UNIVERSIDADE FEDERAL DE OURO PRETO
PROGRAMA DE PÓS GRADUAÇÃO EM ENGENHARIA AMBIENTAL

ALTERNATIVES FOR THE ENERGY REUSE OF COFFEE HUSK WASTE: AN LCA-BASED CARBON FOOTPRINT ANALYSIS

Matheus Augusto de Oliveira Fernandes

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Dissertação apresentada ao Programa de Pós Graduação em Engenharia Ambiental da Universidade Federal de Ouro Preto, como parte dos requisitos necessários para obtenção do título de Mestre em Engenharia Ambiental - Área de Concentração: Meio Ambiente.

Orientação: Prof. Dr. Alberto de Freitas Castro Fonseca

Coorientação: Prof. Dr. Bruno Eduardo Lobo Baêta

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Prof. Dr. Alberto de Freitas Castro Fonseca, orientador do trabalho, aprovou a versão final e autorizou seu depósito no Repositório Institucional da UFOP em 06/02/2023

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RESUMO

Como o maior produtor de café do mundo, uma das fontes de energia renovável mais disponíveis no Brasil é a biomassa, mais especificamente, as cascas de café, resíduos sólidos do processamento do café. Entretanto, este recurso ainda é pouco utilizado e não há informações suficientes na literatura sobre seus impactos ambientais. Devido à quantidade deste resíduo, a gestão sustentável de tais resíduos é uma preocupação crescente. As opções para o manejo sustentável das cascas de café incluem a digestão anaeróbica e a geração de energia utilizando os resíduos agrícolas como matéria-prima, e vários estudos têm demonstrado os grandes benefícios potenciais, tais como a redução dos impactos do manejo de resíduos, a diminuição das emissões de gases de efeito estufa (GEE) e a ajuda ao país a alcançar seus objetivos no Acordo de Paris. A Avaliação do Ciclo de Vida (ACV) é uma ferramenta ambiental amplamente utilizada em todo o mundo para avaliar os impactos ambientais nas cadeias de valor. Quando um estudo de ACV quantifica as emissões diretas e indiretas de gases de efeito estufa de um produto, sua pegada de carbono (PC) é calculada. Este trabalho comparou a deposição de cascas de café em solo com dois cenários de geração de energia utilizando a digestão anaeróbica, um deles incluindo um pré-tratamento da hidrólise hidrotérmica das cascas. Os resultados apontam para o fato de que o principal benefício de utilizar a digestão anaeróbica para produzir eletricidade é evitar os impactos da atual rota de gestão das cascas de café, já que os resultados da PC para o aterramento foram mais de 13 vezes superiores do que os outros cenários. As emissões da gestão de lodos de digestão, especialmente a volatilização de N_2O no solo, foi o maior contribuinte para a pegada de carbono, representando mais de 34% dos resultados. Por outro lado, o uso de digestato para substituir fertilizantes químicos afetou positivamente o desempenho ambiental, em termos de impactos evitados. A pegada de carbono do kWh gerado no cenário pré-tratado é 72% menor do que o cenário com as cascas de café cruas, mas ainda é maior do que a pegada da matriz energética brasileira. Quando comparado com outros tipos de energia, a inclusão do pré-tratamento foi um fator determinante para tornar a bioenergia das cascas de café mais interessante do ponto de vista das emissões de GEE, mas as fontes renováveis como eólica e hidráulica ainda têm uma PC menor. Entretanto, em países como Indonésia e Vietnã, onde a matriz é mais fortemente baseada em combustíveis fósseis, as cascas de café, especialmente com pré-tratamento, mostraram potencial para mitigar a pegada de carbono da geração de energia.

Palavras-chave: Cascas de Café, Pegada de Carbono, Gestão de Resíduos, Energia renovável, avaliação de ciclo de vida

ABSTRACT

As the biggest coffee producer in the world, one of the most readily available renewable energy sources in Brazil is biomass, more specifically, coffee husks, the solid waste of coffee processing. However, this resource is still little used and there is not enough information in the literature about its environmental aspects. Due to the amount of this residue, the sustainable management of such residues is a growing concern. Emerging options for sustainable management of coffee husks include the anaerobic digestion and energy generation using agricultural waste as feedstock, and several studies have shown the great potential benefits, such as reducing the impacts of waste management, decreasing greenhouse gas (GHG) emissions and helping the country achieve its goals in the Paris Agreement. Life Cycle Assessment (LCA) is an environmental tool widely used around the world to assess environmental impacts in value chains. When an LCA study quantifies the direct and indirect GHG emissions of a product, its carbon footprint (CF) is calculated. This work compared coffee husk landfilling to two energy generation scenarios using anaerobic digestion, one of them including a hydrothermal hydrolysis pre-treatment of the husks. The results point to the fact that the main benefit of using anaerobic digestion to produce electricity is to avoid the impacts from the current management route of coffee husks, as the CF results for landfilling were over 13 times higher than the other scenarios. The emissions from digestate management, especially N_2O volatilization on the soil, was the biggest contributor to the carbon footprint, with over 34% of results. On the other hand, the use of digestate to replace chemical fertilizers affected the environmental performance positively, in terms of avoided impacts. The carbon footprint of the kWh generated in the pre-treated scenario is 72% lower than the crude coffee husks, but it is still higher than the footprint of the Brazilian grid. When compared to other types of energy, the inclusion of the pre-treatment was a determining factor to render the bioenergy from coffee husks more interesting from a GHG emissions perspective, but renewable sources such as wind and hydro still have a lower CF. However, in countries such as in Indonesia and Vietnam, where the grid is more heavily based on fossil fuels, coffee husks, especially with pre-treatment, showed potential mitigate the carbon footprint of energy generation.

Keywords: Coffee husks, Carbon footprint, Waste Management, Renewable Energy, Life Cycle Assessment

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> ***“Investir em conhecimento sempre rende os melhores juros.”***
>
> – Benjamin Franklin

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1 INTRODUCTION

Coffee is currently the second most important commodity in the world, only after petroleum (J. CERINO-CÓRDOVA *et al.*, 2020), and its production is expected to increase in the following decades due to the rate of population growth and the concentration in urban areas (HOSEINI *et al.*, 2021). Coffee trade becomes even more critical for big producers such as Vietnam, Ethiopia, Colombia and specially Brazil, which is the world biggest coffee producer and trader (INTERNATIONAL COFFEE ORGANIZATION, 2020).

In 2020, more than 175 million 60-kg bags of coffee were produced in the World, and 39% of that came from Brazil (INTERNATIONAL COFFEE ORGANIZATION, 2020). Due to the large production of coffee, Brazil also generates a high amount of residues, especially coffee husks, a solid residue generated from processing, as from every kilogram of coffee produced, the same amount of coffee husk is generated (GOUVEA *et al.*, 2009). A common management strategy for agricultural waste is to be reused in the agriculture itself, for example, as livestock feed (OLIVEIRA, L.; FRANCA, A., 2015), as this type of management can be done locally and usually does not require additional treatment or high monetary investment. Besides livestock feed, other agricultural reuse options for coffee husks include composting, silage production and the application as direct soil coverage (HOSEINI *et al.*, 2021; OLIVEIRA, L.; FRANCA, A., 2015).

The incorporation of coffee husks in the soil can be a serious environmental problem, as they can inhibit plant root growth and increase in GHG emissions due to anaerobic decomposition (FAN, L. *et al.*, 2003; GÓMEZ-SALCEDO *et al.*, 2021; OLIVEIRA, L.; FRANCA, A., 2015; SHEMEKITE *et al.*, 2014). However, they can also decrease soil erosion, temperature, evapotranspiration, help land reclamation and serve as an organic fertilizer without treatment or composting (HOSEINI *et al.*, 2021; OLIVEIRA, L.; FRANCA, A., 2015). In spite of the potential benefits of this management option, the high amount of coffee husks generated in Brazil, that was of 3 billion tons in 2020 (FONSECA *et al.*, 2021; PANDEY, Ashok *et al.*, 2000), would render it impossible for the agricultural field to absorb all of the residue. Therefore, the sustainable management of such residues is a growing concern.

Emerging options for sustainable management of coffee husks include the application of waste-to-energy solutions, and several studies have shown the potential use of this waste as a resource for biofuel generation (ARISTIZÁBAL-MARULANDA; SOLARTE-TORO; CARDONA ALZATE, 2021; FONSECA *et al.*, 2021; PHIMSEN *et al.*, 2016) or biogas generation using anaerobic digestion (BAÊTA, B. E. L. *et al.*, 2017; DU *et al.*, 2021; SANTOS, L. C. Dos *et al.*, 2018). This type of biomass is suitable for anaerobic digestion due to the large share of carbohydrate content, cellulose and hemicellulose, easily fermentable after hydrolysis (ATELGE *et al.*, 2020; FAN, Y. V. *et al.*, 2019; PRASAD *et al.*, 2020). Energy production from biogas is especially promising, as it is expected to represent 25% of all bioenergy in the future (HOLM-NIELSEN; SEADI, AL; OLESKOWICZ-POPIEL, 2009) and biogas generation through anaerobic digestion was shown to be more advantageous than energy produced from biological or thermo-chemical energy conversion_(ATELGE *et al.*, 2020; CHANDRA *et al.*, 2012). The works of Baêta *et al*. (2017), Santos *et al*. (2018) and Du *et al*. (2021) demonstrated the potential for energy generation through the anaerobic digestion of coffee husks, however, there is still a lack of knowledge regarding the environmental impacts associated with this type of technology, as the environmental analysis was not performed in neither work. An environmental impact assessment, which is necessary to assess the sustainability and viability of the technology, is still lacking in the literature.

The energy generation from biogas produced from the anaerobic digestion of coffee husks and other agricultural waste has the potential to positively affect several problematic areas in Brazil. Firstly, the possibility of generating biogas directly from the agricultural areas where the feedstock is produced can reduce the use of fossil fuels and create jobs and income within the vast rural area of Brazil (BLEY JÚNIOR *et al.*, 2009). This would also be in compliance in line with recent efforts in the country, such as RenovaBio, that encourages, among others, the production of biogas and non-centralized electricity production; and the National Energy Plan 2050 (NEP) (BRAZIL; ENERGY RESEARCH COMPANY, 2020) that recognizes the uncertainties in future scenarios of the energy supply and calls for the need to diversify energy sources and render the energy sector more flexible. Secondly, treating agricultural waste as a resource rich in carbon with potential of utilization to produce biofuel would reduce the environmental impacts of waste management, as these have been identified as a significant form of pollution, besides, of course, of reduction of environmental impact caused by the substitution of non-renewable fuels (BILAL; IQBAL, 2020).

In 2019, 40,5% of all solid waste generated in Brazil had an inadequate destination, such as open dumps, which are uncontrolled sources of air, soil, and water pollution (ABRELPE, 2020). The other 59,5% were disposed of in sanitary landfills, which is still a source of environmental impacts due to the generation of leachate and biogas flared or directly emitted to the atmosphere. The use of agricultural waste in energy generation avoids such adverse impacts. Lastly, the generation of energy from a renewable source would help Brazil meet its goals in the Paris Agreement, adopted by nearly all nations of the world, by possibly reducing the greenhouse gas (GHG) emissions of energy generation and agricultural waste management.

To ensure the sustainability of the coffee industry, a holistic approach is essential to solve the problems that persist in the production process and the value chain of this product (GÓMEZ-SALCEDO *et al.*, 2021). One tool that can be used to aid decision-making is Life Cycle Assessment (LCA), that is an environmental management tool that aims to identify and quantify the potential impacts associated with the full life cycle of products or services. By analyzing the inputs and outputs in each stage of the life cycle of a product or service, LCA has become an important methodology for understanding the potential impacts of the value chain of products, which allows decision-makers to choose alternatives considering technical aspects and its environmental performance. When focusing exclusively on the impacts related to greenhouse gas emission and climate change, the Carbon Footprint (CF) is a tool that uses the life cycle perspective to measure the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product (WIEDMANN; MINX, 2007). Currently, CF is synonymous with a comprehensive GHG account over the life cycle stages of any product or activity (PANDEY, D.; AGRAWAL; PANDEY, J. S., 2011)

Over the years, LCA and CF have been applied agricultural biogas plants and allowed scientists to assess the environmental impact related to this technology and highlight the possible mitigation strategies to improve AD sustainability (HUTTUNEN; MANNINEN; LESKINEN, 2014). To the best of the author’s knowledge, only one study, Lin *et al.* (2021), applied LCA to anaerobic digestion of lignocellulosic substrates in Brazil. Even though other studies estimated GHG emissions from electricity generation using lignocellulosic biomass, such as Carvalho *et al*. (2019), Lopes Silva *et al*. (2014) and Portugal-Pereira *et al*. (2015), none of those included an anaerobic digestion stage, so there is still a lack of data in the literature for the environmental assessment of the AD technology. Such studies are crucial to evaluate the viability of AD of coffee husks and other similar feedstock under Brazilian conditions, as the generation of renewable energy is very dependent on local factors (BLANC, I *et al.*, 2008; PADEY *et al.*, 2012).

As for coffee processing residues, it is notable that LCA studies are focused on the valorization of spent coffee grounds (KOOKOS, 2018; RAJESH BANU *et al.*, 2021), a residue of wet coffee bean processing, and coffee cut-stems (ARISTIZÁBAL-MARULANDA; SOLARTE-TORO; CARDONA ALZATE, 2021). No studies were found that present data from a life cycle analysis for biogas production in anaerobic digestion plants that process coffee husks and is worth mentioning that the coffee husk is the type of residue from the coffee processing industry generated in greater quantity, given that most small and medium producers use the dry processing of coffee, due to its lower cost.

Another gap in the literature is the effect of pre-treatment in the overall effectiveness of the process. It is known that the use of pretreatment before the anaerobic degradation step can improve biogas yield and enhance energy generation, as demonstrated by the works of Baêta *et al.* (2017) and Santos *et al.,* (2018) and Passos *et al.* (2018). This topic is also overlooked in the literature, especially hydrothermal pre-treatments, that authors have identified as highly applicable to lignocellulosic waste (FAN, Y. Van *et al.*, 2018; PECORINI *et al.*, 2016) with great potential benefits when coupled with anaerobic digestion and CHP systems (BAÊTA, B. E. L. *et al.*, 2017; SILVA, N. C. S., 2019). However, there is also a lack of analysis of environmental impacts of the application of pre-treatments, which can be critical for the final impacts of a waste treatment technology, regardless of their potential benefits as these technologies can entail high energy or resource demands (MAYER, F.; BHANDARI; GÄTH, 2019; VOSOOGHNIA *et al.*, 2021).

Therefore, three questions guided the construction of this work: 1) what is the environmental profile of the current relationship between the coffee-producing sector and the management of its residues, in terms of GHG emissions?; 2) what possible reductions would the use of AD entail and what is the effect of pre-treatment technologies?; 3) What are the potential environmental impacts of energy generation through AD and how does it compare to the Brazilian energy matrix and other types of energy, fossil and renewable?. This work aims to fill these gaps by calculating the carbon footprint of three coffee husk management scenarios: Scenario 0, that represents the business-as-usual, with the soil incorporation of the husks and its anaerobic decomposition; Scenario 1, with the energy generation through the combination of anaerobic digestion and a combined-heat-and-power (CHP) engine; and Scenario 2, which is the same and Scenario 1, but with and additional step of a hydrothermal hydrolysis pre-treatment of the husks before the AD plant. By using an LCA-based carbon footprint perspective, this work aims to determine the positive impacts of energy generation from anaerobic digestion of coffee husks, and the possible GHG reductions in comparison to the business-as-usual waste management route and the current Brazilian energy supply grid.

2 OBJECTIVES

2.1 Main goal

The goal of this work is to assess the greenhouse gas emissions in the value chain of the management of coffee husks and its possible reuse options.

2.2 Specific goals

- To compare the GHG emissions of emerging solutions of management of coffee husks to the business-as-usual route;
- To assess the carbon footprint of energy generation based on the anaerobic digestion of coffee husks;
- To compare the GHG emissions of the energy produced using coffee husks and how it can contribute to mitigate GHG emissions in the Brazilian energy sector;
- To evaluate the effect in GHG emissions of the introduction of a thermal pre-treatment before the anaerobic digestion;
- To showcase how a carbon footprint study can be an asset to decision-making regarding climate scenarios.

3 BIBLIOGRAPHIC REVIEW

3.1 Life Cycle-based Carbon Footprint of products

Life Cycle Assessment (LCA) is an environmental management tool that aims to identify and quantify the potential impacts associated with products or services. By analyzing the inputs and outputs in each stage of the life cycle of a product or service, LCA has become an important methodology for understanding the potential impacts of the entire life cycle of products, which allows decision-makers to choose alternatives considering technical aspects and its environmental performance.

As a decision-making tool, LCA aims to help consumers choose technologies, products, and processes that are more sustainable and less harmful to the environment. It can identify previously unknown hotspots as well as opportunities for process improvement. Therefore, since its standardization, which began in the late 1990s with the publication of the ISO 14040 (Environmental Management - Life Cycle Assessment - Principles and framework) (ISO, 2006a), LCA has become an essential decision support tool in business, regulations, and policymaking. The tool has also been applied to product/process improvement and design, environmental management, emission footprints auditing, resource management, best technology selection, among others (JHA; SOREN; MEHTA, 2021).

According to the ISO 14.044 (ISO, 2006b), an LCA study is divided into four stages: 1) Goal and Scope definition, where the purposes of the study, as well as the boundary and the functional unit, are defined, which is a measure of the system performance and will be used as the reference to which all inputs and outputs should be related to. 2) Life Cycle Inventory, which consists of listing the unit operations that are comprised in the system boundaries and quantifying the material and energy-related inputs and outputs to each stage, according to the functional unit. LCI is fundamental to a good LCA study since the potential environmental impacts are calculated from the inputs imported into the boundaries and the outputs emitted out of the boundaries; 3) Life Cycle Impact Analysis, where inventory is converted into the potential environmental impacts using specific software and calculation methods. These impacts are usually typified into impact categories, such as Global Warming Potential and Eutrophication, using a reference parameter, and 4) Interpretation, where the results are analyzed and discussed.

As the origins of LCA can be traced to 50 years ago, the focus of the methodology was to create a holistic picture that avoided problem-shifting, that is, when the impact reduction in one category led to an increase in the impacts of another (WEIDEMA, B. P. *et al.*, 2008). This approach required not only a very robust inventory of the studied object, paying attention to the multifunctionality of the inputs and outputs in the product system, but also the calculation and analysis of a wide number of impact categories. Due to its completeness, the LCA results are usually complicated, difficult to communicate, and hard to draw clear conclusions and make decisions from (WEIDEMA, B. P. *et al.*, 2008).

As there was a demand for streamlined LCA results, popular proxy categories such as Global Warming Potential (GWP) and Cumulative Energy Demand (CED) were commonly used by authors to help diffuse the LCA results to a larger audience (BEEMSTERBOER; BAUMANN; WALLBAUM, 2020). The LCA impact of GWP estimates the GHGs emitted/embodied at each identified step of the product's life cycle, accounting for the total GHG emissions of the object of study (PANDEY, D.; AGRAWAL; PANDEY, J. S., 2011). Therefore, although the concept of "carbon footprinting" started to get traction after 2005, it has been in use for several decades, but as the life cycle impact category indicator Global Warming Potential (FINKBEINER, 2009).

As with the GWP impact, the carbon footprint (CF) of a product is the measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product (WIEDMANN; MINX, 2007). Currently, CF is synonymous with a comprehensive GHG account over the life cycle stages of any product or activity (PANDEY, D.; AGRAWAL; PANDEY, J. S., 2011).

Considering that CF addresses the complexity of the full LCA study, since its early stages authors identified that it had the potential to get life cycle approaches into organizations and decision-making contexts which pure LCA had not reached by that point (FINKBEINER, 2009). CF has helped to popularize important concepts of climate change and carbon emission reduction and played an important role in establishing social-environmental awareness and reducing the environmental impact of systems and products (YUE *et al.*, 2020). With growing awareness regarding climate change, the carbon footprint of products and services began to influence customer behavior, drawing attention from the corporate sector, which saw calculating the CF and cutting down emissions as a competitive advantage (KLEINER, 2007; PANDEY, D.; AGRAWAL; PANDEY, J. S., 2011).

LCA/CF became even more important after the Renewable Energy Directive II (RED II), that aims to increase the percentage of energy from renewable sources in the continent, as specified in the Council Directive 2018/2001 of 2018). The RED II defines a series of sustainability and GHG emission criteria and promotes life cycle thinking and the calculation of life cycle greenhouse gas emissions for the bioenergy solutions. Therefore, CF is used by companies and governments as a way to adjust public and corporate policies and technologies, and in some cases are even made mandatory under legislative frameworks (PANDEY, D.; AGRAWAL; PANDEY, J. S., 2011). According to Yue *et al.* (2020), one of the most used keywords in the most recent trend of CF research is “mitigation”, therefore, focused on using CF measurement for decarbonization purposes.

The international LCA standards provide the basic structure for study elaboration, but also allow great flexibility in terms of methodology, which has consequently lead to the development of several LCA software, databases, impact assessment methods, among others. This same flexibility is applied to the calculation of carbon footprints of products. Therefore, several companies, consulting companies, and governments have developed their own GHG accounting methodologies (PANDEY, D.; AGRAWAL; PANDEY, J. S., 2011). Among these methods, the most used and standardized are the LCA-based ones, which account for GHG emissions in all the stages of the value chain of the products (CHAKRABORTY, D., 2021; PANDEY, D.; AGRAWAL; PANDEY, J. S., 2011). Examples of major product carbon footprint methodologies that use an LCA perspective are PAS 2050, developed by the Department for Environment, Food & Rural Affairs (DEFRA) in the UK; the GHG Protocol, developed by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD); and the ISO 14.067, that defines principles, requirements and guidelines for the quantification and reporting of the carbon footprint of a product consistently with the ISO 14040 and ISO 14044.

The number of publications on CF grew more than 20 times in the last decade, but the scientific production on this topic is still largely dominated by China, the USA, Canada, and Europe (YUE *et al.*, 2020). As more and more of the global production and consumption of products take place in emerging countries and developing economies (SONNEMANN *et al.*, 2018), the lack of CF research in those territories constitutes a major challenge for the development of a less carbon-intensive economy envisaged by the Paris Agreement.

In this context, we performed a literature review of carbon footprint publications focused on renewable energy. Given that CF results are usually comprised in an LCA study, we searched for CF or LCA studies on renewable energy, focusing primarily on energy from anaerobic digestion of agricultural waste or lignocellulosic biomass. The goal was to evaluate the available LCA/CF assessments in Brazil.

3.2 LCA-based carbon footprint of renewable energy generation

A wide range of studies has assessed renewable energy generation from a CF perspective, including, but not limited to, wind (CHEN, G. Q.; YANG; ZHAO, Y. H., 2011; JI; CHEN, B., 2016); geothermal (ADIANSYAH; BISWAS; HAQUE, 2021); and various types of biomass combustion (KYLILI; CHRISTOFOROU; FOKAIDES, 2016; MEDEIROS, D. L.; SALES; KIPERSTOK, 2015; SZABO, G. *et al.*, 2014; TONINI; ASTRUP, Thomas, 2012). These studies analyzed different types of technology in different geographic regions, but a few similarities were found among them.

Several authors highlighted that even though some studies analyzed the same type of technology, cross-comparisons are often not feasible because of the different methodological aspects of LCA, such as the system boundaries, the database used, LCIA methods, the functional unit, and the goal of the study in general (BACENETTI *et al.*, 2016; FAN, Y. V. *et al.*, 2019; LOPES SILVA *et al.*, 2014; VOSOOGHNIA *et al.*, 2021; WHITING; AZAPAGIC, 2014). This is easily seen in the literature review performed by Bacenetti et al. (2016), which listed 69 studies on anaerobic digestion, with great variations in terms of functional unit, system boundary, and other important parameters that compose an LCA study. Therefore, even though several authors analyzed the carbon footprint of renewable energy generation, the GHG emissions were expressed in terms of energy generation (HOBSON; RENOUF, 2013; MEDEIROS, D. L.; SALES; KIPERSTOK, 2015; SZABO, G. *et al.*, 2014; WHITING; AZAPAGIC, 2014) mass of feedstock (KYLILI; CHRISTOFOROU; FOKAIDES, 2016; LIN *et al.*, 2021), mass of output (HOBSON; RENOUF, 2013), area (ADIANSYAH; BISWAS; HAQUE, 2021), the mass of digestate generated

(VOSOOGHNIA *et al.*, 2021), among others, making it difficult to create a database with comparable CFs.

Authors also highlighted that the generation of renewable energy is extremely dependent on local factors (BLANC, I *et al.*, 2008; PADEY *et al.*, 2012) and often the results cannot be generalized (GOULART COELHO; LANGE, 2018). This is especially true since the studies pointed out that indirect GHG emissions are the main contributors to the carbon footprint of such energy technologies. In the specific case of biomass, Szabó *et al.* (2014) pointed out that 53% of the carbon footprint of an AD using agricultural waste in Hungary was due to transportation and agricultural machinery usage. Medeiros *et al.* (2015) observed a 50% reduction in the carbon footprint of their microalgae reactor when changing electricity matrixes for a less carbon-intensive one. Hobson and Renouf (2013) also noted that the use of coal to generate steam was a significant contributor to the carbon footprint of a sugarcane-based energy generation plant, and the viability of such technologies was significantly improved when coal was replaced with bagasse. Finnveden *et al.* (2009) showed that land-use change, both direct and indirect aspects, can greatly affect the GWP impacts when taken into account, and Li *et al.* (2021), Lopes Silva *et al.* (2014) and Carvalho *et al.* (2019) showed that crop cultivation was the main contributor to the GHG emissions of biomass energy generation (FINNVEDEN; MOBERG, 2005; LI, J.; XIONG; CHEN, Z., 2021; LOPES SILVA *et al.*, 2014). The work of Vosooghnia *et al.*, (2021) stated that a more environmentally friendly energy mix positively affected the GHG emissions of the AD process analyzed by the authors. Similar conclusions were found by Ji and Chena (2016) and Bacenetti *et al.* (2016) and Charaborty (2021).

Based on the aforementioned studies, two takeaways are noteworthy. The first one is that the incorporation of renewable energy in the matrix has the potential to improve the viability of other types of renewable energy, from a GHG emissions perspective, by decreasing indirect impacts. The carbon footprint of renewable energy technologies will likely decrease if aspects such as transportation and electricity consumption become less carbon-intensive because they are also renewably sourced.

The second one is that renewable energy technologies should be compared within the same geographical and geo-political reality (HANAKI; PORTUGAL-PEREIRA, 2018). Aspects such as biofuel consumption, average distances, average lifespan and performance of vehicles, and the energy matrix, which greatly vary depending on the region, can influence GHG emissions and, therefore, the viability of new energy technologies. In the specific case of Brazil, the electricity supply mix is less carbon-intensive than in other countries, as it is mainly hydropower sourced. Furthermore, local petrol has 27% of bioethanol and, currently, diesel has a 12% share of biodiesel, and is expected to have 15% by 2025 (BRAZIL, 2016). These aspects must be considered when assessing the viability of new renewable energy technologies, as they have the potential to influence indirect GHG emissions. This was observed by authors such as Medeiros *et al.* (2015), who found that the carbon footprint of the microalgae reactor was between 2,02 and 3,14 $kgCO_2e/20MJ$ using the United States energy mix emission factor and 1,25 - 1,81 $kgCO_2e.20MJ^{-1}$ using the Brazilian one.

Local specificities regarding fuel consumption and energy generation can also greatly influence the GHG savings of energy generation. The replacement of power generation from renewable sources would greatly influence GHG emissions of countries with carbon-intensive energy matrixes, such as China and India, where coal-fired stations are dominant (BHAWAN; PURAM, 2018; TAO; WANG; ZHU, 2016). In a country with less intensive electricity generation, such as Brazil, the same technology could lead to less GHG savings, which can affect how viable it is perceived.

These aspects become even more important when the topic is energy generation from biomass. The type and growth yield of crops greatly depends on the climate of a region (HANAKI; PORTUGAL-PEREIRA, 2018). In Brazil, due to the highly developed bioethanol industry, there are already LCA and carbon footprint studies focused on fuel generation from sugarcane (HOBSON; RENOUF, 2013). Even though biomass can be used in several types of technology, anaerobic reactors have been identified as a viable option and can produce biogas, which has a high energy content and take a big range of feedstocks. As one of the biggest agricultural producers in the world (FOOD AND AGRICULTURE ORGANIZATION, 2019), there is a high potential for energy generation from biomass, as already pointed out by the Brazilian National Energy Plan 2050 (BRAZIL; ENERGY RESEARCH COMPANY, 2020).

3.3 Bibliometric Review of LCA/CF waste-to-energy studies in Brazil

Given the importance of local factors to environmental assessments waste-to-energy technologies, a bibliometric review was carried out aiming to identify LCA/CF studies in this topic, analyze the methodological aspects and how they can be incorporated into the carbon footprint calculation of energy generation from coffee husks.

We performed searches on literature search websites, namely Google Academic and Web of Science, with the keywords: "LCA", "waste", “Brazil” and "energy". Only publications in English and Portuguese, available in full text, were considered. After the search, the studies found were sorted, aiming to exclude those that did not deal with energy generation through waste, that did not include the application of Life Cycle Assessment or that presented analyses from outside the Brazilian territory. The results are presented in Table 1.

Only 13 studies were found that applied LCA to energy generation from waste in Brazil, from 2003 to 2021. The small number of studies confirms what has already been observed in reviews conducted by other authors, that research regarding waste-to-energy are concentrated in only a few developed countries and there’s a knowledge gap regarding Brazil.

In terms of spatial analysis, Mayer *et al.* (2019) noted that there is a correlation between the economic prosperity of the country and the number of LCA papers directed towards energy generation from waste. In their work, the authors observed that more industrialized countries, and consequently the larger waste generators, had a higher number of published studies. In the Brazilian context, the observations of Mayer *et al.* (2019) hold true: out of the 13 papers found, 3 papers analyze the city of São Paulo (SP); one paper analyzes the city of Santo André (SP), comprised in the Metropolitan Region of São Paulo (SP); 3 papers analyze the city of Rio de Janeiro (RJ), and 1 paper analyzes the metropolitan region of Belo Horizonte (MG). These cities represent the main urban areas of Brazil, with great socioeconomic importance, and are in the Southeast region in Brazil, which is the region with the highest generation of urban solid waste in the country, in both absolute values and *per capita* (ABRELPE, 2020).

The only works outside the Southeast region of Brazil are Lin *et al.* (2021), that conducts a study according to the reality of the state of Goiás, Carvalho *et al.* (2019), which analyzes the reality of the state of Paraíba and Morais Lima *et al.* (2019), that analyzed present and future scenarios in

Campo Grande, in the state of Mato Grosso do Sul. Given the large socioeconomic, climatic, energy and environmental disparities between Brazilian regions, these results highlight that not only there is a limited number of waste-to-energy LCA studies, but that they are concentrated in one area of the country. Waste-to-energy technologies can greatly benefit the North and Northeast of Brazil, where states like Amazonas, Acre, Roraima, Maranhão, Ceará and Pernambuco rely largely on thermoelectric plants and other fossil sources as their main source of energy generation (ENERGY RESEARCH COMPANY, 2021); and the Midwest region, which concentrates much of the agricultural production of Brazil, and therefore has great potential for biomass production, besides being the region with the second-highest generation of MSW per capita (ABRELPE, 2020).

Reference	Place	Waste Type	Study goal	Waste management technologies analyzed	System boundaries	FU	Software	Database	Impact categories (LCIA method)
(MENDES; ARAMAKI; HANAKI, 2003)	São Paulo (SP)	Municipal Solid Waste	Using LCA to compare different waste management technologies, focused in the biodegradable fraction of the waste from São Paulo (SP)	Composting, anaerobic digestion and landfilling	Gate-to-grave	1 t of waste	*	*	GWP, AP, NE
(MENDES; ARAMAKI; HANAKI, 2004)	São Paulo (SP)	Municipal Solid Waste	Using LCA to compare landfilling and incineration of the residential fraction of the MSW of São Paulo (SP) regarding some environmental parameters	Incineration and landfilling	Gate-to-grave	1 t of waste	*	*	GWP, AP, NE
(LEME *et al.*, 2014)	metropolitan area of Belo Horizonte (MG)	Municipal Solid Waste	Applying LCA to evaluate the environmental impacts and techno-economic aspects of energy recovery from waste management techniques in Belo Horizonte (MG)	Different energy recovery technologies applied to the current landfill facility in Belo Horizonte.	Gate-to-grave	1 t of MSW with Belo Horizonte's characteristics	Simapro 7.1.8	Ecoinvent	GWP, AP, ODP, HT, ACP, ETP (CML 2001)
(LOPES SILVA *et al.*, 2014)	N/A	Agricultural Waste (sugarcane bagasse)	Using LCA to quantify the potential environmental impacts electricity generation from sugarcane bagasse and its opportunities for improvement	The bagasse is burned in a boiler and the thermal energy produced is used for steam generation. A waste treatment stage was not included.	Cradle to grave	Electricity generation surplus of 1 MWh; Electricity transmission and distribution of 1 MWhkm	*	*	EI; RC (EDIP method)
(PORTUGAL-PEREIRA *et al.*, 2015)	Brazil	Agricultural waste (various types)	Used spatial distribution, GIS mapping and Consequential Life Cycle Assessment (LCA) has been conducted to evaluate fossil fuel savings and GHG reductions of substituting fossil-fuel-based electricity by bioelectricity	The waste is directly applied to the power plant after pre-treatment (sundrying, mechanical crunching and conditioning)	Cradle-to-grave	GWhe of generated bioelectricity	SimaPro 8.0.1	Ecoinvent	GWP (IPCC)
(ANGELO *et al.*, 2017)	Rio de Janeiro (RJ)	Domestic Food Waste	Coupling Multi-criteria Decision Analysis with LCA for decision-making in waste management in Rio de Janeiro (RJ)	Landfilling and anaerobic digestion	Gate-to-grave	1 t of mixed household solid waste	EASETECH software	Ecoinvent	GWP; ODP; PM2,5; IO; POF; FEP; MEP; TEP; AP; ECO; DAR; HR-carc; HT-noncarc
(BERNSTAD SARAIVA; SOUZA, R. G.; VALLE, R. A. B., 2017)	Rio de Janeiro (RJ)	Municipal Solid Waste	Applying consequential LCA to study the environmental performances of different waste management technologies in Rio de Janeiro (RJ)	Landfilling and anaerobic digestion	Gate-to-grave	1 t of mixed municipal solid waste in RJ	EASETECH software and SimaPro	Ecoinvent	GWP; ODP; PM; POF; MEP; AP; HT-carc and HT-noncarc

Reference	Place	Waste Type	Study goal	Waste management technologies analyzed	System boundaries	FU	Software	Database	Impact categories (LCIA method)
(GOULART COELHO; LANGE, 2018)	Rio de Janeiro (RJ)	Municipal Solid Waste	Using LCA to perform an environmental assessment of different waste management technologies in Rio de Janeiro (RJ)	Recycling of separately collected recyclables, composting, anaerobic digestion, aerobic and anaerobic mechanical biological treatment (MBT), incineration and landfilling	Gate-to-grave	The annual amount of MSW generated in Rio de Janeiro	*	*	GWP; DAR; AP; FEP; HT; POF (CML 2001)
(LIIKANEN *et al.*, 2018)	São Paulo (SP)	Municipal Solid Waste	Using LCA to assess the environmental impacts of different management alternatives for MSW in São Paulo (SP)	Composting, landfilling, anaerobic digestion, mechanical biological treatment (MBT),	Gate-to-grave	The annual amount of MSW generated in SP in 2015 (3.8 million tons of MSW)	GaBi v7	GaBi database	GWP, AP, EP (CML 2001)
(TRINDADE *et al.*, 2018)	Santo André (SP)	Municipal Solid Waste	Using LCA to perform a comparative environmental analysis of an incineration plant in Santo André (SP)	Incineration plant, with energy recovery for electricity generation;	Gate-to-grave	1 t MSW	SimaPro	Ecoinvent	GWP; C; TAN; RI; AEC; AP; NRE; ME; HH; EQ; R; CED (IMPACT 2002+; CED)
(CARVALHO *et al.*, 2019)	Paraíba state	Agricultural Waste (sugarcane bagasse)	Using LCA perspective to determine the carbon footprint of electricity generation from sugarcane bagasse	The waste is directly applied to the power plant	Cradle-to-grave	1 kWh of electricity (via sugarcane bagasse and then diesel, in thermoelectric power plants)	SimaPro	Ecoinvent	GWP (IPCC)
(MORAIS LIMA *et al.*, 2019)	Campo Grande (MS)	Municipal Solid Waste	Using LCA to assess the environmental performance of different MSW management pathways in Campo Grande (MS) considering future scenarios	Landfilling (with and without energy recovery), mechanical biological treatment (MBT) composting, anaerobic digestion	Gate-to-grave	the management of the total MSW generated in Campo Grande (MS) between 2017 and 2037 on a yearly basis	EASETECH software	Ecoinvent	GWP, ODP, HT-carc, HT-noncarc, PM, POF, TAP, FEP, TEP, MEP, FEW, DAMR
(LIN *et al.*, 2021)	Goiás state	Agricultural Waste (cassava)	LCA study compares a business-as-usual case to understand the trade-offs of environmental impacts in introducing cassava waste treatment in Brazilian rural areas	Anaerobic digestion and landfill	Cradle-to grave	1 kg cassava products (starch/flour)	*	Ecoinvent	GWP, CED, FEP, WD, TAP (ReCiPe, CED)

*not used or not cited in the paper

Table 1: Brazilian LCA studies regarding waste-to-energy technologies

3.3.1 Software and database usage

As also noted by Mayer *et al.* (2019), most studies rely on classic LCA software, such as SimaPro and GaBi. In the review, 5 papers did not specify the software used and among those that did, 4 used SimaPro, 1 used GaBi, and 3 used software specifically developed for waste management, EASETECH. In the latter case, Mayer *et al.* (2019) noted that studies that relied on waste-specific LCA software presented a very limited view on the life cycle inventory used in the analyses.

The high cost and low accessibility to consolidated software for LCA application constitutes a major barrier to LCA application in Brazil, contributing to it being seen as expensive and time-consuming. Although there are free software programs, such as OpenLCA and Brightway, these have not yet reached a consolidated application level, and their use was not observed in the analysed works.

Regarding databases, the Ecoinvent database was used in most of the works. Access to these databases is also a barrier to the application of the methodology in Brazil. In addition, the lack of a national database containing life cycle inventories (LCIs) of Brazilian products limits the scope of the studies, their operationality, and their costs (COELHO FILHO; SACCARO JUNIOR; LUEDEMANN, 2016). Although there are initiatives such as that of the Brazilian Institute of Information in Science and Technology (IBICT), which develops the Life Cycle Inventory for the Environmental Competitiveness of Brazilian Industry (SICV-Brazil), it is still extremely incomplete, lacking, for example, data on waste treatment.

3.3.2 Type of waste analyzed

Out of the 13 studies, 9 applied LCA to waste generation from municipal solid waste. One of the reasons for this could be because Brazil has a very impactful and deficient waste management system, based mainly on sanitary landfills and open dumps, and suffered from a very intense growth in waste generation in recent years (ABRELPE, 2020; BERNSTAD SARAIVA; SOUZA, R. G.; VALLE, R. A. B., 2017; GOULART COELHO; LANGE, 2018). This context pushed for environmental assessments of alternative waste management strategies to evaluate viable alternatives to the current landfills, especially considering the municipal solid waste (MSW) generated in big Brazilian cities, such as São Paulo and Rio de Janeiro.

Regarding other waste types, only 4 studies analyzed agricultural waste. Brazil being the world's biggest producer of sugarcane (FOOD AND AGRICULTURE ORGANIZATION, 2019) and due to the tradition for bioethanol production since ProÁlcool in the 1970s, one of the biggest opportunities for energy generation lies in sugarcane bagasse, one of the solid residues of the sugarcane industry. According to the 2021 National Energy Balance (ENERGY RESEARCH COMPANY, 2021), 75% of the biomass energy generated in Brazil currently comes from sugarcane bagasse, which is a solid residue from the sugarcane industry. However, sugarcane bagasse electricity generation is very little discussed in the LCA literature (LOPES SILVA *et al.*, 2014). From the 23 studies in the review study by Lopes Silva *et al.* (2014), only four analyzed electricity generation from bagasse, and none of those were in Brazil. Despite Brazil's large sugarcane industry and consequently the availability of its by-products, only 2 works regarding energy generation from sugarcane bagasse in Brazil were found in this review: Lopes Silva *et al.* (2014), that performed a case study to address the gap identified in their work; and Carvalho *et al.* (2019) also analyzed the carbon footprint of electricity generation from bagasse in Brazil.

Lin *et al.* (2021) also addressed the lack of studies using agro-industrial waste, performing an LCA study of the energy generation from the anaerobic digestion of cassava waste. Cassava is a very important food crop in the tropics where Brazil is among the biggest global producers (ADEKUNLE; ORSAT; RAGHAVAN, 2016; FOOD AND AGRICULTURE ORGANIZATION, 2019) and cassava peels, one of the residues from cassava cultivation, is one of the lignocellulosic biomasses generated from cassava processing. Since the availability of the peels is tied to that of cassava processing, Brazil would be one of the biggest producers of peels in the world. However, Lin *et al.* (2021) identified that waste from cassava starch/flour production was not considered in the LCA studies reviewed by the authors, especially in Brazil (LIN *et al.*, 2021).

These observations highlight the gap regarding environmental assessments of lignocellulosic wastes arising from harvesting and processing of agricultural by-products that are potentially abundant in Brazil due to its large agricultural production of crops such as rice, cotton, sugarcane, corn and soybeans (PORTUGAL-PEREIRA *et al.*, 2015).

3.3.3 System boundaries

It was observed that all works that analyzed MSW used the gate-to-grave approach, that is, excluding only the generation of waste from the LCA. In contrast, the cultivation stage, which analogous to waste generation, was included in the system boundaries of the papers that analyzed agricultural waste.

The decision to include the cultivation stage when it comes to generating energy from agricultural waste should be seen with parsimony, since this stage can be decisive in deciding on the environmental viability of a scenario. This could be observed in Tonini & Astrup (2021), whose work evaluated different energy generation scenarios in Denmark, and the authors concluded that the need for additional cultivation of energy crops significantly increased the impacts of the scenario where residual biomass was used. Papers such as Li *et al.* (2021), Lopes Silva *et al.* (2014), Szabó *et al.* (2014) and Carvalho *et al.* (2019) also pointed out the cultivation stage as a significant source of impacts in the energy generation process.

However, when the focus of the environmental analysis is the use of the agro-industrial by-products, the inclusion of the cultivation step in the LCA boundaries could lead to an overestimation of the impacts related to this process, as in some cases the choice of a waste management technology is not necessarily a direct consequence of the generation, and therefore should be detached from it. In the energy generation from sugarcane bagasse, for example, the use of this type of waste for energy generation does not create additional demand for sugar cane cultivation, since it is only using a by-product of another process.

The definition of these boundaries would benefit the comparison between different types of waste. The inclusion of the waste generation stage only with lignocellulosic waste, potentially due to the higher traceability of this kind of waste compared to MSW, could increase its impacts, misleading the conclusion that the application of energy generation technologies is associated with higher environmental impacts with agricultural waste as feedstock than when applied to MSW.

3.3.4 Definition of the functional unit

The functional unit (FU) is a reference that aims to represent the operation and characteristics of that system, to ensure that the comparability of the LCA results is done on a common basis (ISO, 2006a) being particularly critical when different systems are evaluated. According to Mayer *et al.*

(2019), functional units in the field of energy generation through waste are divided into input-based FU and output-based FU. The input-based approach comprises a specific amount of waste treated (e.g., 1 kg of waste) or has a temporal and spatial reference (e.g., a certain amount of waste treated in a municipality in a year). As for the output approach, the units refer to the useful by-products of that system, e.g., 1 MJ of energy.

As previously discussed, the functional unit and other methodological aspects can be a barrier in the comparison of LCA/CF results among works. Such barriers are also observed in the analyzed papers, which present 5 FUs among the 13 studies: mass of waste; electricity generated/transmitted; bioelectricity generated; the annual mass of waste and output mass of cassava products.

As observed in Mayer *et al.* (2019), the input-based approach was more frequent, however, it is important to note that the MSW to which the studies refer are distinct in their characteristics, which may affect the comparability of the results between them. As previously discussed, the main goal of some of the works discussed are not energy generation, but alternative waste generation routes, therefore, it is understandable that the focus is on the input. The output-based perspective was used mainly on the works regarding lignocellulosic waste, which should highlight the potential for this type of residue for energy generation.

The choice of UF should be transparent and representative of the product system studied, since the approach used by the study can change the result of the calculations of potential impacts within a comparative LCA (MAYER, F.; BHANDARI; GÄTH, 2019; TAGLIAFERRI *et al.*, 2016). It becomes even more important in works related to the generation of useful byproducts from waste management, as it can create a paradox that will lead to an increase in impacts (TSALIDIS; KOREVAAR, 2020). If one uses an output-based UF (e.g. kWh of electricity generated) in the LCA of a system that uses waste as feedstock and considers the emissions of the business-as-usual scenario as an avoided impact, it can favor a less efficient treatment option, (e.g. one that demands more residue to generate the same amount of energy), because the bigger input of residue would provide higher avoided impacts to the system. Therefore, this choice of UF in this context would suggest improving the efficiency of the system would be detrimental to the study.

3.3.5 LCIA methods and impact categories

Although ISO 14.044 does not specify a minimum or a maximum number of environmental impact categories, the more impact categories are considered in Life Cycle Impact Assessment (LCIA), the more environmental mechanisms are covered and the analysis becomes more holistic (MAYER, F.; BHANDARI; GÄTH, 2019), corresponding to the original intent of an LCA study (WEIDEMA, B. P. *et al.*, 2008). On the other hand, a wide variety of impact categories can create difficulties in communicating and analyzing results (WEIDEMA, B. P. *et al.*, 2008), which first created the demand for streamlined LCA approaches.

Among the papers reviewed, 6 LCIA methods were used: CML, ReCiPe, IMPACT 2002+, CED and IPCC. These assessment methods carry with them impact categories where environmental impacts are typified and quantified, and different systems for valuing certain elements/parameters to the detriment of others, according to the main goal of the specific method. Each one of them aims to determine formulas to convert environmental loads into potential impacts, based on impact factors. This variety of methods among the works consequently leads to the use of many impact categories, as can be seen in Table 2.

The chosen LCIA method has the potential to further hinder the comparability of LCA/CF results. In the categories used in the papers, one can notice similar categories stemming from works that used different LCIA methods, which could potentially be calculated with different methodologies, such as Human Toxicity, Human Toxicity (non-carc), Human Toxicity (carc) and Carcinogens. Concomitantly, most categories were used in just one paper, with Global Warming Potential and Acidification being the most frequent categories.

The method and impact categories should be chosen according to the purpose of the study and to represent as reliably as possible how environmental loads, associated with system inputs or outputs, would cause potential impacts on the studied environment. However, it can be observed that there is no standard on the impacts to be considered for energy generation from waste.

Furthermore, there are no methods developed specifically for the Brazilian context or even for Latin America, unlike what happens in European and North American countries. For that reason, Brazilian LCA studies tend to use methods that estimate impacts on a global level, such as ReCiPe, CML or IMPACT World+, to conclude the potential impacts in their local environment. However, this kind of approach can potentially generate results that are not illustrative of reality, because in countries with a continental extension like Brazil, with a great variety of ecosystems, each one would react differently to environmental loads.

Table 2: Impact categories present in the bibliometric review

Abbreviation	Impact category	Number of papers it was present
MEP	Marine eutrophication	3
FEP	Freshwater eutrophication	4
TEP	Terrestrial eutrophication	2
WD	Water depletion	1
TAP	Terrestrial acidification	2
AP	Acidification Potential	7
TAN	Terrestrial acid/nutri	1
GWP	Global Warming Potential	12
NE	Nutrient Enrichment	2
ODP	Ozone Layer Depletion	3
PM2,5	Particulate Matter (2,5)	1
PM	Particulate Matter	2
IO	Ionizing radiation	1
POF	Photochemical Oxidant Formation	3
ECO	Ecotoxicity	1
FWE	Freshwater Ecotoxicity	1
AEC	Aquatic Ecotoxicity	1
HT	Human toxicity	2
HT-noncarc	Human toxicity (non-cancer)	3
HT- carc	Human toxicity (cancer)	3
C	Carcinogens	1
DAR	Depletion of abiotic resources	1
EI	Environmental impacts (emissions and waste)	1
RC	Resource consumption (renewable, non-renewable and energy)	1
RI	Respiratory Inorganics	1
NRE	Non-renewable energy	1
ME	Mineral Extraction	1
DAMR	Mineral Fossil and Renewable	1
HH	Human health	1
EQ	Ecosystem Quality	1
R	Resources	1
CED	Cumulative Energy Demand	2

3.3.6 Waste treatment technology

As it can be observed in

Table 1 most works analyzed waste treatment technologies before applying the waste to the energy generation system. Overall, the review is comprised of the main waste management technologies used in Brazil, such as landfills; those technologies that even though consolidated, are very marginally applied to MSW, such as incineration; and some more advanced technologies, such as the mechanical biological treatment (MBT). Interestingly, 3 out of the 4 works that concern agricultural waste did not include a treatment stage, calling attention to the potential effects of treatment before energy generation.

3.3.7 LCA and Carbon Footprint Study Profile for Anaerobic Digestion Plants

Anaerobic digestion is the process where organic matter is decomposed in the absence of oxygen, in a reductant environment, producing biogas rich in methane. This process has been extensively studied in the literature, as it is a cheap option for waste treatment since it does not require oxygenation, does not demand too much land, and, most importantly, can have an efficient energy output/input ratio making it a more efficient method for energy generation from biomass compared to other biological and thermo-chemical conversion processes, such as the production of ethanol from cellulose (DEUBLEIN; STEINHAUSER, 2011; ZHENG *et al.*, 2014).

Anaerobic reaction as an energy source has been extensively studied all over the world, but mostly in a few regions. Mayer *et al.* (2019) conducted an extensive literature review of 315 LCA studies of waste-to-energy technologies, in which 45% included anaerobic digestion (MAYER, F.; BHANDARI; GÄTH, 2019). Out of all the 146 AD-related studies, 58% came from Europe, 23% from Asia, and only 6 studies were focused in Brazil which highlights the need for studies in Brazil, given that the country is one of the largest generators of agricultural organic waste in the world; Bacenetti *et al.* (2016) focused their review on anaerobic digestion of agricultural waste and observed that 80% of the studies analyzed plants based in Europe; and Valenti *et al.* (2020) stated that Germany, Italy and China are the countries that have the most studies using anaerobic technology as an alternative (VALENTI; LIAO; PORTO, 2020). It can be noticed that low, middle and upper-middle-income countries, like Latin American ones and Brazil, are still poorly covered in the literature. This highlights the need to carry out more studies with this scope in these locations.

The main problems identified with the application of AD technology is the ability to maintain the stable operation of the digesters for the long term, which hinders the diffusion of anaerobic digestion and the instability in feedstock supply (LI, J.; XIONG; CHEN, Z., 2021) and given the agricultural production of Brazil, the country would have a greater feedstock availability than countries that are more advanced in the application of AD, such as China, Germany, Italy, and Poland (BACENETTI *et al.*, 2016; LI, J.; XIONG; CHEN, Z., 2021; VOSOOGHNIA *et al.*, 2021). However, the environmental assessment of this technology, especially regarding agricultural waste, is still scarce in Brazil. Based on what was observed, it is worth noting that the diversity of waste generated in Brazil can contribute to the implementation of multi-waste processing plants, this would reduce the impacts caused by the lack of raw material for anaerobic digestion plants, contributing to a better process stability.

As described by Bacenetti *et al.* (2016) in their literature review, the AD plants analyzed could be divided into plants designed with the purpose to produce energy or energy carriers and the plants built for the treatment of waste. Even though the authors analyzed only agriculturally-fed plants, these two divisions can be applied here, and given the context of Brazil, works that were analyzed in the bibliometric review would fall into the second category, as they all studied the anaerobic digestion of municipal solid waste as an alternative for waste management (ANGELO *et al.*, 2017; BERNSTAD SARAIVA; SOUZA, R. G.; VALLE, R. A. B., 2017; GOULART COELHO; LANGE, 2018; LIIKANEN *et al.*, 2018; MENDES; ARAMAKI; HANAKI, 2004). The works tended to have a bigger focus on the input waste characteristics and even though they considered the potential for energy generation and the environmental aspects of anaerobic digestion, the focus was not on providing the life cycle carbon emissions or assessing AD as a renewable energy source.

These studies, however, showed the potential AD has to reduce the environmental impacts of waste management. As previously shown, several works assessed the use of AD in municipal solid waste and its consequences, but there is still a gap in the literature concerning the application of AD to lignocellulosic biomass, or agricultural waste, as only one LCA study analyzed this technology for agro-industrial waste. When compared to MSW, agricultural waste has a higher organic content and a high share of its components are easily fermentable in AD reactors, making it a promising substrate for energy generation.

3.4 Carbon footprint of energy generation from anaerobic digestion of coffee husks and other lignocellulosic biomass

Lignocellulosic biomass is the type of biomass composed of three main components: lignin (15–20%), hemicelluloses (25–30%), and cellulose (40–50%) (KUMAR, A.; CHANDRA, 2020). This type of biomass is mainly found in agricultural waste residues or feedstock, agro-industrial wastes, and energy crops (BILAL; IQBAL, 2020). Due to its natural composition, authors have identified that lignocellulosic waste-based agro-industrial biomass is a paramount source of pollution to the environment (BILAL; IQBAL, 2020). According to Portugal-Pereira *et al.* (2015), the crops with the biggest potential to generate residues are straws from soybean, cotton and peanuts. In terms of Brazilian production, it is possible to highlight the sugarcane, coffee, maize and soybeans as the biggest potential to produce waste, and consequently, energy.

Brazil is the world’s biggest producer of coffee (FOOD AND AGRICULTURE ORGANIZATION, 2019) and due to the large production volume, Brazil also generates a considerable amount of coffee husks. As previously explained, there most common management strategies for this residue can cause environmental damages, causing the need for a sustainable solution. The work of Silva (2019) reviewed published studies focused on the alternative use of residues stemming from coffee processing. The main goal of these studies was the use of these wastes as a resource for energy generation, mainly ethanol or biogas using anaerobic digestion. For the latter, this was shown to be a promising alternative in works such as Santos *et al.* (2018), Baêta *et al.* (2017) and Ulsido *et al.* (2016).

In terms of renewable energy generation from lignocellulosic waste in general, studies showed them to have environmental and productivity benefits over the crops utilized in the first-generation biofuel production process, i.e. the biofuel directly generated from food commodities (ADEKUNLE; ORSAT; RAGHAVAN, 2016). For anaerobic digestion, this type of biomass has a large share of carbohydrate content, cellulose and hemicellulose, easily fermentable after hydrolysis, making it suitable for energy generation (FAN, L. *et al.*, 2003; PRASAD *et al.*, 2020; ZHENG *et al.*, 2014). The review made by Prasad *et al.* (2020) and Fan *et al.* (2019) highlighted the high potential for energy generation and GHG reductions from different types of lignocellulosic substrates. Among the technologies assessed by Cherubini *et al.* (2009), the residue biomass showed the most reliable environment-friendly performance as they avoid the environmental impacts from waste management and the impacts from crop production (CHERUBINI; BARGIGLI; ULGIATI, 2009). Whiting & Azapgic (2014) performed an LCA study on generating electricity and heat from biogas produced by anaerobic digestion in the UK and found that the use of biogas reduced the global warming potential impacts by 34% when compared to natural gas and by over 45% when compared to other fossil sources.

At a national level, there are only a small number of studies that touch on the potential for energy generation from this type of biomass, which present important data limitations, as they usually rely on assumptions and national data, and are restricted to specific areas of the country (PORTUGAL-PEREIRA *et al.*, 2015). To that end, Portugal-Pereira *et al.* (2015) used consequential LCA and geospatial tools to analyze the potential for energy generation and GHG savings from lignocellulosic biomass in Brazil. The authors found that the energy generation potential corresponded to 27% of the total generation in 2010 and that it could avoid up to 17.58 million tons of CO_2e emissions by replacing fossil fuel combustion, which amounts to 4,4% of the total GHG emissions of the energy sector in 2010. One of the suggestions from the authors is the distributed generation of energy from biomass across small municipalities, which is a gap that could be filled by anaerobic digestors.

Over the years, the application of LCA to agricultural biogas plants allowed scientists to assess the environmental impact related to this technology and highlight the possible mitigation strategies to improve AD sustainability (HUTTUNEN; MANNINEN; LESKINEN, 2014). As shown in

Table 1, most of the LCA/CF studies regarding anaerobic digestion in Brazil are focused on municipal solid waste, and to the best of the authors' knowledge, only one study, Lin *et al.* (2021), applied LCA to anaerobic digestion of lignocellulosic substrates in Brazil. Even though other studies demonstrated the GHG emissions from electricity generation from lignocellulosic biomass, neither work included an anaerobic digestion stage, so there is still a lack in the literature for the assessment of the AD technology. These are crucial to evaluate the viability of AD of this type of feedstock under Brazilian conditions.

Lin *et al.* (2021) found that, in the business-as-usual scenario, the landfilling of the waste was responsible for 90% of the carbon footprint of the production of 1 kg cassava starch/flour. Through the introduction of anaerobic digestion, there was a 92% reduction of GHG impacts, going from 2,28 kg CO2e/kg (business as usual) to 0,17 kg CO2e/kg (AD scenario). As previously stated, indirect impacts play an important part in the CF, as emissions from organic fertilizers' application represented 30% of the GHG emissions in the AD scenario. This study showed that the potential of GHG-emission contribution for generating electricity from cassava waste is comparable to other feedstocks.

To perform a similar analysis for coffee husks, it is still necessary to evaluate the current relationship between the sector and the management of its residues, the business-as-usual scenario, and the potential environmental impacts of energy generation and its interaction with the Brazilian energy matrix. In that sense, Santos *et al.,* (2018) performed a technical and economic analysis of anaerobic digestion of coffee husks for energy generation through methane and hydrogen. The authors concluded that the experiment was energetically viable in the right conditions (SANTOS *et al.*, 2018).

Similar observations were made by Baêta *et al.* (2017), who evaluated the potential of energy generation using a combined heat and power co-generation system (CHP) from biogas produced during the anaerobic digestion of coffee husks. This work also showed that thermal pretreatment, namely steam explosion, improved the methane yield and was responsible for the scenario with the highest net energy gain, of 0.59 kWh kg CH^{-1} (BAÊTA, B. E. L. *et al.*, 2017). The works of Baêta and Santos showed the potential for energy generation from coffee husks and the potential effects of pre-treatment, but the environmental analysis was not performed in nether work, and therefore an LCA study would be necessary to assess the sustainability and viability of the technology.

As demonstrated, coffee husks and other types of biomass residues would be readily available for energy generation due to the high agricultural production of the country. Several authors have demonstrated how AD could play an important role in improving the viability of this type of process. However, environmental studies focusing on Brazil's local conditions are necessary to fill the existing gap, and studies concerning other different types of biomass are needed to understand if these technologies are applicable in the reality of the country.

3.5 The effect of thermal pre-treatment of lignocellulosic biomass on the CF of energy generation

Among the studies analyzed in the previous section, only Baêta *et al.* (2017), Santos *et al.* (2018) and Portugal-Pereira *et al.* (2015) took into account the effect of the pre-treatment of the biomass for energy generation. Pre-treatment is an important part of the AD process because it can reduce structural and compositional impediments of lignocellulosic biomass and expose the polymer chains of cellulose and hemicellulose to microbial breakdown (ZHENG *et al.*, 2014). Given that lignin is a recalcitrant component that can slow the digestion process down, the pre-treatment increases the availability of cellulose and hemicellulose to increase the rate of biomass degradation and biogas yield (CIRNE *et al.*, 2007; ZHENG *et al.*, 2014). Furthermore, to enhance the hydrolysis of those recalcitrant substrates, pre-treatment is required (VOSOOGHNIA *et al.*, 2021)

There are various technologies of pre-treatment, such as physical (grinding and milling, which aim at increasing the available area), thermal, chemical (alkaline or acidic treatment, chemical oxidation and organic solvents treatment), physicochemical (steam explosion, hot water, wet oxidation, ammonia fiber expansion) or biological (microbially or enzymatically assisted treatment) (VOSOOGHNIA *et al.*, 2021).

In terms of GHG emissions of energy generation from AD systems, to increase biomass degradation and consequently, the biogas yield would also increase the energy generation potential. Lowering the emissions per kWh generated, and, consequently, the carbon footprint, would have positive effects on the sustainability and viability of the process. Due to the complexity and variability of biomass chemical structures, the optimal pretreatment method and conditions depend on the types of lignocellulose present in that substrate (VOSOOGHNIA *et al.*, 2021).

The work of Fan *et al.* (2018) performed a literature review on pre-treatments of different substrates for anaerobic digestion, with a focus on municipal solid waste improving the biogas yield. Even though the authors did not identify a consistent conclusion about the efficiency of thermal pre-treatment in enhancing the biogas production of municipal solid waste, they highlighted that the key aspect of thermal hydrolysis is increasing the availability of cellulose and hemicellulose, which suggests thermal hydrolysis is more promising for treating a richer lignocellulosic substrate than

MSW (FAN, Y. V. *et al.*, 2019; PECORINI *et al.*, 2016). The authors also observed that high energy consumption and carbon footprint are limitations for pre-treatments.

When analyzing lignocellulosic biomass, Zheng *et al.* (2014) reviewed pre-treatment of this type of biomass. Concerning thermal hydrolysis, the review concluded that the studies showed a 7% to 220% increase in methane yield. From a technical and economic standpoint, Fan *et al.* (2019) reviewed studies that highlight the operational cost of applying pre-treatments, but also that it benefitted the system in a variety of ways. This work also performed a cost and environmental analysis of several pre-treatment technologies of lignocellulosic waste. The chemical methods were, overall, associated with higher CF and cost, except for pre-treatment of CaO, which was the optimal cost option. The biological pre-treatments had the lowest CF associated, followed by physical (water vapor, steam explosion, and grinding), which had lower cost as well even though they are not part of the near cost-optimal solutions. The authors highlighted that there is no universal AD solution, and different scenarios require different assessments.

Vosooghnia *et al.* (2021) was one of the few studies that performed an LCA on the application of pretreatment. Regarding LCA studies, Mayer *et al.* (2019) observed that among the WtE LCA studies reviewed, those that presented a life cycle inventory focused on emissions, products and energy demands, but largely neglected ancillary resources such as those necessary for pre-treatments. In their work, Vosooghnia *et al.* (2021) analyzed ultra-sonication post-treatment of agro-industrial residues and suggested that post-treatment did not have a beneficial effect on the GHG emissions due to its high energy demand. The scenarios without post-treatment always involved lower GHG emissions (from - 1.2 to 12.2 kg CO2eq/t digestate) compared to the other two cases (14.1–36.3 kg CO2eq/t digestate). However, the authors concluded that, even though the post-treatment lead to increased biogas production, the use of sonication is still not an environmentally sound option as it had a significant associated carbon footprint even when the 2030 energy mix was considered.

The conclusions of Mayer *et al.* (2019) and Vosooghnia *et al.* (2021) call attention to the lack of analysis of environmental impacts of the application of pre-treatments, which can be critical for the final impacts of a waste treatment technology, regardless of their potential benefits. In the case of the association of thermal pre-treatment with anaerobic digestion, the process can be attractive, as part of the energy needed for the pre-treatment comes from the increase in biogas caused by the addition of the pre-treatment step, this energy comes back in the form of thermal energy.

As for coffee husks, the gains in biogas/methane yield and energy generation due to the association of AD and pretreatment were already stated in the literature. Apart from the previously cited Baêta *et al.* (2017) and Santos *et al.,* (2018), the work of Passos *et al.* (2018) pretreated coffee husk together along with microalgae by steam explosion aiming to increase the anaerobic biodegradability of the biomass. The authors found that the pretreatment of coffee husks at 120°C for 60 min and 180°C for 15 min led to an increase in biogas production of 37% and 23%, respectively. When performing co-digestion with microalgae, a 14% increase in methane yield was observed when the biomass was pretreated at 120°C for 15 min (PASSOS *et al.,* 2018).

Finally, the work of Silva (2019) evaluated the potential use of coffee husks submitted to hydrothermal pretreatments considering the production of second-generation ethanol and biogas. The author observed that the high levels of phenols in this biomass made its biodegradability difficult and the pretreatment was able to improve the biogas production when compared to the raw bark. Even though hydrothermal pretreatment is associated with high energy demands, it was able to improve the biodegradability of coffee husk, but it was observed that the conditions with lower temperatures were those that showed positive thermal energy balance.

An environmental analysis is still needed to evaluate the impacts of the coupling of the two technologies, especially when applied to lignocellulosic waste. As it was discussed, these types of indirect emissions are highly dependent on the location where the study takes place, so a Brazilian carbon footprint study is necessary to tie those results together and add another layer to the discussion.

In this sense, the literature review shows that in fact there are few studies that evaluate the environmental issues for the integration of the technology of thermal pre-treatment of biomass with anaerobic digestion, which justifies the accomplishment of the present study. In addition, it is worth noting that the assessment of environmental issues since the birth of technologies can be important tools for decision-making related to the environmental feasibility of new technologies developed.

4 MATERIALS AND METHODS

The LCA/Carbon Footprint study was carried out following the guidelines of the ISO 14.040 and 14.044 standards, using a process-based attributional approach to assess the climate change potential impact of the investigated process and compare alternative scenarios. Primary data was used regarding the anaerobic digestion process, which includes the characteristics of the coffee husks, the potential for methane generation, the CHP potential for energy generation, and the pretreatment. Secondary data for the LCA study were obtained from the ecoinvent® v3.8 database (WERNET *et al.*, 2016), LCA literature concerning AD plants, and other literature sources concerning GHG emissions from the processes involved. The LCA models for quantification of the impacts were specifically developed in the present study.

4.1 Description of scenarios and system boundaries

As aforementioned the main objective of this study was to assess the climate change impacts of the energy reuse of coffee husk waste, using Brazil as the empirical context. The scope of this study includes the thermal pre-treatment of the biomass, the anaerobic digestion (AD) process, and energy generation in a combined heat and power (CHP) process, the management of the digestate and the end of life of the lubricating oil used in the CHP system. The coffee cultivation stage was not included, as it is considered to take place regardless of the waste management scenario.

This study used two functional units: one input-based, t of coffee husks; and another output-based, the generation of 1kWh of net energy from coffee husks. The study considers two operational scenarios: 1) energy generation with, and 2) without hydrothermal hydrolysis pre-treatment of biomass. A scenario with pre-treatment preceding anaerobic digestion was included as it can increase the rate of biomass degradation and biogas yield, being potentially more advantageous to the carbon footprint of energy generation (ATELGE *et al.*, 2020; BAÊTA, B. E. L. *et al.*, 2017). Thermal pre-treatment was chosen due to its important potential gains, technical feasibility, and applicability to lignocellulosic substrates (PODDAR *et al.*, 2022) especially coffee husks, as studies have shown an increase in methane production with the application of this technology (BAÊTA, B. E. L. *et al.*, 2017; PASSOS *et al.*, 2018; SILVA, N. C. S., 2019).

The process flows were defined through literature reviews and the authors' prior knowledge of the industry and the logistics of coffee husks' management. Regarding transportation, this stage was modeled to represent the reality of coffee husks, whose logistics are influenced by coffee cooperatives, particularly in the south of Minas Gerais state. The study's production system can be seen in Figure 1.

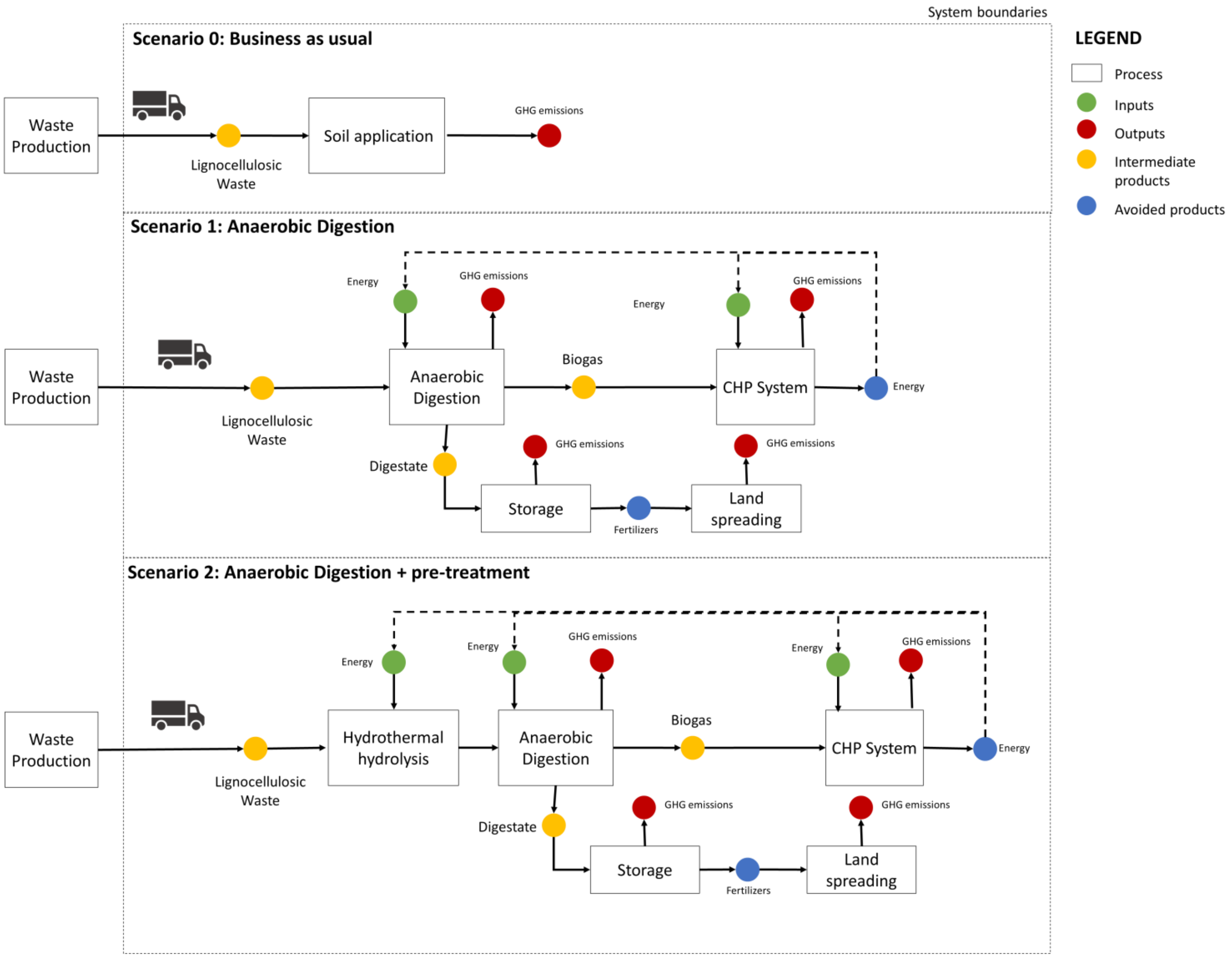


Figure 1: System boundaries and scenarios evaluated in the stud

4.2 Life Cycle Inventory Modelling

4.2.1 Background information and laboratory analyses

Most of the data used in this study were based on laboratory analyses (SILVA, N. C. S., 2019). One of the authors performed analyses on coffee husks obtained in the southwestern region of the state of Minas Gerais, Brazil, which is responsible for 60% of Brazil's coffee production. The husks belonged to the 2015/2016 harvest.

The author analyzed the anaerobic digestion and energy generation using a CHP engine with and without hydrothermal hydrolysis pre-treatment of coffee husk. The pre-treatment experiments were performed under different conditions to evaluate the energy efficiency of the process. According to the authors, this type of pre-treatment presented better results in terms of biogas yield than oxidative treatment (SANTOS, L. C. Dos *et al.*, 2018), but led to worse results than steam explosion (BAÊTA, B. E. L. *et al.*, 2017; PASSOS *et al.*, 2018).

The data used in this work correspond to the pre-treatment performed under 120°C, for 90 min and the solid-liquid ratio of 5 ml/g. The AD analyses were performed using a controlled mesophilic temperature of 35ºC and no energy demand for the AD was assumed, as the reactor was able to maintain optimal temperature without the use of outside heating. After the AD, the generated biogas was collected and burned in a CHP engine with 85% efficiency, 65% being thermal energy and 35% electricity(BAÊTA, B. E. L. *et al.*, 2017) . The calorific value used for methane was 34,5 MJ.$(Nm^3CH_4)^{-1}$.

Methane leaks in anaerobic digesters can vary significantly among plants, reaching up to 7% of the total biogas produced (EVANGELISTI, Sara *et al.*, 2014; MØLLER; BOLDRIN; CHRISTENSEN, T. H., 2009; PATTERSON *et al.*, 2011). A loss rate of 3% was assumed in this study, which is in line with recent scientific studies (FUSI *et al.*, 2016; LIN *et al.*, 2021; TAUBER *et al.*, 2019). Any heat demands for the AD could be supplied by the CHP with no additional use of fuels. In Scenario 2, the heat produced by the CHP was sufficient to supply the energy demands of the pre-treatment, generating a positive energy balance. In both scenarios, the heat surplus was considered as a loss. Other than the energy demands, there were no impacts associated with the pre-treatment. All the demands and productions for both scenarios are presented in Table 3.

Table 3: Energy demand and production from Scenarios 0, 1 and 2.

Scenario	Hydrothermal pre-treatment energy demand	Methane Production	Electricity production	Thermal energy production
	MJ.t^{-1} CH	Nm^3.t^{-1} CH	kWh.t^{-1} CH	MJ.t^{-1} CH
Business as usual (Scenario 0)	0	0	0	0
Crude coffee husk (Scenario 1)	0	8,78	24,31	162,63
Pre-treated coffee husk (Scenario 2)	420	36,20	100,21	669,99

4.2.2 CHP emissions

The CHP was assumed to consume 4,5% of its energy production for functioning (LIN *et al.*, 2021; MOHAMMADI *et al.*, 2019a). The emissions from burning biogas were obtained from literature data, based on a CHP gas engine operating with 86% efficiency, similar to the one used in this study (EVANGELISTI, Sara *et al.*, 2014; FRUERGAARD; ASTRUP, T, 2011). The main GHG emission at this stage is the unburned CH_4, of 0,465 g.MJ^{-1} of biogas, assuming 63% methane content. The emissions related to the construction of the CHP and the AD reactor were not included in this study, as these have been found to be irrelevant (FUSI *et al.*, 2016).

4.2.3 Electricity production

The total electricity produced by Scenarios 1 and 2 were calculated by Silva (2019) (SILVA, N. C. S., 2019). The electricity available was assumed to be used locally, to avoid the usage of electricity supplied by the national energy grid. The surplus electricity was considered as an avoided product and was accounted as credits for the system.

The life cycle emission factor for Brazilian energy was modeled using the process present in Ecoinvent 3.8 (WERNET *et al.*, 2016). The process was adapted using data from the Brazilian 2020 national energy balance and statistical yearbook (EPE - EMPRESA DE PLANEJAMENTO ENERGÉTICO, 2020a, 2020b), using the characteristics of the national grid as it was in 2019, and to account for transformation and distribution losses. The final value was 0,2466 kgCO_2e.kWh^{-1}.

4.2.4 Digestate generation and storage

The mass of digestate of the anaerobic digester was obtained through mass balances. Digestate storage emissions were calculated based on the default scenario presented in Styles et al. (2018) (STYLES *et al.*, 2018). The authors estimated the CH_4 emissions from the storage of food waste liquid digestate in an open tank for a period of 3 to 6 months, which are 0,31 kg $CH_4.m^{-3}$ of digestate. N_2O emissions in this stage were considered negligible.

The digestate storage was assumed to take place in open tanks exposed to air (FANTIN *et al.*, 2015; FUSI *et al.*, 2016; REHL; LANSCHE; MÜLLER, 2012). The final CH_4 emissions for digestate storage accounted for 10,94 kg CH_4. MWh^{-1}, which is comparable to the value reported by Fusi *et al*. (2016) (FUSI *et al.*, 2016) , of 8,9 kg CH_4. MWh^{-1}. As for Scenario 2, they were 2,23 kg CH_4. MWh^{-1}, which is explained by the higher electricity generation in this scenario due to the inclusion of the pre-treatment of CH.

4.2.5 Digestate soil application

After the storage period, the digestate is usually applied to the soil to replace the usage of chemical fertilizers. The avoided fertilizers are also accounted as credits to the system and reported separately.

Diesel consumption for spreading was 0,5 kg of $diesel.m^{-3}$ of digestate, considering the use of a trailing hose (STYLES *et al.*, 2018). The diesel commercialized in Brazil has an average of 11% biodiesel, so the production and usage of diesel in the machines were considered. Ecoinvent 3.8 was used to determinate the upstream emissions and the GHG Protocol Brazilian Program (2022) tool was used to determine the emissions of the stationary combustion of diesel.

From soil application, a part of the nitrogen of coffee husks was assumed to be volatized in terms of N_2O. The nitrogen content of 0,6%, was assumed (VÉLEZ *et al.*, 2009)and 1% of all nitrogen applied to the soil was considered to be converted into N_2O (IPCC, 2006; STYLES *et al.*, 2018). For both scenarios, the same amount of nitrogen was applied to the soil, as no losses of nitrogen were assumed to take place in the previous stages.

4.2.6 Biofertilizer

The mass of nitrogen applied to the soil by digestate was assumed to avoid the usage of nitrified fertilizers. Ecoinvent 3.8 was used to estimate the positive impacts of avoiding fertilizers. The credits are 5,8193 kgCO_2e. kg^{-1} of N avoided (WERNET *et al.*, 2016). As a conservative assumption, the digestate was assumed to substitute only 70% of the fertilizer’s use.

4.2.7 Transport emissions

The transport between the agricultural properties where the waste is produced, and the energy generation plant was assumed to be 100 km. For Scenario 0, a 20 km distance was assumed from the property to the landfilling site. The GHG emissions were based on Ecoinvent 3.8.

In order to minimize production costs, each process of the energy generation plant is designed as close as possible from raw material source, and thus transport between different production stages are unnecessary;

4.2.8 Coffee Husk Landfilling

The land spread of the coffee husks was used to represent the business-as-usual scenario of the management of this residue. The main goals of this management technique are to improve soil physical properties and soil organic carbon through the decomposition of the residue. In this work, the husks are considered to be buried in the top layer of the soil, as the literature showed this to reduce erosion and soil runoff when compared to superficial application (MORENO-RAMÓN; QUIZEMBE; IBÁÑEZ-ASENSIO, 2014).

As previously mentioned, to the best of the authors' knowledge, an impact assessment of coffee husks management in terms of GHG emissions is still not available in the scientific literature. Therefore, the IPCC (2006) (IPCC, 2006) model for solid waste management was used to estimate the GHG emission of the degradation of coffee husks while buried in the soil. As this is an approximation, emissions from supporting activities, such as the machine fuel usage to collect and apply the waste to the soil are not included due to the lack of data and its high variability among properties. Therefore, the results a real-life setting are expected to be higher than the ones showcased here.

This model estimated CH_4 emissions from anaerobic decomposition of the biomass in the soil. The CO_2 emissions caused by organic waste in landfills are excluded in this study as they are considered as biogenic carbon content, which is a part of the natural atmospheric cycle, hence they add no additional impact on GHG concentrations in the atmosphere. The coffee husk was considered to be food waste and default values present on IPCC (2006) were used. The was applied to an unmanaged shallow grave (<5m). The "unmanaged" means it does not fit the criteria for a managed site (cover material; mechanical compacting; or leveling of the waste).

The results are 0,025 kg CH_4. kg of waste^{-1}. Using the IPCC 2013 global warming potential values, the final result for this scenario is 0,71 kgCO_2e. kg of waste^{-1}.

5 RESULTS AND DISCUSSION

The complete life cycle inventory of the three scenarios used in this study is presented in Table 4.

Table 4: Life Cycle Inventory of Scenarios 0, 1 and 2, per t of coffee husks.

			Value			
Life Cycle Stage	Input/Output	Unit	Scenario 0	Scenario 1	Scenario 2	Source
Landfilling	CH_4 emissions (unburned)	kg	2,52E+01	0,00E+00	0,00E+00	(IPCC, 2006)
Transport between waste production and treatment site	CO_2e (diesel burn)	kg	2,39E+00	1,19E+01	1,19E+01	(GHG PROTOCOL BRAZILIAN PROGRAM, 2022; WERNET *et al.*, 2016)
Pre-treatment	Thermal Energy demand	MJ	0,00E+00	0,00E+00	4,20E+02	(SILVA, N. C. S., 2019)
Anaerobic Digestion	CH_4 emissions (losses)	m^3	0,00E+00	1,41E-01	5,80E-01	Estimated Mass Balance
	Digestate generation	kg	0,00E+00	9,84E+02	8,25E+02	
CHP	CH_4 emissions (unburned)	kg	0,00E+00	1,16E-01	4,79E-01	(EVANGELISTI, Sara *et al.*, 2014; FRUERGAARD;

						ASTRUP, T, 2011)
	Total electricity generated	kWh	0,00E+00	2,32E+01	9,57E+01	(LIN *et al.*, 2021; MOHAMMADI *et al.*, 2019b; SILVA, N. C. S., 2019)
	Total thermal energy generated	MJ	0,00E+00	1,55E+02	6,40E+02	(SILVA, N. C. S., 2019)
	Avoided CO_2e emissions (electricity Brazilian grid)	kWh	0,00E+00	-5,73E+00	-2,36E+01	(SILVA, N. C. S., 2019; WERNET *et al.*, 2016)
Digestate Storage	CH_4 emissions	kg	0,00E+00	2,54E-01	2,13E-01	(STYLES *et al.*, 2018)
Digestate soil application	CO_2e emissions (diesel production)	kg	0,00E+00	1,43E-01	1,20E-01	(WERNET *et al.*, 2016)
	CO_2 emissions (diesel burn)	kg	0,00E+00	1,12E+00	9,39E-01	(GHG PROTOCOL

						BRAZILIAN PROGRAM, 2022)
	CH_4 emissions (diesel burn)	kg	0,00E+00	7,79E-05	6,53E-05	(GHG PROTOCOL BRAZILIAN PROGRAM, 2022)
	N_2O emissions (diesel burn)	kg	0,00E+00	6,07E-05	5,09E-05	(GHG PROTOCOL BRAZILIAN PROGRAM, 2022)
	N_2O emissions (volatilization)	kg	0,00E+00	9,43E-02	9,43E-02	(IPCC, 2006; STYLES *et al.*, 2018; VÉLEZ *et al.*, 2009)
	Avoided CO_2e emissions (fertilizer)	kg	0,00E+00	-2,51E+01	-2,51E+01	(WERNET *et al.*, 2016)

5.1 Results per ton of coffee husks

The results of the carbon footprint of the management of 1 ton of coffee husks, including absolute emissions and avoided emissions (credits) can be found in Table 5. The graphic representation including the different life cycle stages can be found in Figure 2.

Table 5: Greenhouse gas emissions from Scenarios 0, 1 and 2 (kgCO2e.t^{-1} coffee husks)

	Scenario 0		Scenario 1		Scenario 2	
	kgCO2e.t^{-1} coffee husks	% of absolute emissions	kgCO2e.t^{-1} coffee husks	% of absolute emissions	kgCO2e.t^{-1} coffee husks	% of absolute emissions
Absolute emissions	707.77	100%	52.52	100%	73.62	100%
Landfilling	705.60	100%	0	0%	0	0%
Transport	2.39	0%	11.94	23%	11.94	16%
Anaerobic Digestion	0	0%	3.94	8%	16.24	22%
CHP	0	0%	3.26	6%	13.42	18%
Digestate Storage	0	0%	5.96	14%	5.96	8%
Diesel usage for digestate soil application	0	0%	1.28	2%	1.07	1%
Volatilization on the soil	0	0%	24.99	48%	24.99	34%
Avoided emissions from Chemical Fertilizer	0	-	-24.44	-	-24.44	-
Avoided emissions from Electricity (Brazilian Mix)	0	-	-5.73	-	-23.61	-
Total net emissions	707.77	-	22.35	-	25.57	-

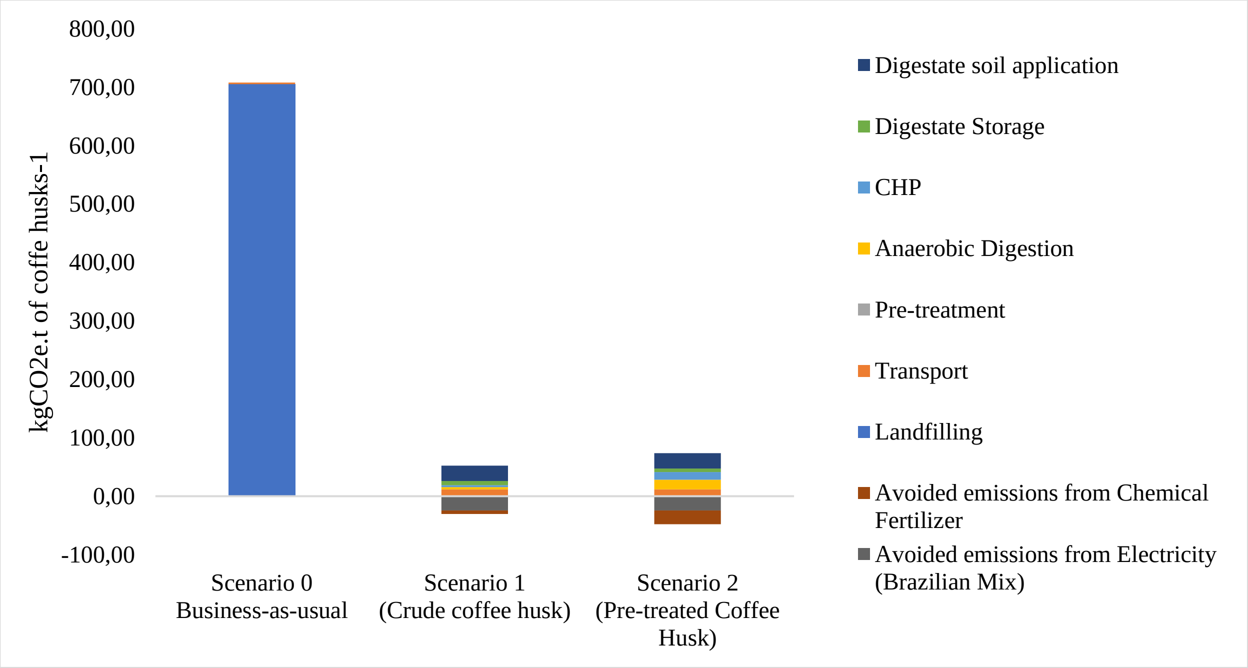


Figure 2: Carbon footprint results for Scenarios 0, 1 and 2, per ton of coffee husks

When comparing scenarios, it can be noted that the business as usual (Scenario 0), which correspond to the landfilling of coffee husks, has the worst results, with a CF of 707.99 $kgCO_2e.t^{-1}$ of coffee husks, which is 13 and 10 times higher than the absolute emissions for Scenarios 1 and 2, respectively. This is in line with the results of Lin et al. (2021), which had the landfilling scenario with results over 13 times bigger when compared to the scenario with energy generation (LIN *et al.*, 2021). Most importantly, the results corroborate the hypothesis that landfilling coffee husks is not only a waste of energy and resources, but it is also environmentally damaging from a GHG standpoint.

When comparing Scenario 1, with crude coffee husks, and Scenario 2, with pre-treated coffee husk, it can be observed that the total and absolute emissions for Scenario 2 are higher than Scenario 1, which suggests that the use of pre-treatment could worsen the performance of the AD system. This, however, is not due to the energy demand of the pre-treatment, as observed by authors who analyzed other pre-treatment technologies (VOSOOGHNIA *et al.*, 2021), but due to the way of considering biogas leakages, as percentage of biogas production.

While many studies have shown leakage emission factors in terms of biogas production (FUSI *et al.*, 2016; IPCC, 2006; LIN *et al.*, 2021; TAUBER *et al.*, 2019), this can lead to the paradox that optimizing AD systems is damaging to the environment from a GHG standpoint. The assumption that the leakages is directly proportional to the production is a simplification in this work and several others, as these leakages are usually diffuse and can be due to the physical conditions the reactor, such as age and lack of maintenance. A reactor in good conditions that would ensure the minimal leakages in the AD reactor could reduce Scenario 2's fugitive emissions while maintaining the amount of electricity harnessed, which can improve its performance significantly, as these leaks are responsive for 22% of the absolute emissions. Therefore, it is important to emphasize the importance of working with engineering projects for efficient and low leakage methanization plants. In this way, the development of safer and more efficient technologies in terms of leakage is the way to help in the low emission of greenhouse gases from these plants. Overall, the N_2O emissions volatilized in the soil application of the digestate was the main hotspot of both scenarios, representing 48% and 34% of the absolute emissions in Scenarios 1 and 2, respectively.

When considering the avoided emissions, it can be observed that the credits from the avoided chemical fertilizer are higher than the ones from electricity, especially in Scenario 1. These credits represent 81% of the total avoided emissions in Scenario 1 and 51% in Scenario 2. This is because the Brazilian electricity grid is composed mainly of low-carbon intensive sources, such as hydropower (EPE - EMPRESA DE PLANEJAMENTO ENERGÉTICO, 2020b); and the fact that the use of chemical fertilizers, especially the nitrified ones, are associated with high GHG emissions. In the studies that carried out LCA of energy generation from the anaerobic digestion of lignocellulosic waste, the usage of fertilizers is often identified as a hotspot not only in the biomass production stage but in the system as a whole (ARISTIZÁBAL-MARULANDA; SOLARTE-TORO; CARDONA ALZATE, 2021; FANTIN *et al.*, 2015; LIN *et al.*, 2021; RANA *et al.*, 2016). On the other hand, scholars have identified the digestate as an alternative to replace commercial fertilizers (CHEONG *et al.*, 2020) and shown that this use can positively affect the environmental performance of systems (ARISTIZÁBAL-MARULANDA; SOLARTE-TORO; CARDONA ALZATE, 2021). Therefore, the results for the avoided impacts are in line with the literature, which has shown that the substitution of chemical fertilizers can lead to important credits to the system.

Accordingly, while most of the impacts were found to come from digestate downstream management, its potential reuse as a biofertilizer is also the biggest source of avoided impacts. This was also noted by Rehl et al. (2012), who stated that the digestate contributes on the one hand positively to the environment as plant macronutrients like N, P, K is contained, which can substitute mineral fertilizer, but on the other hand, affects the environment negatively as nitrogen emissions are released in different forms during storage and field application.

The comparison of these results with those obtained in previous studies (FANTIN *et al.*, 2015; FUSI *et al.*, 2016; LIN *et al.*, 2021; STYLES *et al.*, 2018) proved to be challenging due to the different approaches to quantify environmental impacts. As a versatile tool, LCA allows for a range of methodological choices, such as system boundaries, secondary database, functional units, among others, a situation that impairs cross-comparisons, even when studies analyzed the same technology. However, it is possible to discuss to a certain extent the representation of the life cycle stages in the carbon footprint within the boundaries of each study. Such discussions are carried out below with a focus on Scenario 1, as none of the studies included a pre-treatment stage.

When analyzing the management of the digestate, two studies focused more on the emissions from digestate storage than the volatilization of dinitrogen oxide (FUSI *et al.*, 2016; LIN *et al.*, 2021). Both works had scenarios in which they did not account for the soil application of digestate, and in those cases, methane emissions from digestate storage were found to be main source of GHG emissions, only after biomass production. The storage stage was also representative in Scenario 1 and 2 of this study, representing 14% and 8%, respectively. The results draw attention to the fact that this stage should not be overlooked as it can potentially be a hotspot in the life cycle of energy generation from coffee husks, as previous studies have shown that these emissions can be fifteen times greater depending on storage location and infrastructure alternatives (STYLES *et al.*, 2018).

Given the larger amount of biogas produced in Scenario 2, and conversely methane and carbon dioxide, smaller CH_4 emissions are expected to take place in the downstream digestate of the pre-treated husks, as the majority of the carbon content of the husks would have already been converted into gas. However, due to the limited number of models available in the literature, a simplified emission factor for the storage stage was considered in this work, not taking into account the actual carbon content. This is a conservative approach to Scenario 2, as more in-depth look would potentially reduce the estimated CH_4 emissions for this scenario.

In regards to the N_2O emissions volatilized in the soil, this stage was also found to be the most representative stage in other studies (FANTIN *et al.*, 2015; STYLES *et al.*, 2018). Authors also pointed out the significance of nitrogen emissions and the importance of literature models for their consideration, which is usually how it is done, as their direct measure is complex, not frequently feasible (FANTIN *et al.*, 2015). However, there is no scientific consensus on what model should be adopted (FANTIN *et al.*, 2015).

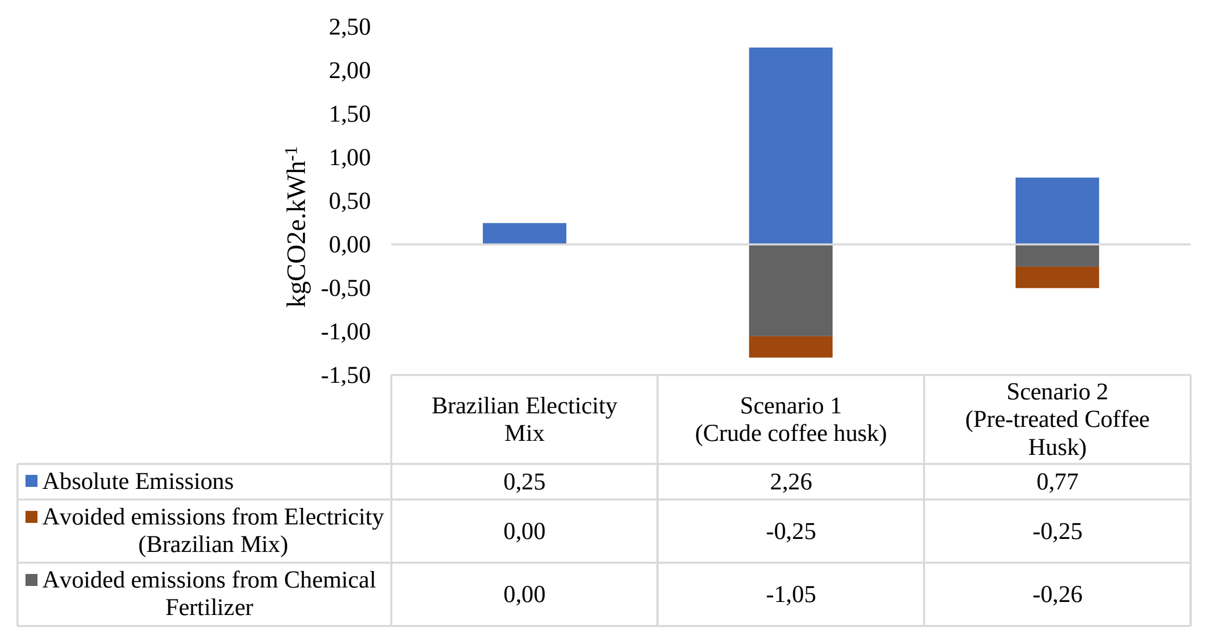
As previously mentioned, none of the studies included a pre-treatment stage in their analyses. Furthermore, the transport emissions were not relevant in any of the studies where they were considered. In this study, transport emissions were found to 23% of absolute emissions. Even though Brazil has continental dimensions, which usually means high transport distances, it highlights that attention must also be paid to the logistics in order to reduce GHG emissions.

To conclude, both Scenarios 1 and 2 presented important reductions in GHG emissions when compared to Scenario 0, business as usual, which highlights the potential benefits of treating coffee husks to generation of energy. Scenario 1 stands out as the best option from a carbon footprint standpoint, despite the smaller energy production when compared to Scenario 2. However, the environmental performance of Scenario 2 was hindered by the literature models available to calculate emissions, especially the AD methane leakages and the digestate storage emissions, and a more in-depth analysis of GHG emissions in these stages can potentially render it more interesting when compared to the crude coffee husks. Furthermore, the heat generated was considered as a loss, and if it was harnessed to also provided avoided impacts to the system, it could benefit Scenario 2 due to the higher heat production.

As for avoided impacts, the results indicate greater advantages in generating digestate to be used in the field instead of chemical fertilizer, in comparison with the production of biogas to generate electricity, as the emission factor of Brazilian electricity is low due to the usage of renewable energy sources. The important benefit of the biofertilizer was also noted from an economic perspective, as value added of the biogas produced is limited, which enables the development of waste-fed processes that yield higher-value end-products, such as biofertilizers. This becomes especially valuable when such products are kept in the short value chains, ideally being used where the waste is generated (KLEEREBEZEM *et al.*, 2015).

5.2 Results per kWh generated

When looking at the results *per* kWh generated, shown in Figure 3, the conclusions differ from the mass-based functional unit. That is because Scenario 2 produces more energy than Scenario 1, due to the inclusion of the pre-treatment, which lowered the carbon footprint of the kWh generated by 72%. The energy generated from the management of coffee husks, however, remain more carbon-intensive than the Brazilian Electricity Mix. The net carbon footprint of the kWh produced in Scenarios 1 and 2 are, respectively, 0.96 $kgCO_2e.kWh^{-1}$ and 0.27 $kgCO_2e.kWh^{-1}$, against 0.25 $kgCO_2e.kWh^{-1}$ emitted by the Brazilian national energy grid.



	Brazilian Electicity Mix	Scenario 1 (Crude coffee husk)	Scenario 2 (Pre-treated Coffee Husk)
🟦 Absolute Emissions	0,25	2,26	0,77
🟫 Avoided emissions from Electricity (Brazilian Mix)	0,00	-0,25	-0,25
⬛ Avoided emissions from Chemical Fertilizer	0,00	-1,05	-0,26

Figure 3: Carbon footprint results per kWh generated for Scenario 1 and 2, compared with the emission factor of Brazilian Electricity Mix

Differently from the comparison with the typical waste management technology, in which the scenarios with energy generation from coffee husks were proven to be less impactful, in this comparison, the results show that the coffee husks would produce electricity with an emission factor slightly higher than the Brazilian mix. Given the boundaries of the study and the conservative approaches taken, the small difference in results between Scenario 2 and the Brazilian Mix can categorize it as a promising alternative for waste-to-energy technologies .

Furthermore, when analyzing this result and the previous comparison with Scenario 0 (Table 5), one possible conclusion is that the main environmental benefits of using coffee husks to produce electricity do not rely on the production of low-carbon electricity to reduce GHG emissions, but to avoid emissions from inadequately managing the waste while generating useful by-products.

These results were also compared to other types of energy, fossil and renewably sourced. The emission factors are taken from Ecoinvent (WERNET *et al.*, 2016) and all the emission factors are from Brazil. The results are in Figure 4.

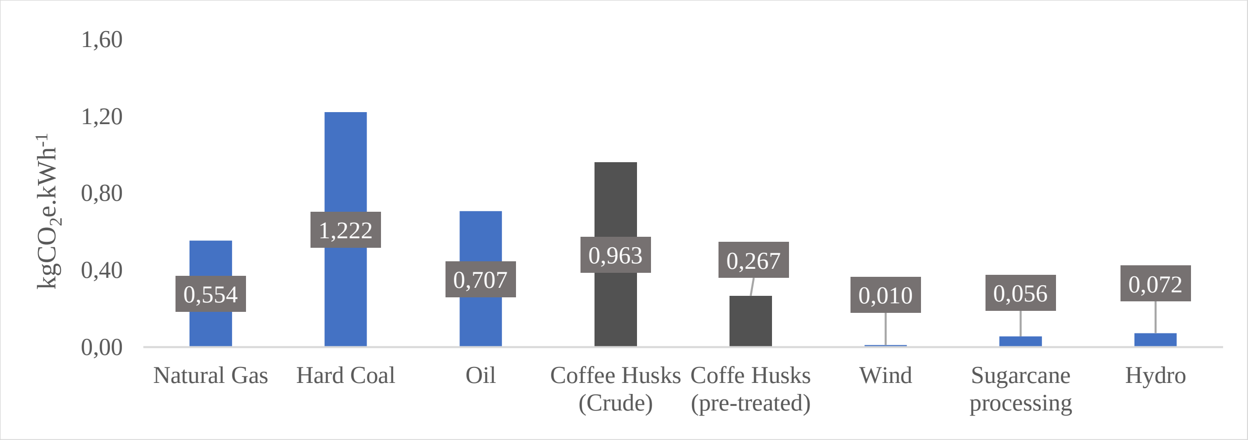


Figure 4: Carbon footprint results of the energy generation per energy source.

The results in Figure 4 showcase that the pre-treatment is a determining factor in how interesting the energy from coffee husks will be when compared to other energy sources from a carbon footprint perspective. The results from crude coffee husks, which correspond to Scenario 1, have worse results than all other energy sources, except from Hard Coal, which is the worst-case scenario. Conversely, the pre-treated coffee husks (Scenario 2) has lower GHG emissions than all fossil sources, but it is still more impactful than the renewable sources.

This last observation was also made by other authors (FUSI *et al.*, 2016). Biomass-sourced energy was compared to energy from other sources, and though the emissions were lower than the Italian electricity grid, it was higher than the renewable sources such as hydro, wind, geothermal, solar and biomass-based (wood) to which the authors recommended that to invest in other types of renewables could be more beneficial than biogas for energy generation from a GHG perspective (FUSI *et al.*, 2016).

These results point to the fact that energy generation from coffee husks can be a promising alternative to fossil-based energy carriers, but it is not as environmentally beneficial as renewable sources in terms of GHG emissions. In the contexts of countries whose electricity grid rely heavily on renewable sources, such as Brazil, the results show that it would not contribute to reduce the carbon intensity of the mix. The focus, therefore, should be on avoiding their incorrect management of coffee husks while generating locally sourced useful byproducts.

5.3 Sensitivity analysis: location

As previously seen, the avoided emissions from electricity generation were not sufficient to counterbalance the absolute emissions from the management of coffee husks. However, the Brazilian energy mix is notably less carbon-intensive than the ones from other big coffee-producing countries, such as Indonesia and Vietnam, which have a more fossil-based electricity generation (WERNET *et al.*, 2016). As the calculation of the potential avoided impacts are directly dependent on the emission factor of the electricity generation mix of the country, a sensitivity analysis was performed based on the location. In this comparison, the emissions related to the transportation between the waste producing site and the energy generation site were not included, as the logistics are expected to greatly vary among the countries.

The analysis considered the country electricity mix and the production of inorganic nitrogen fertilizer emissions from five countries: Brazil, Colombia, Ethiopia, Indonesia and Vietnam, to which the result can be seen in Figure 5. It can be observed that in terms of kWh generated, Scenario 1 generated more carbon-intensive electricity than the country mix in all countries, except for Indonesia and Vietnam. According to the Ecoinvent 3.8 modeling, the Indonesian and Vietnamese electricity mix is over 80% and 60%, respectively, based on coal or natural gas, causing it to be the higher emission factor among the countries analyzed.

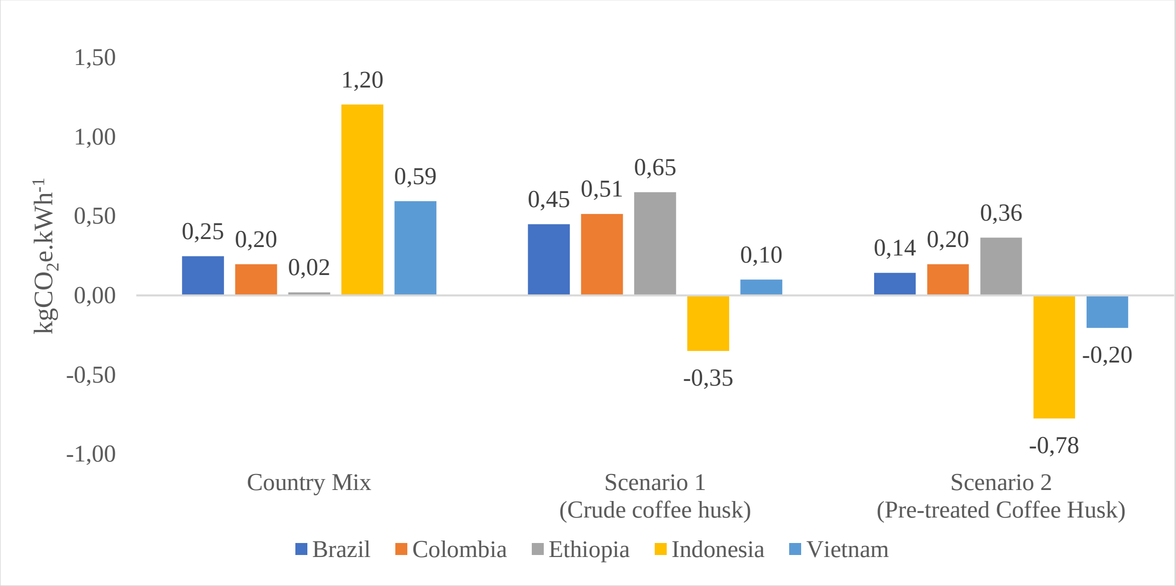


Figure 5: Carbon footprint results per kWh generated in Scenarios 1 and 2, for Ethiopia, Colombia, Indonesia, Vietnam and Brazil, compared with the emission factor of each country's electricity mix. Emissions related to logistics of the coffee husks were not considered.

As for Scenario 2, the energy from coffee husks is less carbon-intensive than county mix in Brazil, Indonesia, and Vietnam; generates the same GHG emissions than the country mix in Colombia; and more carbon-intensive than the country mix in Ethiopia, where 96% of the electricity comes from hydropower (WERNET *et al.*, 2016). This result further corroborates the observation that the pre-treatment is decisive for carbon footprint of lignocellulosic-based electricity generation. It is important to note, however, that the transport emissions are not considered here, and they were responsible for 16% of absolute emissions in Scenario 2 in the analysis focused on Brazil.

Hydro-based electricity generation is not a significant source of greenhouse gases, but it is a source of social-economic conflicts, due to the construction of reservoirs, the change in the river course, and so on, not to mention highly dependent on the rainfall regime, which can face scarcity issues (FREITAS *et al.*, 2019; PORTUGAL-PEREIRA *et al.*, 2015). Despite the data from Ecoinvent, scholars have stated that most Ethiopia's population live in rural areas and most of the energy comes from biomass such as wood (DU *et al.*, 2021). This is not a carbon-intensive type of energy, but in this specific case has led to great deforestation in the last 4 decades. This type of land use can potentially be a great source of GHG emissions for the country. The authors find that the use of energy from coffee husks is timely for Ethiopia, as energy production from biomass sources could be a reliable source due to the abundance of feedstock. These observations call for a holistic view of energy generation, as even though the use of coffee husks for energy generation produces more GHG emissions in these countries, it could be an asset for improving energy security and reduce problems such as deforestation.

From a climate change perspective, the use of coffee husks with thermal pre-treatment to generate electricity as a form of GHG mitigation of energy generation is indicated to be the best-case scenario in most countries, as it can be seen in Figure 5. However, a full LCA study analyzing other environmental aspects, such as logistics, as well as other impacts and economic and social aspects is still needed.

When comparing the waste treatment *per* ton of coffee husks (Figure 6), the pre-treatment is only beneficial in those locations where the avoided emission from energy generation surpass the credits from the fertilizer, which happen in Indonesia and Vietnam. As for Brazil, Colombia and Ethiopia, it would still be preferable to focus on the generation of biofertilizers instead of harnessing biogas to generate electricity, as the production of inorganic fertilizers generate more GHG emissions than electricity, therefore it would be more beneficial to avoid the usage of those. However, as stated in the Brazilian results, the environmental performance of Scenario 2 is hindered by the methodology used to estimate methane emissions, calling for a more in-depth analysis of those.

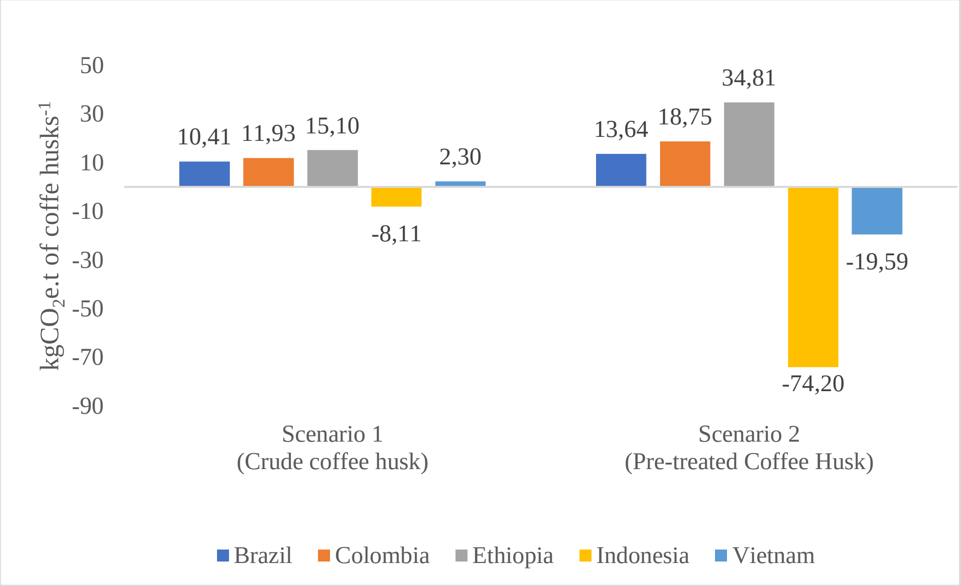


Figure 6: Carbon footprint results per ton of coffee husks of Scenarios 1 and 2, for Ethiopia, Colombia, Indonesia, Vietnam and Brazil

6 CONCLUSIONS

This study carried out one of the first LCA-based carbon footprint analysis of the anaerobic digestion of coffee husks, a significant waste in the value chains of coffee. The environmental impacts of coffee husks, anaerobic digestion and pre-treatment of lignocellulosic biomass are topics that have been poorly covered in the literature, especially in developing economies, a situation that highlights the need for more studies like this.

The carbon footprint results point to the fact that the main benefit of using AD/CHP to produce electricity is to avoid the impacts from the current landfilling route of coffee husks. The emissions from digestate management, especially N_2O volatilization on the soil, was the biggest contributor to the carbon footprint, and further research on how to quantify these emissions is needed to improve the reliability of LCAs. On the other hand, the use of digestate to replace chemical fertilizers affected the environmental performance positively, in terms of avoided impacts. The carbon footprint per ton of coffee husks increased with the inclusion of the pre-treatment, but the performance of the pre-treated scenario was hindered by the assumptions used to calculate leakages in the AD reactor and the digestate storage emissions. A more detailed analysis on methane emissions, preferably by primary data, is needed to evaluate if the pre-treatment scenario is more carbon-intensive. Furthermore, the heat surplus generated by the CHP was considered as a loss, which constitutes an opportunity for the system.

The carbon footprint of the kWh generated in the pre-treated scenario (Scenario 2) is 72% lower than the crude coffee husks (Scenario 1), but it is still higher than the footprint of the Brazilian grid, which makes it less interesting from a GHG perspective. For countries like Ethiopia and Colombia, whose electricity mix rely heavily on renewable sources, only Scenario 2 proves to be an interesting alternative. The inclusion of the pre-treatment was a determining factor to render the bioenergy from coffee husks more interesting from a GHG emissions perspective when compared to other types of energy. The results showed that renewable sources such as wind and hydropower are still preferable to coffee husk-based, which is in line with the literature. However, the use of coffee husks and other types of waste biomass for electricity generation can help improve energy security and avoid impacts such as deforestation. In Indonesia and Vietnam, where the grid is more heavily based on fossil fuels, coffee husks, especially with pre-treatment, can mitigate the carbon footprint of energy generation.

Future studies should continue to investigate gas emission measurements associated with coffee husks. They should also consider the inclusion of other environmental categories in LCAs, such as eutrophication and acidification, in order to broaden the scope of analysis. Finally, more studies are needed on the carbon footprints associated with the anaerobic digestion of other lignocellulosic wastes.

7 REFERENCES:

ABRELPE. **Overview of solid waste in Brazil 2020**. São Paulo: [s.n.], 2020.

ADEKUNLE, A.; ORSAT, V.; RAGHAVAN, V. Lignocellulosic bioethanol: A review and design conceptualization study of production from cassava peels. **Renewable and Sustainable Energy Reviews**, out. 2016. v. 64, p. 518–530. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S1364032116302994>.

ADIANSYAH, J. S.; BISWAS, W.; HAQUE, N. Life cycle based carbon footprint assessment of Indonesia's geothermal energy exploration project. **Chemical Engineering Transactions**, 2021. v. 83, n. February, p. 61–66.

ANGELO, A. C. M. *et al.* Life Cycle Assessment and Multi-criteria Decision Analysis: Selection of a strategy for domestic food waste management in Rio de Janeiro. **Journal of Cleaner Production**, fev. 2017. v. 143, p. 744–756. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0959652616321011>.

ARISTIZÁBAL-MARULANDA, V.; SOLARTE-TORO, J. C.; CARDONA ALZATE, C. A. Study of biorefineries based on experimental data: production of bioethanol, biogas, syngas, and electricity using coffee-cut stems as raw material. **Environmental Science and Pollution Research**, 27 maio. 2021. v. 28, n. 19, p. 24590–24604.

ATELGE, M. R. *et al.* A critical review of pretreatment technologies to enhance anaerobic digestion and energy recovery. **Fuel**, jun. 2020. v. 270, p. 117494.

BACENETTI, J. *et al.* Agricultural anaerobic digestion plants: What LCA studies pointed out and what can be done to make them more environmentally sustainable. **Applied Energy**, 2016. v. 179, p. 669–686. Disponível em: <http://dx.doi.org/10.1016/j.apenergy.2016.07.029>.

BAÊTA, B. E. L. *et al.* Steam explosion pretreatment improved the biomethanization of coffee husks. **Bioresource Technology**, dez. 2017. v. 245, p. 66–72. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0960852417314244>.

BEEMSTERBOER, S.; BAUMANN, H.; WALLBAUM, H. Ways to get work done: a review and systematisation of simplification practices in the LCA literature. **International Journal of Life Cycle Assessment**, 2020. v. 25, n. 11, p. 2154–2168.

BERNSTAD SARAIVA, A.; SOUZA, R. G.; VALLE, R. A. B. Comparative lifecycle assessment of alternatives for waste management in Rio de Janeiro – Investigating the influence of an attributional or consequential approach. **Waste Management**, 2017. v. 68, p. 701–710. Disponível em: <http://dx.doi.org/10.1016/j.wasman.2017.07.002>.

BHAWAN, S.; PURAM, R. K. **CO2 Baseline Database for the Indian Power Sector**. New Delhi: [s.n.], 2018.

BILAL, M.; IQBAL, H. M. N. Recent Advancements in the Life Cycle Analysis of Lignocellulosic Biomass. **Current Sustainable/Renewable Energy Reports**, 18 set. 2020. v. 7, n. 3, p. 100–107. Disponível em: <http://link.springer.com/10.1007/s40518-020-00153-5>.

BLANC, I *et al.* Espace-PV: Key Sensitive Parameters for Environmental Impacts of Grid-Connected PV Systems With LCA. **23rd European Photovoltaic Solar Energy Conference and Exhibition**, 2008. n. September, p. 3779. Disponível em: <c:/pdflib/00022150.pdf>.

BLEY JÚNIOR, C. *et al.* **Agroenergia da biomassa residual: perspectivas energéticas, socioeconômicas e ambientais**. 2. ed. Foz do Iguaçu/Brasília: Itaipu Binacional: Organização das Nações Unidas para Agricultura e Alimentação, TechnoPolitik Editora, 2009.

BRAZIL. **Lei Nº 13.263, de 23 de Março 2016.**

______; ENERGY RESEARCH COMPANY. **National Energy Plan 2050**. Brasília: [s.n.], 2020.

CARVALHO, M. *et al.* Carbon footprint of the generation of bioelectricity from sugarcane bagasse in a sugar and ethanol industry. **International Journal of Global Warming**, 2019. v. 17, n. 3, p. 235. Disponível em: <http://www.inderscience.com/link.php?id=98495>.

CHAKRABORTY, D. Carbon Footprint Estimation of an Indian Thermal Power Plant Towards Achieving Sustainability Through Adoption of Green Options and Sustainable Development Goals (SDGs). [S.l.]: [s.n.], 2021, p. 93–110.

CHANDRA, R. *et al.* Improving biodegradability and biogas production of wheat straw substrates using sodium hydroxide and hydrothermal pretreatments. **Energy**, jul. 2012. v. 43, n. 1, p. 273–282.

CHEN, G. Q.; YANG, Q.; ZHAO, Y. H. Renewability of wind power in China: A case study of nonrenewable energy cost and greenhouse gas emission by a plant in Guangxi. **Renewable and Sustainable Energy Reviews**, 2011. v. 15, n. 5, p. 2322–2329. Disponível em: <http://dx.doi.org/10.1016/j.rser.2011.02.007>.

CHEONG, J. C. *et al.* Closing the food waste loop: Food waste anaerobic digestate as fertilizer for the cultivation of the leafy vegetable, xiao bai cai (Brassica rapa). **Science of The Total Environment**, maio. 2020. v. 715, p. 136789.

CHERUBINI, F.; BARGIGLI, S.; ULGIATI, S. Life cycle assessment (LCA) of waste management strategies: Landfilling, sorting plant and incineration. **Energy**, dez. 2009. v. 34, n. 12, p. 2116–2123. Disponível em: <http://linkinghub.elsevier.com/retrieve/pii/S0360544208002120>. Acesso em: 13 jul. 2014.

CIRNE, D. G. *et al.* Hydrolysis and microbial community analyses in two-stage anaerobic digestion of energy crops. **Journal of Applied Microbiology**, set. 2007. v. 103, n. 3, p. 516–527. Disponível em: <http://doi.wiley.com/10.1111/j.1365-2672.2006.03270.x>.

COELHO FILHO, O.; SACCARO JUNIOR, N. L.; LUEDEMANN, G. **A Avaliação de Ciclo de Vida como ferramenta para a formulação de políticas públicas no Brasil**. IPEA - Instituto de Pesquisa Econômica Aplicada.

DEUBLEIN, D.; STEINHAUSER, A. **Biogas from waste and renewable resources: an introduction**. 2nd. ed. [S.l.]: Weinheim: WILEY-VCH Verlag GmbH & Co. KGaA, 2011.

Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast). **Official Journal of the European Union**.

DU, N. *et al.* Study on the biogas potential of anaerobic digestion of coffee husks wastes in Ethiopia. **Waste Management & Research: The Journal for a Sustainable Circular Economy**, 14 fev. 2021. v. 39, n. 2, p. 291–301. Disponível em: <http://journals.sagepub.com/doi/10.1177/0734242X20939619>.

ENERGY RESEARCH COMPANY. **Balanço Energético Nacional 2021**. [S.l.]: [s.n.], 2021.

EPE - EMPRESA DE PLANEJAMENTO ENERGÉTICO. **Anuário Estatístico de Energia Elétrica 2020: ano base 2019**. [S.l.]: [s.n.], 2020a.

______. **Balanço Energético Nacional 2020: ano base 2019**. Rio de Janeiro: [s.n.], 2020b.

EVANGELISTI, Sara *et al.* Life cycle assessment of energy from waste via anaerobic digestion: A UK case study. **Waste Management**, jan. 2014. v. 34, n. 1, p. 226–237. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0956053X13004443>.

FAN, L. *et al.* Cultivation of Pleurotus mushrooms on Brazilian coffee husk and effects of caffeine and tannic acid. **Micología Aplicada International**, 2003. v. 15, n. 1, p. 15–21.

FAN, Y. V. *et al.* Anaerobic digestion of lignocellulosic waste: Environmental impact and economic assessment. **Journal of Environmental Management**, fev. 2019. v. 231, n. July 2018, p. 352–363. Disponível em: <https://doi.org/10.1016/j.jenvman.2018.10.020>.

FAN, Y. Van *et al.* Anaerobic digestion of municipal solid waste: Energy and carbon emission footprint. **Journal of Environmental Management**, out. 2018. v. 223, n. June, p. 888–897. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0301479718307564>.

FANTIN, V. *et al.* Environmental assessment of electricity generation from an Italian anaerobic digestion plant. **Biomass and Bioenergy**, 2015. v. 83, p. 422–435. Disponível em: <http://dx.doi.org/10.1016/j.biombioe.2015.10.015>.

FINKBEINER, M. Carbon footprinting-opportunities and threats. **International Journal of Life Cycle Assessment**, 2009. v. 14, n. 2, p. 91–94.

FINNVEDEN, G.; MOBERG, Å. Environmental systems analysis tools - An overview. **Journal of Cleaner Production**, 2005. v. 13, n. 12, p. 1165–1173.

FONSECA, Y. A. *et al.* Steam explosion pretreatment of coffee husks: a strategy towards decarbonization in a biorefinery approach. **Journal of Chemical Technology & Biotechnology**, 8 nov. 2021.

FOOD AND AGRICULTURE ORGANIZATION. Countries by commodity. 2019. Disponível em: <http://www.fao.org/faostat/en/#data/QC>.

FREITAS, F. F. *et al.* The Brazilian market of distributed biogas generation: Overview, technological development and case study. **Renewable and Sustainable Energy Reviews**, mar. 2019. v. 101, n. October 2018, p. 146–157.

FRUERGAARD, T.; ASTRUP, T. Optimal utilization of waste-to-energy in an LCA perspective. **Waste Management**, mar. 2011. v. 31, n. 3, p. 572–582. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0956053X10004861>.

FUSI, A. *et al.* Life cycle environmental impacts of electricity from biogas produced by anaerobic digestion. **Frontiers in Bioengineering and Biotechnology**, 2016. v. 4, n. MAR.

GHG PROTOCOL BRAZILIAN PROGRAM. **Ferramenta GHG Protocol v.2022.1.0**.

GÓMEZ-SALCEDO, Y. *et al.* Contribution of the Environmental Biotechnology to the Sustainability. *Em*: MADDELA, N. R.; GARCÍA CRUZATTY, L. C.; CHAKRABORTY, S. (Org.). **Advances in the Domain of Environmental Biotechnology of the Coffee Processing Industry in Developing Countries**. Singapore: Springer Singapore, 2021, p. 565–590.

GOULART COELHO, L. M.; LANGE, L. C. Applying life cycle assessment to support environmentally sustainable waste management strategies in Brazil. **Resources, Conservation and Recycling**, 2018. v. 128, p. 438–450. Disponível em: <https://doi.org/10.1016/j.resconrec.2016.09.026>.

GOUVEA, B. M. *et al.* Feasibility of ethanol production from coffee husks. **Biotechnology Letters**, 23 set. 2009. v. 31, n. 9, p. 1315–1319.

HANAKI, K.; PORTUGAL-PEREIRA, J. The Effect of Biofuel Production on Greenhouse Gas Emission Reductions. *Em*: TAKEUCHI, K. *et al.* (Org.). **Biofuels and Sustainability**. [S.l.]: [s.n.], 2018, p. 53–71.

HOBSON, P. A.; RENOUF, M. A. Development of a tool for rapid life cycle assessment of sugar and associated energy products. Townsville, QLD, Australia: Australian Society of Sugar Cane Technologists, 2013.

HOLM-NIELSEN, J. B.; SEADI, T. AL; OLESKOWICZ-POPIEL, P. The future of anaerobic digestion and biogas utilization. **Bioresource Technology**, nov. 2009. v. 100, n. 22, p. 5478–5484.

HOSEINI, M. *et al.* Coffee by-products derived resources. A review. **Biomass and Bioenergy**, maio. 2021. v. 148, p. 106009.

HUTTUNEN, S.; MANNINEN, K.; LESKINEN, P. Combining biogas LCA reviews with stakeholder interviews to analyse life cycle impacts at a practical level. **Journal of Cleaner Production**, out. 2014. v. 80, p. 5–16. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0959652614005605>.

INTERNATIONAL COFFEE ORGANIZATION. International Coffee Organization Trade statistics tables: coffee production by exporting countries. **http://www.ico.org/trade_statistics.asp**, 2020.

IPCC. **IPCC Guidelines for National Greenhouse Gas Inventories**. **Institute for Global …**. Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). IGES Japan: [s.n.], 2006. Disponível em: <http://library.wur.nl/WebQuery/clc/1885455>. Acesso em: 24 jul. 2014.

ISO. **ISO 14040:2006 Environmental management—Life cycle assessment—Principles and Framework**. Geneva, Switzerland: [s.n.], 2006a.

______. **ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines**. Geneva, Switzerland: [s.n.], 2006b.

J. CERINO-CÓRDOVA, F. *et al.* Revalorization of Coffee Waste. **Coffee - Production and Research**. [S.l.]: IntechOpen, 2020.

JHA, G.; SOREN, S.; MEHTA, K. D. Carbon Footprint Assessment with LCA Methodology. [S.l.]: [s.n.], 2021, p. 1–34.

JI, S.; CHEN, B. Lca-based carbon footprint of a typical Wind farm in China. **Energy Procedia**, 2016. v. 88, p. 250–256. Disponível em: <http://dx.doi.org/10.1016/j.egypro.2016.06.160>.

KLEEREBEZEM, R. *et al.* Anaerobic digestion without biogas? **Reviews in Environmental Science and Bio/Technology**, 8 dez. 2015. v. 14, n. 4, p. 787–801.

KLEINER, K. The corporate race to cut carbon. **Nature Climate Change**, ago. 2007. v. 1, n. 708, p. 40–43. Disponível em: <http://www.nature.com/articles/climate.2007.31>.

KOOKOS, I. K. Technoeconomic and environmental assessment of a process for biodiesel production from spent coffee grounds (SCGs). **Resources, Conservation and Recycling**, jul. 2018. v. 134, p. 156–164.

KUMAR, A.; CHANDRA, R. Ligninolytic enzymes and its mechanisms for degradation of lignocellulosic waste in environment. **Heliyon**, fev. 2020. v. 6, n. 2, p. e03170. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S2405844020300153>.

KYLILI, A.; CHRISTOFOROU, E.; FOKAIDES, P. A. Environmental evaluation of biomass pelleting using life cycle assessment. **Biomass and Bioenergy**, 2016. v. 84, p. 107–117. Disponível em: <http://dx.doi.org/10.1016/j.biombioe.2015.11.018>.

LEME, M. M. V. *et al.* Techno-economic analysis and environmental impact assessment of energy recovery from Municipal Solid Waste (MSW) in Brazil. **Resources, Conservation and Recycling**, 2014. v. 87, p. 8–20.

LI, J.; XIONG, F.; CHEN, Z. An integrated life cycle and water footprint assessment of nonfood crops based bioenergy production. **Scientific Reports**, 2021. v. 11, n. 1, p. 1–14. Disponível em: <https://doi.org/10.1038/s41598-021-83061-y>.

LIIKANEN, M. *et al.* Steps towards more environmentally sustainable municipal solid waste management – A life cycle assessment study of São Paulo, Brazil. **Journal of Cleaner Production**, 2018. v. 196, p. 150–162. Disponível em: <https://doi.org/10.1016/j.jclepro.2018.06.005>.

LIN, H. *et al.* Life cycle assessment of a biogas system for cassava processing in Brazil to close the loop in the water-waste-energy-food nexus. **Journal of Cleaner Production**, 2021. v. 299, p. 126861. Disponível em: <https://doi.org/10.1016/j.jclepro.2021.126861>.

LOPES SILVA, D. A. *et al.* Life cycle assessment of the sugarcane bagasse electricity generation in Brazil. **Renewable and Sustainable Energy Reviews**, abr. 2014. v. 32, p. 532–547. Disponível em: <http://dx.doi.org/10.1016/j.rser.2013.12.056>.

MAYER, F.; BHANDARI, R.; GÄTH, S. Critical review on life cycle assessment of conventional and innovative waste-to-energy technologies. **Science of the Total Environment**, 2019. v. 672, p. 708–721. Disponível em: <https://doi.org/10.1016/j.scitotenv.2019.03.449>.

MEDEIROS, D. L.; SALES, E. A.; KIPERSTOK, A. Energy production from microalgae biomass: Carbon footprint and energy balance. **Journal of Cleaner Production**, 2015. v. 96, p. 493–500.

MENDES, M. R.; ARAMAKI, T.; HANAKI, K. Assessment of the environmental impact of management measures for the biodegradable fraction of municipal solid waste in São Paulo City. **Waste Management**, 2003. v. 23, n. 5, p. 403–409.

______; ______; ______. Comparison of the environmental impact of incineration and landfilling in São Paulo City as determined by LCA. **Resources, Conservation and Recycling**, 2004. v. 41, n. 1, p. 47–63.

MOHAMMADI, A. *et al.* Life cycle assessment of combination of anaerobic digestion and pyrolysis: focusing on different options for biogas use. **Advances in Geosciences**, 29 ago. 2019a. v. 49, p. 57–66.

______ *et al.* Life cycle assessment of combination of anaerobic digestion and pyrolysis: focusing on different options for biogas use. **Advances in Geosciences**, 29 ago. 2019b. v. 49, p. 57–66. Disponível em: <https://adgeo.copernicus.org/articles/49/57/2019/>.

MØLLER, J.; BOLDRIN, A.; CHRISTENSEN, T. H. Anaerobic digestion and digestate use: accounting of greenhouse gases and global warming contribution. **Waste Management & Research: The Journal for a Sustainable Circular Economy**, 11 nov. 2009. v. 27, n. 8, p. 813–824.

MORAIS LIMA, P. *et al.* Life Cycle Assessment of prospective MSW management based on integrated management planning in Campo Grande, Brazil. **Waste Management**, maio. 2019. v. 90, p. 59–71.

MORENO-RAMÓN, H.; QUIZEMBE, S. J.; IBÁÑEZ-ASENSIO, S. Coffee husk mulch on soil erosion and runoff: experiences under rainfall simulation experiment. **Solid Earth**, 26 ago. 2014. v. 5, n. 2, p. 851–862.

OLIVEIRA, L.; FRANCA, A. An Overview of the Potential Uses for Coffee Husks. **Coffee in Health and Disease Prevention**. [S.l.]: Elsevier, 2015, p. 283–291.

PADEY, P. *et al.* A Simplified Life Cycle Approach for Assessing Greenhouse Gas Emissions of Wind Electricity. **Journal of Industrial Ecology**, abr. 2012. v. 16, n.

SUPPL.1, p. S28–S38. Disponível em: <http://doi.wiley.com/10.1111/j.1530-9290.2012.00466.x>.

PANDEY, Ashok *et al.* Biotechnological potential of coffee pulp and coffee husk for bioprocesses. **Biochemical Engineering Journal**, out. 2000. v. 6, n. 2, p. 153–162.

PANDEY, D.; AGRAWAL, M.; PANDEY, J. S. Carbon footprint: Current methods of estimation. **Environmental Monitoring and Assessment**, 2011. v. 178, n. 1–4, p. 135–160.

PASSOS, F. *et al.* Anaerobic co-digestion of coffee husks and microalgal biomass after thermal hydrolysis. **Bioresource Technology**, abr. 2018. v. 253, p. 49–54. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0960852417322162>.

PATTERSON, T. *et al.* Life cycle assessment of biogas infrastructure options on a regional scale. **Bioresource Technology**, ago. 2011. v. 102, n. 15, p. 7313–7323.

PECORINI, I. *et al.* Biochemical methane potential tests of different autoclaved and microwaved lignocellulosic organic fractions of municipal solid waste. **Waste Management**, out. 2016. v. 56, p. 143–150. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0956053X1630352X>.

PHIMSEN, S. *et al.* Oil extracted from spent coffee grounds for bio-hydrotreated diesel production. **Energy Conversion and Management**, out. 2016. v. 126, p. 1028–1036.

PODDAR, B. J. *et al.* A comprehensive review on the pretreatment of lignocellulosic wastes for improved biogas production by anaerobic digestion. **International Journal of Environmental Science and Technology**, 31 abr. 2022. v. 19, n. 4, p. 3429–3456.

PORTUGAL-PEREIRA, J. *et al.* Agricultural and agro-industrial residues-to-energy: Techno-economic and environmental assessment in Brazil. **Biomass and Bioenergy**, 2015. v. 81, n. April, p. 521–533.

PRASAD, S. *et al.* Sustainable utilization of crop residues for energy generation: A life cycle assessment (LCA) perspective. **Bioresource Technology**, maio. 2020. v. 303, n. February, p. 122964. Disponível em: <https://doi.org/10.1016/j.biortech.2020.122964>.

RAJESH BANU, J. *et al.* Spent coffee grounds based circular bioeconomy: Technoeconomic and commercialization aspects. **Renewable and Sustainable Energy Reviews**, dez. 2021. v. 152, p. 111721.

RANA, R. *et al.* Greenhouse gas emissions of an agro-biogas energy system: Estimation under the Renewable Energy Directive. **Science of the Total Environment**, 2016. v. 550, p. 1182–1195. Disponível em: <http://dx.doi.org/10.1016/j.scitotenv.2015.10.164>.

REHL, T.; LANSCHE, J.; MÜLLER, J. Life cycle assessment of energy generation from biogas - Attributional vs. consequential approach. **Renewable and Sustainable Energy Reviews**, 2012. v. 16, n. 6, p. 3766–3775. Disponível em: <http://dx.doi.org/10.1016/j.rser.2012.02.072>.

SANTOS, L. C. Dos *et al.* Production of biogas (methane and hydrogen) from anaerobic digestion of hemicellulosic hydrolysate generated in the oxidative pretreatment of coffee husks. **Bioresource Technology**, set. 2018. v. 263, n. March, p. 601–612. Disponível em: <https://doi.org/10.1016/j.biortech.2018.05.037>.

SHEMEKITE, F. *et al.* Coffee husk composting: An investigation of the process using molecular and non-molecular tools. **Waste Management**, mar. 2014. v. 34, n. 3, p. 642–652. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0956053X13005631>.

SILVA, N. C. S. **Avaliação do pré-tratamento hidrotérmico da casca de café na hidrólise enzimática e produção de biogás**. [S.l.]: Universidade Federal de Ouro Preto, 2019. Dissertation (MSc).

SONNEMANN, G. *et al.* Life Cycle Thinking and the Use of LCA in Policies Around the World. **Life Cycle Assessment**. Cham: Springer International Publishing, 2018, p. 429–463.

STYLES, D. *et al.* Life Cycle Assessment of Biofertilizer Production and Use Compared with Conventional Liquid Digestate Management. **Environmental Science & Technology**, 3 jul. 2018. v. 52, n. 13, p. 7468–7476. Disponível em: <https://pubs.acs.org/doi/10.1021/acs.est.8b01619>.

SZABO, G. *et al.* THE CARBON FOOTPRINT OF A BIOGAS POWER PLANT. **Environmental Engineering and Management Journal**, 2014. v. 13, n. 11, p. 2867–2874. Disponível em: <http://www.eemj.icpm.tuiasi.ro/pdfs/vol13/no11/22_692_Szabo_14.pdf>.

TAGLIAFERRI, C. *et al.* Life cycle assessment of conventional and advanced two-stage energy-from-waste technologies for methane production. **Journal of Cleaner**

Production, ago. 2016. v. 129, p. 144–158. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0959652616303687>.

TAO, X.; WANG, P.; ZHU, B. Measuring the interprovincial CO2 emissions considering electric power dispatching in China: From production and consumption perspectives. **Sustainability (Switzerland)**, 2016. v. 8, n. 6.

TAUBER, J. *et al.* Quantifying methane emissions from anaerobic digesters. **Water Science and Technology**, 1 nov. 2019. v. 80, n. 9, p. 1654–1661.

TONINI, D.; ASTRUP, Thomas. LCA of biomass-based energy systems: A case study for Denmark. **Applied Energy**, 2012. v. 99, p. 234–246. Disponível em: <http://dx.doi.org/10.1016/j.apenergy.2012.03.006>.

TRINDADE, A. B. *et al.* Advanced exergy analysis and environmental assesment of the steam cycle of an incineration system of municipal solid waste with energy recovery. **Energy Conversion and Management**, fev. 2018. v. 157, p. 195–214.

TSALIDIS, G. A.; KOREVAAR, G. From the allocation debate to a substitution paradox in waste bioenergy life cycle assessment studies. **International Journal of Life Cycle Assessment**, 2020. v. 25, n. 2, p. 181–187.

VALENTI, F.; LIAO, W.; PORTO, S. M. C. Life cycle assessment of agro-industrial by-product reuse: a comparison between anaerobic digestion and conventional disposal treatments. **Green Chemistry**, 2020. v. 22, n. 20, p. 7119–7139. Disponível em: <http://xlink.rsc.org/?DOI=D0GC01918F>.

VÉLEZ, J. F. *et al.* Co-gasification of Colombian coal and biomass in fluidized bed: An experimental study. **Fuel**, mar. 2009. v. 88, n. 3, p. 424–430. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0016236108004122>.

VOSOOGHNIA, A. *et al.* Carbon footprint of anaerobic digestion combined with ultrasonic post-treatment of agro-industrial organic residues. **Journal of Environmental Management**, 2021. v. 278, n. June 2020.

WEIDEMA, B. P. *et al.* Carbon footprint: A catalyst for life cycle assessment? **Journal of Industrial Ecology**, 2008. v. 12, n. 1, p. 3–6.

WERNET, G. *et al.* ecoinvent Version 3. **The International Journal of Life Cycle Assessment**, 2016. v. 21, n. 9, p. 1218–1230.

WHITING, A.; AZAPAGIC, A. Life cycle environmental impacts of generating electricity and heat from biogas produced by anaerobic digestion. **Energy**, jun. 2014. v. 70, p. 181–193. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0360544214003673>.

WIEDMANN, T.; MINX, J. A Definition of ' Carbon Footprint. **Ecological Economics Research Trends**. [S.l.]: [s.n.], 2007, V. 1, p. 1–11.

YUE, T. *et al.* Research trends and hotspots related to global carbon footprint based on bibliometric analysis: 2007–2018. **Environmental Science and Pollution Research**, 2020. v. 27, n. 15, p. 17671–17691.

ZHENG, Y. *et al.* Pretreatment of lignocellulosic biomass for enhanced biogas production. **Progress in Energy and Combustion Science**, 2014. v. 42, n. 1, p. 35–53.