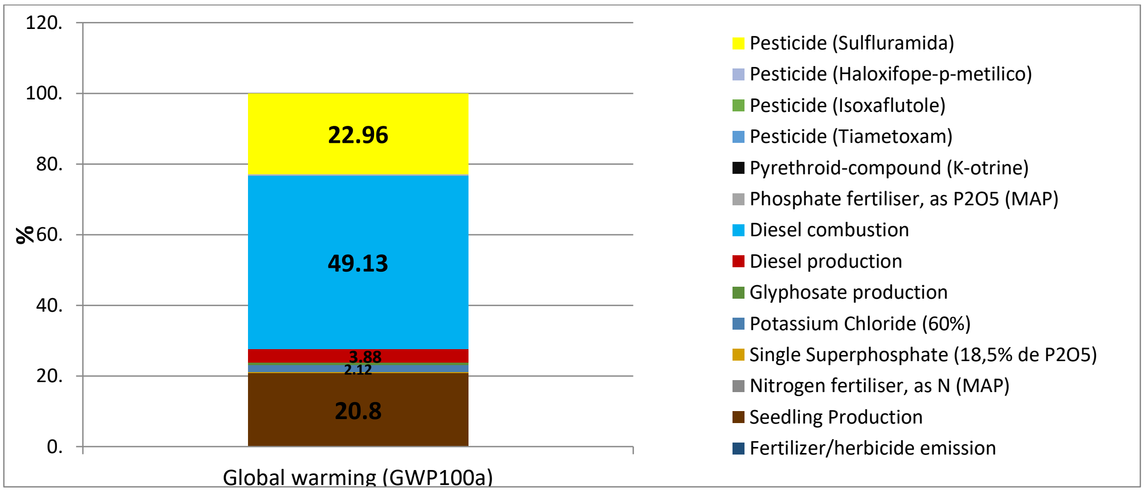

Figure 4. LCIA: Global Warming (GWP 100a), during Eucalyptus Forest Production stage

4. CONCLUSIONS

A significant portion of the wood energy that is carbonized ends up being lost in most Charcoal Production Units, however, this energy can be used through the combustion of carbonization gases and, furthermore, it is possible to generate electricity of, approximately, 0.1923 MWh per ton of charcoal produced, which reduces energy waste and increases the efficiency of the system.

According to the LCIA, the combustion of carbonization gases is a good option to reduce impacts, especially when considering the categories Global Warming (GWP 100a), Human Toxicity and Photochemical Oxidation, because the combustion of CH_4 and CO minimizes these impacts. However, in terms of Acidification and Eutrophication, emissions of nitrogen oxides from NCGs combustion can be harmful. Scenario 3, where electricity is being generated through the use of thermal energy generated in the combustion of NCGs, obtained the best performance in all impact categories evaluated, since the electricity generated within the CHPU indirectly offsets the impacts that would occur during electricity generation to supply Brazilian Interconnected System. Electricity generation reduces GHG emissions by 89.57%, which is the best scenario, from an environmental point of view, for Plantar's Charcoal Production Unit at Curvelo.

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7. RESPONSIBILITY

The authors are the only responsible for the printed material included in this paper.