FEDERAL UNIVERSITY OF SÃO CARLOS

CENTER FOR SCIENCE AND TECHNOLOGY FOR SUSTAINABILITY

POSTGRADUATE PROGRAM IN PLANNING AND USE OF RENEWABLE RESOURCES

Antonio Carlos Farrapo Junior

CARBON CREDITS FOR SOLID BIOFUELS IN LATIN AMERICA: A COMPUTATIONAL TOOL BASED ON CIRCULAR BIOECONOMY PRINCIPLES

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Thesis submitted to the Graduate Program in Planning and Use of Renewable Resources to obtain the title of Doctor in Planning and Use of Renewable Resources.

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“Here comes the sun, and I say, it's all right.”

George Harrison, Here Comes the Sun (The Beatles, 1969)

ABSTRACT

FARRAPO JR, Antonio Carlos Carbon credits for solid biofuels in Latin America: A computational tool based on circular bioeconomy principles. 2025. Thesis (Doctorate in Planning and Use of Renewable Resources) – Federal University of São Carlos, Sorocaba, 2025

The accelerating global population growth and the burgeoning demand for products forecasted by 2030 necessitate a sustainable transformation in production and consumption patterns to avert ecological catastrophe. Recognizing this urgency, the United Nations (UN) Agenda 2030 emphasizes the need for a Bioeconomy paradigm shift, aiming to reconcile economic growth with environmental stewardship. Within this framework, Bioenergy emerges as a pivotal component, encompassing renewable energy derived from biological sources, notably solid biofuels like biomass pellets and briquettes. Latin America, endowed with abundant biomass resources, has experienced notable growth in solid biofuel production. However, the region continues to face a significant gap in methodological harmonization and policy recognition of these biofuels within carbon credit mechanisms. To address this gap, a life cycle-based methodological framework was developed to estimate the carbon intensity and decarbonization potential of solid biofuels. Inspired by Brazil's RenovaBio program and its RenovaCalc calculator, a novel tool, namely BioCalc, was designed to quantify greenhouse gas emissions and simulate carbon credit generation for pellets and briquettes. This doctoral thesis is structured into six chapters, four of which are presented in the form of scientific articles. These chapters address global bioenergy policy analysis, comparative assessment of carbon allocation methodologies, evaluation of transportation-related emissions in export contexts, and the design and application of the BioCalc tool to estimate carbon intensity and decarbonization credit potential for solid biofuels. Modeling results demonstrate substantial variability in greenhouse gas emissions and credit generation depending on the methodological approach adopted. Estimated decarbonization potentials ranged from 3.1 to 6.2 million tCO_2e per year, with associated revenue potential between USD 35.8 million and USD 103.9 million annually, highlighting the financial significance of methodological transparency and harmonization. By combining policy analysis, life cycle modeling, and computational innovation, the work contributes a replicable and policy-relevant framework to support the quantification and market integration of solid biofuels. The outcomes provide strategic insights for incorporating pellets and briquettes into national decarbonization programs, such as RenovaBio and the Brazilian Emissions Trading System (SBCE), as well as into emerging mechanisms established under Article 6 of the Paris Agreement. More broadly, the findings underscore the crucial role of circular economy principles and methodological clarity in promoting sustainable energy transitions in Latin America and globally.

Keywords: Life Cycle Assessment; Greenhouse Gas Emissions; Renewable Energy Policy; Carbon Market; Biomass.

RESUMO

FARRAPO JR, Antonio Carlos Créditos de carbono para biocombustíveis sólidos na América Latina: uma ferramenta computacional baseada nos princípios da bioeconomia circular. 2025. Tese (Doutorado em Planejamento e Uso de Recursos Renováveis) – Universidade Federal de São Carlos, Sorocaba, 2025.

O crescimento populacional global e a demanda projetada por produtos até 2030 impõem a necessidade de uma transformação sustentável nos padrões de produção e consumo. A Agenda 2030 da Organização das Nações Unidas (ONU) destaca a Bioeconomia como paradigma essencial para alinhar crescimento econômico à sustentabilidade ambiental. Nesse contexto, a Bioenergia, especialmente proveniente de biocombustíveis sólidos como pellets e briquetes, assume papel estratégico. A América Latina, rica em biomassa, tem ampliado sua produção de biocombustíveis sólidos, embora ainda careça de reconhecimento regulatório e metodologias padronizadas nos mecanismos de créditos de carbono. Para enfrentar esse desafio, desenvolveu-se um arcabouço metodológico baseado em Avaliação do Ciclo de Vida (ACV) voltado à estimativa da intensidade de carbono e do potencial de descarbonização desses combustíveis. Inspirada no RenovaBio e na ferramenta RenovaCalc, foi criada a ferramenta BioCalc, destinada à quantificação de emissões e simulação de créditos de carbono para pellets e briquetes. A pesquisa está estruturada em seis capítulos, sendo quatro em formato de artigo científico, abrangendo políticas públicas para bioenergia, avaliação de metodologias de alocação, impactos do transporte em cadeias de exportação e a aplicação da BioCalc. Os resultados mostram variações significativas nas emissões de gases de efeito estufa e na geração de créditos conforme o método adotado. Os potenciais de descarbonização variaram entre 3,1 e 6,2 milhões de tCO_2e/ano, com receitas estimadas entre USD 35,8 milhões e USD 103,9 milhões/ano, evidenciando a relevância de metodologias transparentes e harmonizadas. Ao combinar análise de políticas públicas, modelagem de ciclo de vida e inovação computacional, a pesquisa oferece uma estrutura replicável e aplicável à inserção dos biocombustíveis sólidos em mercados regulados e voluntários de carbono. Os resultados fornecem subsídios estratégicos para sua inclusão em programas como o RenovaBio e o Sistema Brasileiro de Comércio de Emissões (SBCE), além de mecanismos previstos no Artigo 6 do Acordo de Paris, reforçando o papel da economia circular e da padronização metodológica nas transições energéticas sustentáveis.

Palavras-chave: Avaliação do Ciclo de Vida; Gases de Efeito Estufa; Políticas de Energia Renovável; Mercado de Carbono; Biomassa.

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1 INTRODUCTION

The introduction chapter comprises contextualization and justification (section 1.1), objectives (section 1.2), and a description of the structure adopted in this thesis (section 1.3). It is important to highlight that this thesis was structured in an article format, consisting of 03 papers developed according to the structure mentioned in section 1.3.

1.1 CONTEXTUALIZATION AND JUSTIFICATION

Studies indicate a significant population increase shortly; in November 2022, the global population surpassed 8 billion people (UN, 2022). Consequently, the demand for products will also increase, with an estimated three billion new middle-class consumers expected to enter the market by 2030 (UNFPA, 2023). Given the finite nature of natural resources and unsustainable consumption patterns, this scenario presents an urgent challenge for humanity, demanding a systemic transformation toward sustainable development.

Recognizing this scenario, the UN's Agenda 2030, composed of 17 Sustainable Development Goals (SDGs), emerged intending to promote the eradication of poverty and hunger, gender equality, health and well-being, quality education, and the reduction of adverse environmental impacts on ecosystems (ONU, 2015). The seventh SDG addresses the global energy matrix, aiming to enhance efforts for the development of technologies related to energy generation using renewable sources to increase their share in the planet's overall energy matrix. This objective is supported by Bioeconomy, which aims to add value to natural resources and ecosystemic environmental services.

Bioenergy is a fundamental element within the overarching concept of Bioeconomy, encompassing the production and utilization of renewable energy derived from biological sources, encompassing various sources such as liquids (alcohol and biodiesel), biogas, and solid biomass-based fuels (charcoal, firewood, agro-industrial residues, briquettes, and pellets).

According to The Critical Raw Materials Act (European Commission, 2023), Latin America is endowed with abundant and diverse natural resources, as well as significant potential for growth in supplying critical raw materials to the world. Before the COVID-19 pandemic, the region recorded the highest growth rates in solid biofuel production for export. Nevertheless, it remains one of the least explored in terms of Life Cycle Assessment (LCA) studies, which limits the formulation of evidence-based policies and integration into international carbon markets (Sfez et al., 2019; Zhang et al., 2025).

Among solid biofuels, the pellet industry stands out due to its growing global demand and being considered less polluting than fossil fuels (Garcia et al., 2022). Pellets and briquettes are generally produced from agroforestry residues (sawdust, wood shavings, wood chips, husks, bagasse, etc.), undergoing a process of drying to 12% moisture, grinding, and densification in a pelletizing or briquetting machine (Garcia et al., 2018; Silva et al., 2022a). These solid biofuels are internationally traded commodities with low moisture content, allowing for high energy density (11-14 GJ/m^3). Their cylindrical geometry ensures excellent flowability and facilitates the automation of residential, commercial, and industrial burning processes, serving as an alternative to other biofuels such as charcoal (Christoforou & Fokaides, 2017).

Global pellet production has seen steady growth, with a 12% increase in 2023 compared with 2022. In South America, where pellet production is primarily concentrated in Brazil, Chile, and Argentina, there was a considerable increase of 29% in production during 2021/2022. Despite this significant growth, South America still only accounts for 3.8% of global pellet production (Bioenergy Europe, 2023). In Brazil, the main sources of raw materials used in pellet production are more than 50% derived from the waste of reforested Pinus sp. wood. (ABIPEL, 2023). The fact that they are produced from solid waste demonstrates economic, environmental, and social advantages. From an economic standpoint, value is added to waste that would otherwise be discarded into the environment (Garcia et al., 2018). From an environmental perspective, the productive cycle is closed, contributing to the Circular Bioeconomy (Muench & Guenther, 2013; Rampasso et al., 2021b). From a social perspective, it generates new jobs and businesses in the biofuel value chain (Silva et al., 2024).

Recognizing these opportunities, the Brazilian government, through the Ministry of Mines and Energy, launched the National Biofuels Policy, known as RenovaBio, through Law n° 13.576/2017 (Brasil, 2017). The program promotes, within more sustainable standards, the increased production of biofuels, providing differentiated treatment for biofuels with lower greenhouse gas emissions in the life cycle of products in the market (Matsuura et al., 2018). Also underway is Bill No. 1874 of 2022 (Brasil, 2022), establishing the Brazilian National Circular Economy Policy to promote resource circularity and environmental sustainability. Such initiatives aim to foster actions to reduce greenhouse gas emissions, increase the participation of biofuels in the national energy matrix, and advance Circular Bioeconomy promotion.

The RenovaBio program is a pioneering global initiative that utilizes the Life Cycle Assessment (LCA) technique to validate decarbonization credits generated by biofuel plants, specifically those related to ethanol and biodiesel facilities, within a regulated market context (Silva et al., 2022).

In contrast to liquid biofuels, solid biofuels in Latin America remain largely excluded from regulatory frameworks that promote decarbonization based on Life Cycle Assessment (LCA) methodologies. While Brazil has an established history with traditional solid biofuels, particularly charcoal, the emergence of densified biofuels such as pellets and briquettes has gained momentum only more recently, largely driven by Small and Medium-sized Enterprises (SMEs) that often lack the institutional and managerial capacity to adopt sustainability-focused practices (Puglieri et al., 2024). Although the RenovaBio program stands as a pioneering initiative by employing LCA to generate carbon credits for ethanol and biodiesel, it does not currently include solid biofuels within its regulatory scope. Nevertheless, RenovaBio may serve as a valuable reference model for the development of a parallel policy dedicated to solid biofuels under the auspices of the Ministry of Mines and Energy (MME), particularly in light of Brazil's recent commitments to energy transition. A key structural limitation, however, is the absence of an obligated party in the solid biofuels market analogous to the fuel distributors in RenovaBio—entities that constitute a highly concentrated and economically influential sector. Designing a mechanism that ensures demand for decarbonization credits from solid biofuels will be essential for replicating the effectiveness of the RenovaBio framework in this context.

The RenovaBio program's calculation framework is founded on RenovaCalc, a model designed to quantify carbon credits derived from biofuel utilization. This tool, adopted by the National Petroleum Agency (ANP), employs the framework of the LCA technique to calculate the carbon intensity of a biofuel. It does so by comparing the biofuel's carbon emissions to those of its equivalent fossil fuel counterpart, quantified in CO_2-eq units. In RenovaCalc, GHG emissions from each process comprising the biofuel life cycle are estimated, resulting in its carbon intensity, which subtracted from the carbon intensity of its equivalent fossil fuel, generates the environmental energy efficiency score of the biofuel and provides access to decarbonization credits (or carbon credits), issued from the sale of certified biofuel, after a registration process conducted by a financial institution and registered in the national stock exchange, the "B3".

The credits traded as CBIO assets (1 CBIO = 1 ton of CO_2 equivalent emission avoided), in 2023, represented more than 45 million CBIOs traded, generating a financial turnover of over 5 billion reais (UDOP, 2024). Silva et al. (2022) in an exploratory LCA using primary and secondary data from pellet and briquette production in Latin America, concluded that there is a possibility of generating carbon credits of up to 68.7 g CO_2-eq/MJ of pellets/briquettes.

Regarding its operation, RenovaCalc calculates emissions based on information from the agricultural, industrial, and distribution phases provided by producers. This generates the biofuel's carbon intensity index, which is then subtracted from the corresponding fossil fuel index (in the case of ethanol and gasoline), thus establishing the Environmental Energy Efficiency Score (NEEA) in g CO_2 eq./MJ.

Therefore, this study aims to develop a robust methodological framework for quantifying the carbon intensity of solid biofuels, specifically pellets and briquettes, by adapting the structure of the RenovaCalc calculator to the specificities of densified biomass. This adaptation incorporates additional technical parameters grounded in Circular Bioeconomy principles, such as waste valorization and carbon circularity, alongside refined allocation approaches including the Circular Footprint Formula. A dedicated computational tool (BioCalc) was developed to operationalize this framework, enabling the modeling of life cycle emissions and the estimation of decarbonization credits. Sensitivity analyses were conducted to evaluate the influence of key variables, such as feedstock origin, energy source, and transportation modes, on carbon intensity results. By providing a harmonized and replicable methodology, this research supports evidence-based policy design and opens new opportunities for monetizing avoided emissions in emerging carbon markets.

1.2 OBJECTIVES

The general objective of this study is to develop a computational tool based on the principles of Life Cycle Assessment (LCA) and inspired by the RenovaCalc model, capable of estimating the carbon intensity and the potential for decarbonization credit generation of pellets and briquettes produced in Latin America. The tool will be grounded in the analysis of the environmental performance of different production systems, taking into account biomass types, technological routes, and regional contexts. The specific objectives are listed below:

- To conduct a critical review of the scientific literature on LCA applied to pellets and briquettes, identifying methodological trends, data gaps, and regional specificities in Latin American contexts.
- Map global public policies that promote bioenergy, with particular emphasis on regulatory instruments that incentivize the use of densified solid biofuels.

- Analyses the applicability and limitations of the Circular Footprint Formula (CFF) for bioenergy systems, comparing its results with conventional LCA allocation methods and discussing its relevance within circular bioeconomy frameworks.
- Assess the environmental impacts of transportation from Latin America to Europe and verify the feasibility of incorporating solid biofuels into decarbonization policies, such as RenovaBio, based on a harmonized analysis of international policy instruments and carbon market mechanisms.
- Propose and develop a novel computational tool for quantifying the carbon intensity and decarbonization credit potential of densified biofuel, incorporating methodological refinements derived from policy analysis and circular economy principles.
- Perform a sensitivity analysis of the developed tool by customizing the main parameters that affect the decarbonization credits calculation, thereby assessing the robustness and reliability of the results

1.3 THESIS STRUCTURE

This work comprises six chapters, which, except for this introductory chapter, are presented in article format. Chapter 2 consists of a bibliographical and documentary review of the research topic. The bibliographical review, entitled *"Overview of Scientific Production on Public Policies Promoting the Use of Solid Biofuels"* was published in the *Proceedings of the VIII Brazilian Congress on Life Cycle Management*. The documentary review involves an extensive investigation into worldwide legislation promoting Bioenergy and could be published in indexed journals.

Chapter 3 presents the study *"The application of Circular Footprint Formula in Bioenergy/Bioeconomy: challenges, case study, and comparison with life cycle assessment allocation methods"*, published in the journal *Sustainability*. This study examined the potential of the Circular Footprint Formula in assessing circularity in bioenergy systems while also pointing out areas for refinement and enhancement in evaluating energy recovery and recycling processes within the Circular Bioeconomy context.

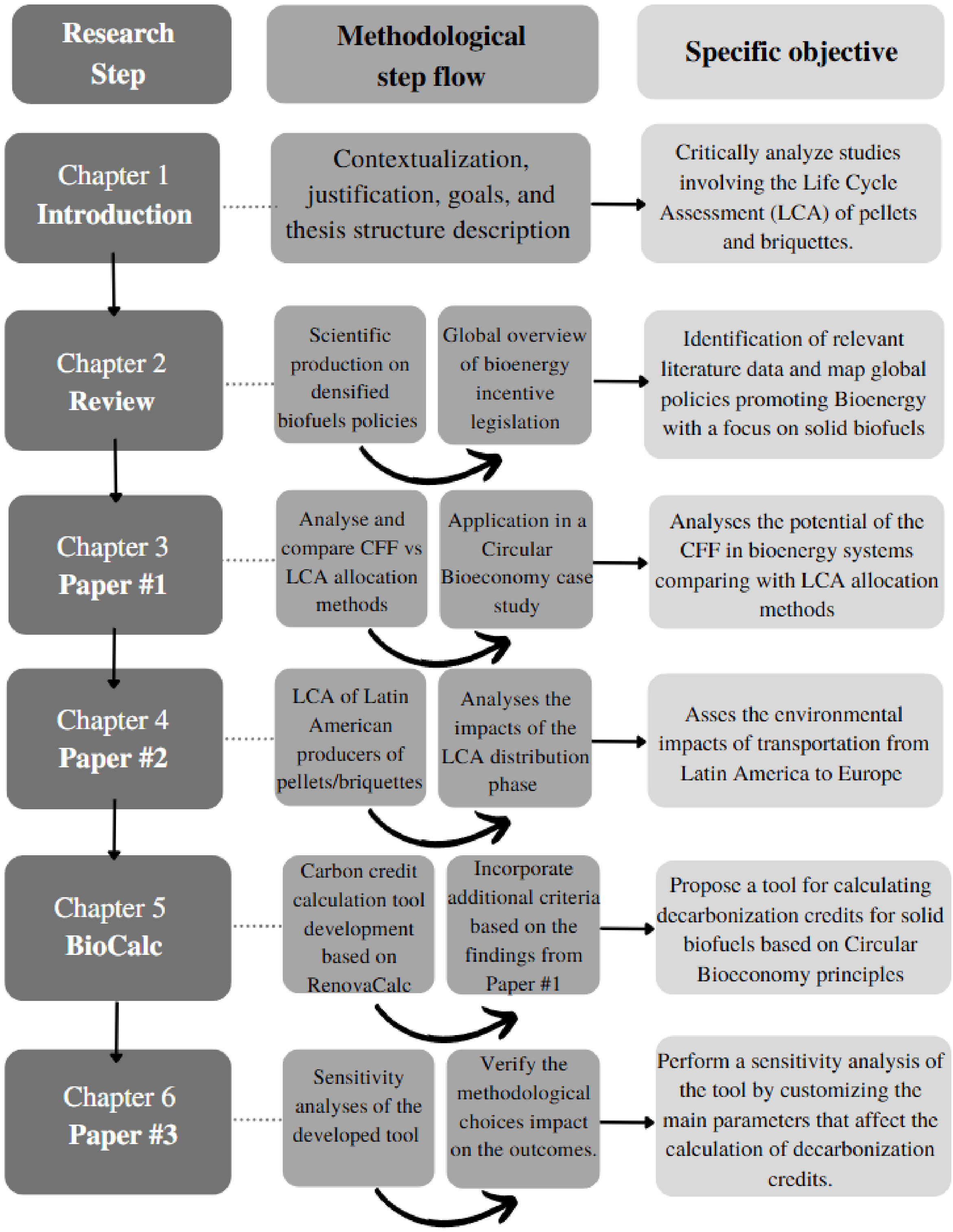
Chapter 4 is an article titled *"The effect of transportation choices for mitigating climate-related impacts: The case of solid biofuels exported to Europe produced by Latin American countries"* published in the journal *Sustainable Production and Consumption*. This work highlighted that transportation choices play a significant role in the environmental emissions associated with the export of pellets and briquettes from Latin American countries to Europe.

Chapter 5, entitled "BioCalc: Technical Description and Application in Carbon Intensity Assessment of Solid Biofuels", presents the development and technical structure of the computational tool BioCalc, designed to quantify the carbon intensity of pellets and briquettes based on LCA principles. The tool is structured according to the framework of RenovaCalc and adapted to the particularities of solid biofuels by incorporating methodological refinements derived from bibliographic reviews, regulatory mapping, and allocation method comparisons. It integrates technical parameters aligned with the Circular Bioeconomy, and its initial application includes sensitivity analyses of key modeling variables such as feedstock origin, logistics, and energy inputs.

Chapter 6, titled *"BioCalc: A Novel Life Cycle-Based Tool for Quantifying the Carbon Credit of Solid Fuels*", expands the application of the BioCalc tool through case studies focused on the carbon credit potential of solid biofuels. The analysis explores different life cycle modeling approaches to evaluate greenhouse gas emissions and carbon intensity associated with pellet production. By applying the tool to diverse production scenarios, the study demonstrates how variations in methodological assumptions, such as emission attribution, feedstock origin, and allocation procedures, can significantly influence environmental outcomes and the estimation of avoided emissions. The results offer important insights for the development of harmonized frameworks in carbon accounting and for supporting the integration of solid biofuels into emerging carbon credit mechanisms.

Finally, the concluding chapter synthesizes the key findings, highlighting its contributions to advancing methodological consistency in LCA applied to bioenergy systems. It also reflects on the practical and policy implications of the results, particularly regarding the potential integration of solid biofuels into carbon credit frameworks. In addition, the chapter outlines recommendations for future research and public policy development aimed at supporting the recognition and effective incorporation of densified biomass fuels into national and international decarbonization strategies. Figure 1.1 delineates the overall structure of the study, detailing the methodological procedures and specific objectives of each chapter.

Figure 1.1 - Thesis structure



2 PUBLIC POLICIES TO PROMOTE BIOENERGY: SOLID BIOFUELS STRATEGIES BASED ON LITERATURE AND A DOCUMENTAL REVIEW

2.1 INTRODUCTION

The growing demand for sustainable energy sources has promoted significant attention to the potential of biomass as a viable and potentially underutilized alternative in various regions (Silva et al., 2022). Brazil, which already stands out in producing liquid biofuels, such as ethanol and biodiesel, presents a favorable scenario for producing plant biomass, especially densified biofuels, such as pellets and briquettes (FAPESP, 2022).

Briquettes are larger products (Figure 2.1b), with a density of 650-1200 kg/m³, a diameter of approximately 60 mm, and a length of 25 to 300 mm. Pellets (Figure 2.1a) are smaller, with a density of 650 to 700 kg/m³, a diameter of 6 to 16 mm, and a length of 25 to 30 mm. Both have a moisture content of 7 to 12% (EMBRAPA, 2012). Briquetting and pelletizing are the most common processes for compacting biomass into blocks ready for burning in stoves, boilers, and cookers, for domestic and commercial purposes (Silva et al., 2022). These processes only change the physical shape of the raw material, preserving its chemical composition. This is an effective strategy for mitigating some undesirable characteristics of agro-industrial byproducts, such as low density, reduced calorific value, and irregular shape. They also add commercial value to the product (Moraes et al., 2019).

Figure 2.1 Illustration of (a) wood pellets and (b) wood briquettes

(a) (b)

In Brazil, biomass accounts for 24.4% of the energy matrix and 4.7% of the electricity matrix, being predominantly composed of sugarcane derivatives (EPE, 2023). On the other hand, the revised Renewable Energy Directive increases the binding target from 32% to a 42.5% share of renewables in the EU energy consumption, intending to achieve 45% (EEA, 2024). This initiative aims not only to reduce carbon emissions into the atmosphere but is also driven, especially after the conflict between Ukraine and Russia, by increasing the continent's independence from energy sources from Russia. In 2022, the EU was dependent on Russian sources for 40% of the gas and 27% of the oil it consumed (McWilliams et al., 2023). Moreover, biomass utilization not only fosters the bioeconomy and a more circular economic approach but also contributes to energy security by diversifying the sources of fuel, thereby reducing reliance on volatile geopolitical factors such as those exemplified by the EU's dependence on Russian energy sources (Muscat et al., 2021).

In this context, it is estimated that over 250,000 new pellet boilers have been installed in Europe in recent years, resulting in a significant increase in pellet consumption, reaching 14.1 million tons in 2021, an 18% increase compared to the previous year (Beenergy, 2022). This surge in demand led to an inflation of nearly 100% in the average price of a pellet package, rising from 0.30 euros/kg in the first quarter of 2022 to 0.53 euros/kg in the last quarter of 2022. However, by the last quarter of 2023, prices had returned to stability, ranging around 0.30 euros/kg (Garcia et al., 2023). Currently, biomass contributes approximately 12% of global energy consumption (Silva et al., 2022), and in Latin America, Brazil has the potential capacity to meet growing energy demands in an environmentally sustainable manner (Matheus et. al., 2024).

However, the global energy matrix is primarily based on the use of fossil fuels (Garcia, 2013), and for the effective integration of biomass into the energy matrix, a comprehensive understanding of the regulations governing it will be necessary, especially in light of environmental challenges associated with its production and exportation (Matheus et al., 2024). The absence of a consolidated normative approach may influence the effectiveness and applicability of initiatives aimed at reducing Greenhouse Gas (GHG) emissions in the global energy matrix (Brazil, 2022).

In light of this, this chapter is structured into two main sections. The first section aimed to map the literature surrounding this theme, identifying, selecting, and synthesizing theoretical evidence regarding the current state of actions initiated by global public management concerning decarbonization. Subsequently, the second section consists of documentary research, delving into the government legislation currently promoting the use of biomass as an energy source, specifically focusing on public policies directed towards solid biofuels such as pellets and briquettes.

The proposed literature review and documentary research also directly align with the thesis's purpose, which is the development of a calculation tool for quantifying carbon credits for solid biofuels. By deeply understanding public policies promoting bioenergy and the scientific aspects related to solid biofuels, it will be possible to substantiate the construction of this tool in a robust and comprehensive manner. The literature review will identify best practices, methodologies, and data used in previous studies, contributing to the development of a reliable model for the calculator. Furthermore, the documentary research on regulations will provide essential information on criteria and guidelines established by regulatory bodies, ensuring that the tool complies with current regulations. Thus, the literature review and documentary research will not only expand knowledge on the subject but also provide fundamental support for the development of a tool of significant relevance for the assessment and promotion of sustainability in the solid biofuel sector.

2.2 OVERVIEW OF SCIENTIFIC PRODUCTION ON PUBLIC POLICIES TO PROMOTE THE USE OF SOLID BIOFUELS

This section of the literature review is based on the research "Overview of Scientific Production on Public Policies to Promote the Use of Solid Biofuels" (Farrapo Junior et al., 2024), which was published in the 8th Brazilian Congress on Life Cycle Management (GCV 2024).

2.2.1 Introduction

The topics of Bioeconomy and Bioenergy have emerged as key considerations in the realm of sustainable development and the transition towards a Circular Economy (CE). Bioeconomy focuses on the efficient utilization of resources to minimize environmental impact and prevent resource depletion (Venkatesh, 2022). On the other hand, bioenergy is a way to add value to agroforestry and industrial waste widely produced worldwide (Omran and Baek, 2022). From the perspective of the Circular Bioeconomy, the utilization of solid bio-waste as an environmentally friendly solution for energy supply has gained significant global relevance (Mohanty et al., 2022). Among the promising sources of bioenergy generation, biomass energy, derived from solid biofuels such as pellets and briquettes, is particularly noteworthy (Yang et al., 2021). Therefore, the expansion of bioenergy utilization relies on the development of effective public policies that support the entire production chain involved in biofuel production.

Given the importance of expanding the entire production chain involved in the production of solid biofuels, this research aimed to conduct a literature review covering this theme. Through this review, it will be possible to identify, select, evaluate, and synthesize theoretical evidence regarding the current state of actions initiated by global public management concerning decarbonization. This will enable the development of tools to assist in pricing the avoided emissions of Greenhouse Gases (GHG).

2.2.2 Methodology

The methodological flowchart applied was based on the study by Oliveira et al. (2016) and was divided into four phases, following the sequence: planning, literature review, data collection, and presentation of results.

Planning: The review is justified by the need to measure and analyze global public policies aimed at reducing carbon footprint, with a focus on solid biofuels (biomass pellets and briquettes). Mapping the state-of-the-art of recent research is important for proposing new studies and will assist in developing recommendations for expanding policies that contribute to carbon footprint mitigation.

The aim is to deepen understanding of studies addressing public policies aimed at reducing carbon footprint through the promotion of solid biofuels from plant biomass. Thus, data were collected on October 19, 2022, from the Web of Science (WoS) and Scopus platforms owned by Clarivate Analytics and Elsevier, respectively. The search was conducted exclusively in English, with no geographical limitations. Search parameters and cutoff criteria are summarized in Table 2.1.

Table 2.1– Search parameters and cutoff criteria

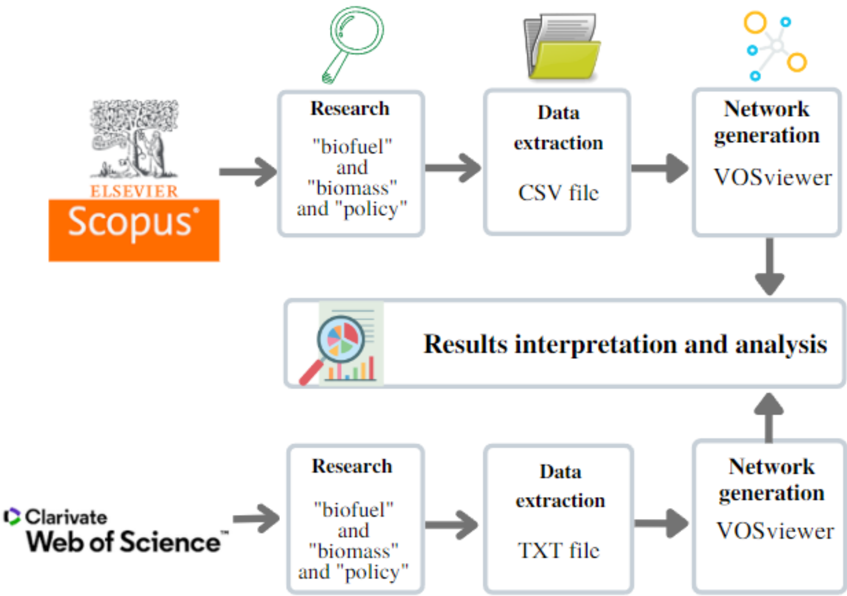
Search Term	"BIOFUEL" and "BIOMASS" and "POLICY”
Fields	Topic, which encompasses the title, abstract, author keywords, and Keywords Plus
Document Types	Papers and reviews
Publication year	2018, 2019, 2020, 2021 e 2022

Source: Own authorship

Literature Review: A total of 987 papers were obtained from the two analyzed databases; however, 293 publications were found in both databases, thus, identified as duplicates. Therefore, the combined total sample consisted of 694 scientific articles. All works remained in the sample for data collection, and the top ten works with the highest number of global citations (across both databases) were meticulously analyzed. Thus, for comprehensive review, works most closely aligned with the review's scope were selected, as highlighted in Table 2.1.

Data Collection: General data were extracted, including title, authors, year of publication, country/region of origin, affiliated journal, type of work, and the work's proposal. VOSviewer® software version 1.6.11 was applied for bibliometric analysis, allowing for the quantification of global citations, the density of relationships among sample articles, and the most frequently used keywords. Figure 2.2 summarizes the methodological flow, which encompasses the identification and collection of articles from the databases (WoS and Scopus), organization of data in text files, generation of graphs, and interpretation of results.

Figure 2.2 - Methodological procedure



Source: Own authorship

2.2.3 Results and Discussion

Out of the 987 works found, it was observed that 513 (52%) were indexed in WoS and 474 (48%) in the Scopus database. In this context, 293 were present in both databases and, therefore, identified as duplicates. Thus, the unified total sample consisted of 694 works. The bibliometric analyses, derived from the VOSviewer® software, were independently studied in each of the databases, as described in section 3.1.

Temporal analysis shows a growing trend in the number of publications over the last five years. In absolute numbers, in the current year of 2022, there are 160 publications on this topic (up to October), representing a 25% increase compared to 2020 with 120 publications. Regarding the journals in which the works were published, the publications were quantified, followed by indicators measuring the average annual number of citations of recent articles published (CiteScore and the Impact Factor - IF) of each journal.

In this regard, the journal Renewable and Sustainable Energy Reviews stands out, concentrating the majority of publications on this topic, with 62 works published (9% of the sample), followed by the journals: Energies (34) and Journal of Cleaner Production (31). Table 2.2 presents the top ten journals that appeared most frequently in the analysis of this topic, along with their respective indicators.

Table 2.2 - Journals that published the most on the topic

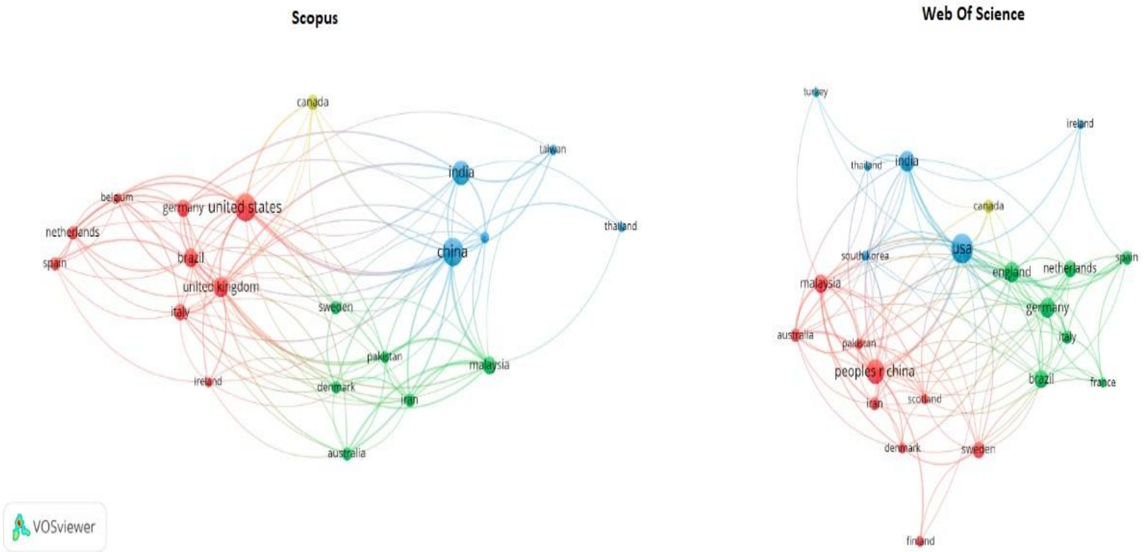
Journal	Papers	CiteScore	IF
Renewable and Sustainable Energy Reviews	62	28.5	16.799
Energies	34	5.0	3.252
Journal of Cleaner Production	31	15.8	11.072
Biofuels, Bioproducts and Biorefining	29		5.239
Biomass and Bioenergy	25	8.8	5.774
Applied Energy	24	20.4	11.446
Bioresource Technology	20	17.4	11.889
Energy	14	13.4	8.857
Renewable Energy	14	13.6	8.634
Science of the Total Environment	14	14.1	10.753

Source: Own authorship

2.2.3.1 Network analysis

Network analysis allows for investigating the connections between countries that publish the most on a particular topic. The visualization of the elements of the VOSviewer® network is based on the distance between two nodes (keywords), indicating the relationship between them in a two-dimensional Euclidean space. The closer the nodes, the greater the affinity between them. Meanwhile, the size of the label and circle is proportional to the node's importance in the network (Van Eck; Waltman, 2022).

Figure 2.3 - Countries Network Analysis



Source: Own authorship

Concerning the Scopus database, it is observed that publications by Brazilian authors have a stronger connection with Europeans (United Kingdom, Germany, and Italy) and North Americans, as can be seen in Figure 2.3 - red cluster. Additionally, a strong connection is also noted between research by authors from China and India (blue cluster), with many works published by both countries, 111 in WoS and 148 in Scopus. In the green cluster, led by Malaysia, there is a strong relationship with Iran and Pakistan and also includes Sweden and Denmark. Canada appears alone in the yellow cluster, with few connections to other countries in the sample.

On the other hand, WoS database publications by Brazilian authors still have strong relationships with European authors: England, Germany, Italy, the Netherlands, and France, located in the green cluster. However, there is little connection with works from authors in the USA, which are allocated in the blue cluster. In this sense, the relationship strength between authors from the USA and India is strong with many documents published, 98 and 45, respectively, and they are more connected with authors from South Korea, Ireland, Turkey, and Thailand, which complements the blue cluster. Chinese authors have many works and citations concerning Malaysia, Pakistan, and Iran (red cluster). Additionally, Canada appears again in the yellow cluster, with few connections to other countries in the sample.

2.2.3.1 Content analysis

Table 2.3 summarizes the works with the highest number of global citations in both the WoS and Scopus databases. In this context, works directly addressing the research theme—biomass, biofuels, and public policies—are selected for thorough reading (highlighted in bold in the table).

Table 2.3 - Characterization of the main works classified based on global citations in both databases

Paper	Authors	Year	Journal	Citations
Biofuel policy in India: A review of policy barriers in sustainable marketing of biofuel	**Saravanan A.P. et al.**	**2018**	**Journal of Cleaner Production**	**301**
Co-pyrolysis of biomass and waste plastics as a thermochemical conversion technology for high-grade biofuel production: Recent progress and future directions elsewhere worldwide	Uzoejinwa B.B. et al.	2018	Energy Conversion and Management	294
Insights into the microalgae cultivation technology and harvesting process for biofuel production: A review	Suparmaniam U. et al	2019	Renewable and Sustainable Energy Reviews	258
Moving towards the second generation of lignocellulosic biorefineries in the EU: Drivers, challenges, and opportunities	**Hassan S.S. et al.**	**2019**	**Renewable and Sustainable Energy Reviews**	**253**
A review of densified solid biomass for energy production	**Bajwa D.S.et al.**	**2018**	**Renewable and Sustainable Energy Reviews**	**239**
Potentials and challenges in lignocellulosic biofuel production technology	**Raud M. et al.**	**2019**	**Renewable and Sustainable Energy Reviews**	**236**
A comprehensive review on cultivation and harvesting of microalgae for biodiesel production: Environmental pollution control and future directions	Yin Z. et al.	2020	Bioresource Technology	202
Review of trends in biogas upgradation technologies and future perspectives	Sahota S. et al.	2018	Bioresource Technology Reports	172
Energy transitions or additions? Why a transition from fossil fuels requires more than the growth of renewable energy	**York & Bell**	**2018**	**Journal of Cleaner Production**	**146**
Mapping Industrial Symbiosis Development in Europe_ typologies of networks, characteristics, performance and contribution to the Circular Economy	Domenech T. et al.	2019	Resources, Conservation and Recycling	138

Source: Own authorship.

In the most cited work in the sample, Saravanan et al. (2018) discuss India's National Biofuel Policy, where the Indian government has implemented biofuel promotion programs over the past two decades. According to the authors, in addition to the high cost of biomass cultivation, there are other conflicting issues common in developing countries, such as the "food versus fuel" debate. In contrast, Hassam et al. (2019) provide an overview of the opportunities involving European second-generation biorefineries, this time focusing on the reuse of agroforestry residues, with their main objective being to refute the argumentation about the "food versus fuel" trade-off by promoting the utilization of lignocellulosic residues that cannot be used as food sources.

Bajwa et al. (2018) conducted a survey on the types of densified biomass (pellets, briquettes, or cubes), their sources (wood-derived or not), and their production processes for energy production, concluding that government incentives are crucial for growth in the use of this energy source. In the same line of reasoning, Raud et al. (2019) present different technologies for the production of lignocellulosic biofuels: liquid, solid, and gaseous, and also conclude that public policies need to be strengthened, especially for the collection of organic waste. Finally, York & Bell (2018) provide a perspective on the use of renewable energy, arguing that the term "transition" would not be appropriate for reducing the consumption of fossil fuels, which would also tend to inhibit the implementation of public policies to reduce the use of non-renewable sources.

2.2.4 Final remarks

From the analyses, it was possible to verify that the researched topic is in a stage of development, due to the progress of publications in the last five years, especially in this last year of 2022, with 160 publications (up to October). The United States and China were the countries with the highest number of publications, where the active participation of India in research development on this topic is also noteworthy. Brazil was classified as a recent contributor, greatly impacted by the repercussions of the National Biofuels Policy - Law No. 13,576 (RenovaBio). Additionally, the journals that published the most on this topic are highlighted, especially the Renewable and Sustainable Energy Reviews, with an impact factor of 16.79, representing 9% of the total publications.

Since the research was limited only to scientific articles, it was not possible to find greater connections between the data found and public policies derived from laws and regulations, as these are not necessarily published in academic texts. To obtain greater accuracy in future work, it is advisable to conduct a survey of existing laws and regulations, especially in countries that are most interested in and effectively apply such policies.

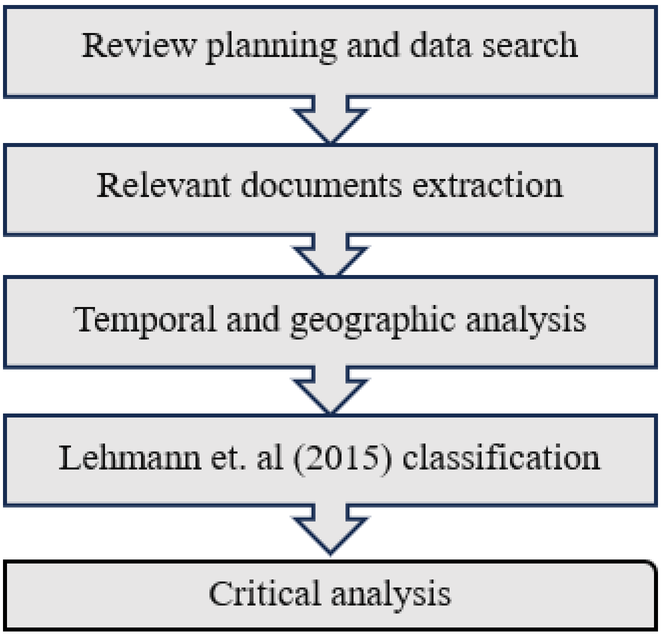
2.3 GLOBAL OVERVIEW OF BIOENERGY INCENTIVE GOVERNMENT POLICIES: A REVIEW AND PROPOSAL OF STRATEGIES FOR SOLID BIOFUELS

Driven by government policies, biofuels are not economically viable without incentives, highlighting the crucial role of supportive regulatory frameworks in shaping the viability and sustainability of the bioenergy industry (Ebadian et. al., 2020). Policies regarding biofuels trading play a pivotal role in shaping the global energy landscape by facilitating the efficient exchange of biomass-derived fuels across borders. This documentary research aims to enhance understanding of the policy's governing and encouraging the utilization of biomass as an energy source. The study seeks to examine current global legislation on this topic, with a specific emphasis on densified biomass such as pellets and briquettes. The evolution of these laws over time and how their geographical location impacts their features are analyzed. Furthermore, strategies for effectively promoting bioenergy in the Brazilian context are discussed.

2.3.1 Methodology

This study employed a structured process encompassing five stages, designed to comprehensively understand and critically analyze global legislation concerning biofuels. The methodological review framework is illustrated in Figure 2.4:

Figure 2.4 - Methodological review framework



Source: Own authorship.

2.3.1.1 Review planning and data search

An examination of Brazilian legislation was performed, focusing primarily on two key enactments: the National Biofuels Policy – RenovaBio (2017) and the Carbon Market Regulatory Framework (2022). These legislative frameworks were deemed indispensable for establishing an initial understanding of the national regulatory context, thereby providing a sturdy foundation for subsequent research phases. Following this, an extensive search was conducted on the climate-laws.org website. Employing a range of strategic keywords such as "Public Policy", "Renewable Energy", "Circular Economy", and "Bioeconomy" this search aimed to identify relevant legislative documents. However, due to the platform's inherent limitations, which restrict the display to a maximum of 100 policies/legislations per search, the query was refined by incorporating additional keywords such as "Biomass" and "Biofuel". Subsequently, the abstracts of the identified legislations were meticulously reviewed to facilitate the stratification and organization of subsequent data analysis.

2.3.1.2 Relevant documents extraction

To conduct a comprehensive geographical mapping, policies from economically influential countries on each continent were selected. Therefore, 31 governmental legislations were identified as the most pertinent to the scope of the research. Countries with policies directly referencing biomass and possessing the highest energy footprints, defined as the sum of all energy inputs required to supply a country's chains of goods and services (Pan et al., 2024) were prioritized. To address identified spatial gaps, such as the absence of legislation from Oceania and the United States, additional filters were applied within the website search tool. These geographical filters, which segmented laws by global region, facilitated the inclusion of six new government policies, notably from New Zealand, representing Oceania, and the Nordic countries, including Finland, Norway, and Sweden.

2.3.1.3 Temporal and Geographic Analysis

The third stage entailed a temporal and geographical analysis of the government regulations. For the temporal analysis, policies were classified based on the decade of their promulgation. This method provided a chronological perspective of regulatory changes over time, enabling the identification of patterns, cycles, and distinctive elements within each period. On the other hand, geographical analysis involves a comparative assessment of the content, incentives, and level of innovation across the continents. This approach not only facilitated the identification of specific regional trends but also enhanced the understanding of disparities and similarities in legislative efforts about biofuels and carbon markets across different regions of the globe.

2.3.1.4 Lehmann et. al (2015) classification

Lehmann et al. (2015) proposed a set of policy options for LCA deployment in legislation aiming to comprehend their legislative characteristics. As a result, governmental policies were categorized based on several key dimensions, including their execution type (mandatory or voluntary), levers (performance or process), use of LCA (direct or indirect), and market role (access or incentive). Furthermore, to enhance comprehension of the collected legislation, the study incorporates the following elements: *Stakeholders* - identifying the parties involved in the regulation, and *Main Environmental Aspect* - elucidating the nature of the interaction between the regulated element and the environment. This systematic classification approach enabled a nuanced examination of the diverse regulatory strategies employed in promoting the adoption and implementation of LCA methodologies within legislative frameworks.

2.3.1.5 Critical analysis

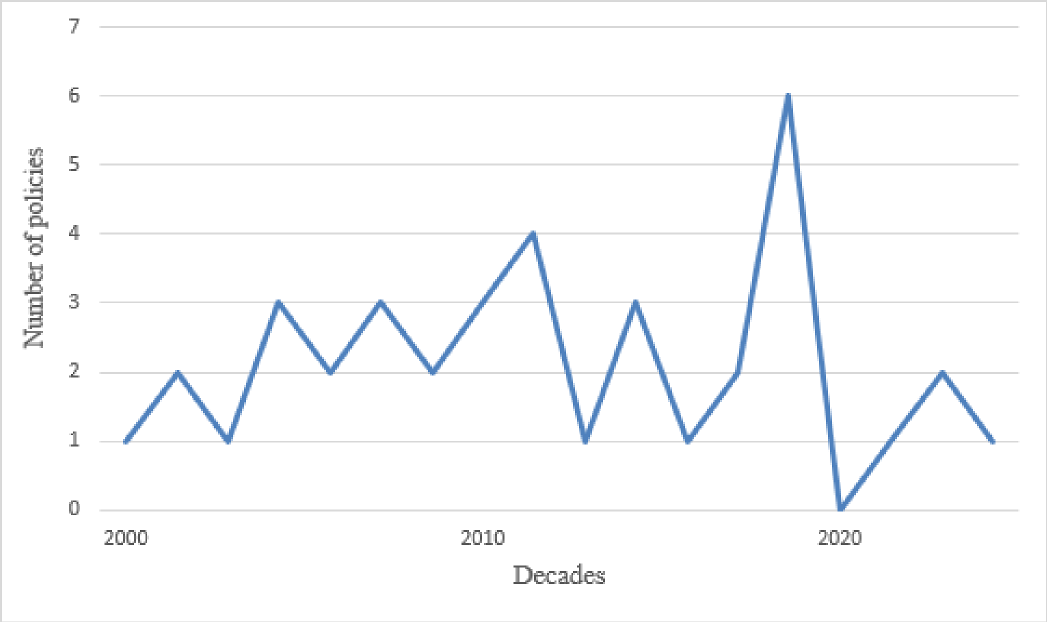
During this phase, analyses were conducted on the stakeholders involved in each policy, examining the key environmental aspects influenced, and developing a comparative assessment of the carbon markets established or envisioned within the studied legislations. In addition, a SWOT matrix was devised, representing a strategic analysis tool based on both internal and external factors pertinent to the Brazilian bioenergy sector. Thus, based on this analysis, a set of strategies was formulated and classified such as Offensive, Defensive, Reinforcement, and Confrontation categories (Weirich, 1982). The formulation of these strategies played a crucial role in delineating the avenues for incentivizing bioenergy in Brazil over both short and long-term horizons.

2.3.2 Results and Discussions

2.3.2.1 Temporal analysis

The temporal analysis of the biofuel policies aims not only to observe transformations in regulatory approaches but also to comprehend the global context that influenced the formulation of these laws over time. This analysis was conducted by grouping regulations by decade, delineating patterns of evolution and countries' responses to environmental challenges. Figure 2.5 illustrates the distribution of these laws over time, spanning the period from 2000 to 2023, providing a comprehensive overview of the regulations studied in the global context.

Figure 2.5 - Policies distribution by year



Source: Own authorship.

It is noteworthy to highlight the Energy Rationalization Act of 1979 (South Korea, 1979), which demonstrates the country's early commitment to promoting sustainable energy sources. However, the prematurity of this legislation is evident in its lack of specificity regarding renewable energies, with the absence of clear measures to promote biomass, for example. While the legislation represents an initial concern for energy efficiency, it lacks the precision and scope necessary to address contemporary climate challenges. Therefore, due to its significant temporal distance from other laws, it was not included in Figure 2.5 or any specific subtopic.

Throughout the decades, certain elements have consistently emerged in environmental legislation. Ambitious goals related to the incorporation of renewable energy sources, financial incentives directed at producers adopting sustainable practices, and strategies aimed at achieving carbon neutrality emerge as recurrent components. These elements underscore the imperative of continuous innovation and adaptation in regulatory strategies, highlighting the need for dynamic approaches to address contemporary environmental challenges.

2.3.2.1.1 2000s Decade

The turn of the millennium marked the onset of a more robust global environmental consciousness, reflected in emerging legislation. In 2000, the Renewable Energy Act was established in Germany (Germany, 2000), representing a more ambitious initiative with a focus on achieving long-term outcomes. This pioneering milestone exerted a significant influence on the creation of similar laws in subsequent years.

In 2007, China reaffirmed its environmental commitment with the Energy Conservation Law (China, 2007), imposing the obligation to submit annual reports on energy savings targets, a practice that subsequently became common and recurrent in numerous countries. This period witnessed the emergence of more assertive regulations, signaling the imperative of effective measures to combat climate change.

2.3.2.1.2 2010s Decade

The second decade of the 21st century witnessed the consolidation and enhancement of environmental legislation, particularly in European countries. At the beginning of the decade, Spain established the Economic Sustainability Law (Spain, 2011), setting an ambitious target of 20% renewable energy by 2020. During this period, mechanisms such as feed-in tariffs and carbon certificates were introduced to incentivize sustainable practices.

In Brazil, in 2017, the National Biofuels Policy (Brazil, 2017) was enacted, creating the RenovaBio program aimed at reducing carbon intensity in the Brazilian energy matrix. The program is based on ten-year carbon emission reduction targets for the national fuel matrix, which are defined through an economic modeling approach and whose achievement is assessed using the RenovaCalc tool, grounded in Life Cycle Assessment (LCA) principles, as established by Resolution No. 758/2018. Additionally, Decarbonization Credits (CBIOs) were also created, generated by the difference in CO_2 emissions between a base scenario (based on the use of fossil fuels) and the actual scenario of each producer, based on the use of the RenovaCalc tool. In Asia, the National Action Plan for Climate Change (India, 2010) was established, prioritizing solar energy and feed-in tariffs. These legislations highlight a growing emphasis on diversifying energy sources and striving for carbon neutrality.

2.3.2.1.3 2020s Decade

The current decade presents a more urgent and immediate response to climate challenges. New Zealand responded with the Climate Emergency Response Fund (New

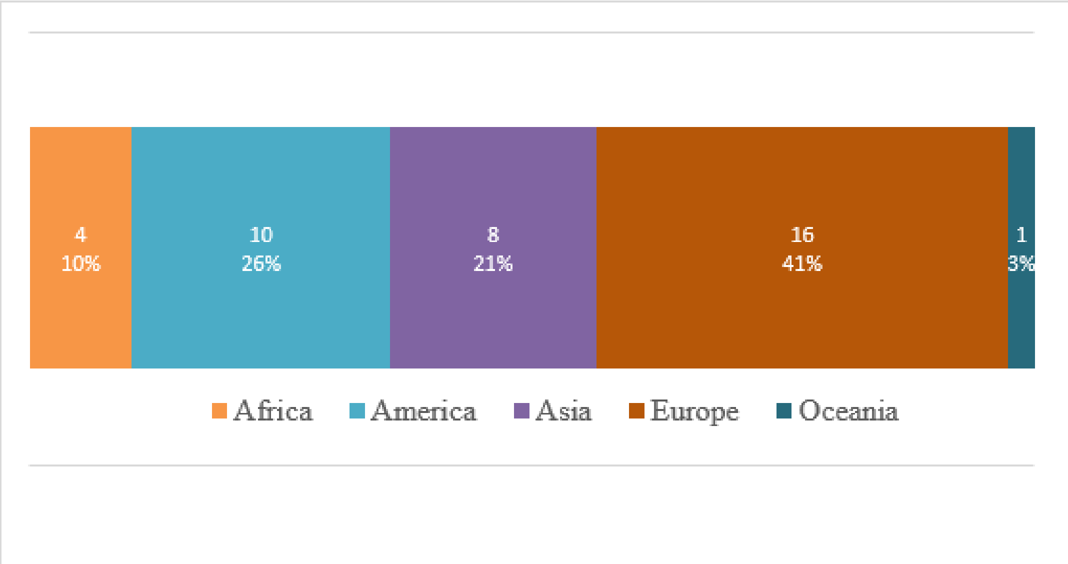
Zealand, 2022), allocating billions of dollars to carbon sequestration initiatives and energy source substitution. This emergency focus signals a growing awareness of the need for swift action to combat climate change.

The United Kingdom expanded the Renewable Domestic Heating Incentive (RDHI) in 2022, reinforcing its commitment to promoting low-carbon heating solutions at the residential level. This policy provides quarterly financial compensation to households that adopt renewable energy technologies for space and water heating, such as biomass boilers, heat pumps, and solar thermal panels, over a period of seven years. The initiative not only encourages the replacement of fossil-fuel-based systems but also stimulates consumer awareness of the environmental and economic benefits of renewable technologies. By targeting the residential sector, which accounts for a significant share of national GHG emissions, the RDHI represents a strategic effort to decentralize decarbonization and foster behavioral change at the individual and community scales. This legislation exemplifies the growing emphasis on sustainability within household infrastructure and highlights a broader policy trend in the 2020s: the dynamic adaptation of regulatory frameworks to rapidly evolving climate conditions and technological capabilities, as well as the prioritization of immediate and localized action in pursuit of long-term climate goals.

2.3.2.2 Geographic analysis

The findings unveil a heterogeneous distribution of biofuel laws, with Europe leading in terms of quantity and diversity, showcasing a substantial commitment to legislative approaches for sustainability. The Americas and Asia exhibit a significant number of laws, while Africa demonstrates efforts on a smaller scale. The distribution of legislation can be visualized in Figure 2.6:

Figure 2.6 - Policies distribution by continent



Source: Own authorship.

The following subtopics delineate the general contexts of each continent, emphasizing certain legislations and their technical intricacies while summarizing shared elements within each scenario.

2.3.2.2.1 Africa

The African context reveals significant differences and similarities in the approaches adopted by the countries in question. The temporal discrepancy between the periods of legislation creation, ranging from 2010 to 2018, may reflect varying levels of awareness and political readiness among the countries.

Regarding the themes of the legislation, South Africa presents a more specific focus with the Renewable Energy Independent Power Producer Program (REIPPPP), while Kenya, Tunisia, and Uganda share a more generic designation related to the global carbon market. This distinction suggests a higher specificity in the goals and objectives outlined by South Africa compared to other countries, whose legislations seem to encompass a broader range of strategies and international collaborations, also aligning more synergistically to incentivize the use of bioenergy.

Concerning the concrete measures outlined in the legislation, emblematic examples stand out. South Africa, through the REIPPPP, establishes a program where companies are incentivized to submit competitive proposals and self-finance sustainable energy production projects, resulting in an estimated reduction of over 22 million tons of CO_2eq (South Africa, 2011). Kenya, on the other hand, adopts a feed-in tariff policy for renewable energies, providing fixed tariff payments to attract investments in the sector (Kenya, 2010).

Tunisia and Uganda, both engaged in the Global Carbon Market, demonstrate a commitment to participating in international negotiations on new carbon markets. However, their approaches differ in terms of specific projects, with Tunisia collaborating with the private sector on initiatives such as low-clinker cement production and waste reuse (Tunisia, 2018), while Uganda adopts more general measures, such as policy guidance on the carbon market and seeking regional cooperation on markets and climate finance in East Africa (Uganda, 2018).

From a comprehensive perspective, it is observed that the policies adopted by African countries tend to favor the implementation of feed-in tariffs, in addition to active participation in global carbon markets. The response to climate change emerges as a key point of convergence among these nations, reflecting the shared commitment of African nations to environmental sustainability and greenhouse gas emissions mitigation. There is no specificity regarding densified biomass, as they are generally encompassed within the concept of renewable energy sources by the regulations.

2.3.2.2.2 America

The Brazilian National Biofuels Policy, implemented in 2017, stands out for the creation of RenovaBio, which introduces Biofuel Decarbonization Credits (CBIOs), each equivalent to one ton of avoided carbon. This system incentivizes emission reduction and establishes an energy efficiency score that is converted into CBIOs, which are actively traded on the stock exchange (B3), showcasing an approach based on financial incentives and carbon offsets (Brazil, 2017). Within the proposed Carbon Regulatory Framework, Brazil seeks to establish guidelines for a carbon trading and pricing system. This proposal suggests a more comprehensive approach, aligned with international trends in combating climate change through market mechanisms (Brazil, 2022).

In Canada, the Pan-Canadian Framework on Clean Growth and Climate Change, implemented in 2016, demonstrates a notable focus on progressively pricing carbon, reaching up to 50 dollars per ton of CO_2 equivalent emitted in 2022. This legislation emphasizes carbon storage in forests and promotes the use of wood in construction, highlighting a strategy that integrates environmental and economic considerations and fosters ecosystem services (Canada, 2016).

On the other hand, in South America, the Chilean creation of carbon pricing instruments and the projection of a national emission reduction certificate market by 2023 reflect an approach aimed at creating economic incentives through the Global Carbon Market. The continuation of carbon taxes, initiated in 2017, also demonstrates a long-term commitment to carbon pricing (Chile, 2018). In Colombia, multiple legislations address various aspects. The Law of Rational and Efficient Energy Use of 2001 holds the Ministry of Mining and Energy responsible for energy efficiency programs, including incentives such as VAT exemption on biomass boiler installations (Colombia, 2001). Other policies, such as guidelines for promoting bioenergy production (Colombia, 2008) and the Law of Non-Conventional Energies (Colombia, 2014), reflect strategies for diversifying the energy matrix and promoting energy efficiency.

The United States, with the Alternative Energy Portfolio Initiative (United States, 2009) stands out for creating Alternative Energy Certificates (AECs), generated and sold to incentivize the installation of alternative energy systems. AECs are granted to energy producers based on the amount of clean energy produced, with one credit for each megawatt-hour. This approach of financial incentives demonstrates a strategy that promotes active participation of both the public and private sectors in transitioning to cleaner energy sources.

Mexico, through the Renewable Energy Utilization Law of 2008, demonstrates a more regulatory approach (Mexico, 2008). Meanwhile, the General Law on Climate Change of 2012 stands out for the subsequent creation of the Promotion and Development of Bioenergetics Law, aiming at transitioning to a low-carbon economy with a high prominence of biomass (Mexico, 2012).

In a broader scope, legislations in the Americas demonstrate a notable inclination towards instituting carbon pricing policies, coupled with the establishment of goals concerning the use of biofuels. Additionally, the implementation of financial incentives, linked to obtaining decarbonization credits such as CBIOs and AECs, aimed at promoting clean energy production, is observed. However, despite the significant focus on liquid biofuels, the region still lacks prominence in densified biomass, such as pellets and briquettes, with tax reductions on biomass boiler installations being the only legislation that exclusively covers these energy sources.

2.3.2.2.3 Asia

The Chinese Energy Conservation Law of 2007 (China, 2007), stands out for imposing annual reports to local governments on energy-saving targets. Additionally, it prohibits the construction of energy generation units that do not comply with national energy conservation regulations, highlighting a stringent approach to reducing the use of fossil fuels.

India, on the other hand, presents a variety of laws addressing different aspects of energy sustainability. The National Electricity Policy of 2005 prioritizes hydroelectric power and the reduction of damage caused by the use of coal thermal energy (India, 2005). Also, the National Action Plan on Climate Change (NAPCC) of 2008 emphasizes strategies for climate change adaptation, including the creation of feed-in tariffs for renewable energies, with a greater focus on solar energy (India, 2008). Among Indian legislations, the Renewable Purchase Obligation (RPO) of 2003 stands out for determining that electricity distribution licensees must procure a minimum share of their electricity from renewable sources, with increasing targets over time (India, 2003). The National Clean Energy Fund (NCEF) of 2010 demonstrates a financial approach, creating a fund to finance clean and renewable energy projects and imposing levies on coal production and imports (India, 2010).

South Korea, as one of the pioneers in creating legislation to promote renewable energy in 1979, adopted an approach that includes loans from the Energy Efficiency Fund. This measure, in effect since 1980, seeks to encourage investments in energy efficiency and conservation, highlighting a long-standing concern for sustainable practices (South Korea, 1979).

In summary, Asian legislations indicate a range of approaches, from stringent conservation measures to financial and regulatory strategies aimed at promoting more sustainable energy sources. In this regard, India stands out for the wide range of distinct legislations focused on reducing greenhouse gas emissions. Additionally, India was also the Asian country that gave more prominence to solid biomass but did not bring any specificity about densified biofuels, mentioning the raw material in a more generalistic manner.

2.3.2.2.4 Europe

Findings obtained within the European continent have revealed notable diversity, stemming from the vast array of countries and prominent legislations existing in the region. Germany, through the Renewable Energy Act of 2000, sets an ambitious target of 80% energy generation from renewable sources by 2030, alongside offering financial incentives to biomass producers (Germany, 2000). In contrast, Spain, with Law 2/2011, prioritizes the purchase of carbon credits from domestic producers, demonstrating a focus on domestic emissions trading (Spain, 2011).

Finland, with the National Bioeconomy Strategy of 2014, focuses on supporting small and medium-sized enterprises to expedite the commercialization of materials resulting from an efficient bioeconomy (Finland, 2014). This approach highlights a strategy of supporting the development and scaling of new materials, as opposed to the broader commercial focuses of most legislations.

The French Environmental Assessment in Public Decision-Making of 2023, outlines goals to achieve carbon neutrality by 2050, emphasizing the importance of biomass in the National Biomass Mobilization Strategy (SNMB) (France, 2023). On the other side, Italy, with various laws including the Ministerial Decree of 2017, establishes minimum percentages of biofuels, demonstrating a commitment to the gradual incorporation of more sustainable sources into its energy mix (Italy, 2017).

Portugal, through Decree-Law No. 117/2010, incentivizes biofuel production with minimum percentage criteria. With a target of 10% incorporation by 2020, producers are required to prove compliance with the target through the calculation of Biofuel Titles (TbB) or by purchasing titles from other producers. Each TbB represents the incorporation of a one-tonne equivalent of oil (Tep) of biofuels, with greater valorization for waste-based biofuels and wood-cellulosic raw materials. Also in Portugal, the Operational Program for Sustainability and Resource Efficiency (POSEUR) highlights support for clean energy generation projects, including biomass (Portugal, 2014).

The United Kingdom, with the Renewable Domestic Heating Incentive (DRHI), promotes the transition to renewable heating systems. The Carbon Plan of 2011 sets out a comprehensive roadmap to 2050, indicating the country's intention to reduce reliance on fossil fuels (United Kingdom, 2022). Also, Sweden, through the Renewable Energy Strategy of 2017, prioritizes increasing the share of renewable sources, especially biomass, in its energy mix (Sweden, 2017). Turkey, with Act No. 5346 of 2005, emphasizes the obligation to provide grid access for renewable energy generators and feed-in tariffs for independent producers (Turkey, 2005).

The European Union, through the EU-RED of 2018, mandates the obligatory use of biofuels in fuel blends and introduces Renewable Energy Certificates (European Union, 2018), while the EU Bioeconomy Directive highlights partnerships with the private sector to create a sustainable circular bioeconomy.

In summary, Europe is distinguished by formulating ambitious targets aimed at renewable energy generation. Additionally, it stands out for implementing various financial incentives for biomass producers, as well as instituting funds and operational programs aimed at promoting sustainability. In this regard, of all the regulations analyzed, the DRHI was the one that most favored the use of densified biomass, in the form of pellets, with quarterly financial compensations provided to residents who demonstrated the use of this biofuel for heating their homes (United Kingdom, 2022).

2.3.2.2.5 Oceania

The sole noteworthy legislation identified in the Oceania region was the enactment of the Climate Emergency Response Fund in 2022 in New Zealand. This emergency fund was established with a financial allocation of 4.5 million dollars, aimed at its utilization in collaborations with the private sector for the development of new technologies. Additionally, ongoing initiatives to establish a new carbon market are noteworthy, albeit still in the initial phase (New Zealand, 2022). While directly mentioning the incentive for biomass use, the legislation does not specify densified biofuels and makes no direct reference to pellets or briquettes.

2.3.2.3 Lehmann et al. (2015) classification

The structural elements delineate distinct characteristics inherent in potential policy alternatives. The features reflect different enforcement approaches (mandatory or voluntary), levers (on a process or a product level), stringencies on the use of LCA (direct or indirect), and different market roles (access or incentive). Also, for a better understanding of the content of the collected laws, the following elements have been included: Stakeholders - listing the stakeholders involved in the regulation, and Main Environmental Aspect - detailing the form of interaction between the element involved in the policy and the environment. Table 2.4 shows the classification adapted from Lehmann et al. (2015) to the set of government policies obtained in the review.

Table 2.4 - Government policies characterization according to Lehmann et. al. (2015) adapted model

Country	Year	Policy	Type of enforcement	Lever	Use of LCA	Market role	Stakeholders	Main environmental aspect
South Korea	1979	Renewable Energy Promotion Law	Voluntary	Performance	Indirect	Incentive	Government and Producers	Carbon Emissions
Germany	2000	Renewable Energy Law (Erneuerbare-Energien-Gesetz - EEG)	Mandatory	Performance	Indirect	Access	Government, Producers and Final Consumer	Carbon Emissions
Colombia	2001	Law 697/2001 - Rational and Efficient Use of Energy	Mandatory	Process	Indirect	Access	All	Carbon Emissions
Norway	2001	ENOVA	Voluntary	Process	Indirect	Incentive	All	Carbon Emissions
India	2003	Renewable Purchase Obligation (RPO)	Mandatory	Process	Indirect	Access	Government and Producers	Carbon Emissions
Italy	2005	Decree no. 128/2005 and Ministerial Decree of 13-dec-17	Mandatory	Performance	Indirect	Access	Government and Producers	Consumption of Fossil Fuels
India	2005	National Electricity Policy 2005	Mandatory	Performance	Indirect	Access	All	Carbon Emissions
Türkiye	2005	Renewable Energy Law (Act No. 5346) (2005)	Mandatory	Process	Indirect	Access	Government and Producers	Carbon Emissions
Philippines	2007	Biofuels Acts RA 9367 and amending Act RA 10745	Mandatory	Process	Indirect	Access	Government and Producers	Consumption of Fossil Fuels
China	2007	Energy Conservation Law	Mandatory	Performance	Indirect	Access	Government and Producers	Natural Res. depletion
Colombia	2008	Conpes 3510/2008 - Policy guidelines for the promotion of biofuel production	Voluntary	Process	Indirect	Incentive	Government	Carbon Emissions
India	2008	National Action Plan for Climate Change (NAPCC) 2008	Voluntary	Process	Indirect	Incentive	Government and Producers	Carbon Emissions
Mexico	2008	Law for the Use of Renewable Energy	Voluntary	Process	Indirect	Incentive	Government and Producers	Carbon Emissions
Poland	2009	ENERGY TRANSITION FINANCING	Voluntary	Performance	Indirect	Access	Government and Producers	Carbon Emissions
U.S.A	2009	Alternative Energy Portfolio Standard	Mandatory	Process	Indirect	Access	All	Carbon Emissions
Portugal	2010	Decree-Law No. 117/2010 - Establishes sustainability criteria for the production and use of biofuels and bioliquids	Mandatory	Performance	Indirect	Access	Government and Producers	Consumption of Fossil Fuels
India	2010	National Clean Energy Fund (NCEF)	Mandatory	Process	Indirect	Access	Government and Producers	Carbon Emissions

Kenya	2010	National Strategy in response to climate change	Voluntary	Process	Direct	Access	Government and Producers	Carbon Emissions
European Union	2011	Carbon Plan (2011)	Mandatory	Process	Direct	Access	All	Carbon Emissions
South Africa	2011	REIPPPP (2011)	Voluntary	Process	Indirect	Access	Government and Producers	Carbon Emissions
Spain	2011	Law 2/2011, of March 4, of Sustainable Economics	Voluntary	Performance	Indirect	Access	Government and Producers	Carbon Emissions
Italy	2011	Ministerial Decree 28/2011	Voluntary	Performance	Direct	Incentive	All	Carbon Emissions
Mexico	2012	General Climate Change Law	Voluntary	Performance	Indirect	Incentive	Government	Carbon Emissions
Colombia	2014	LAW 1715/2014	Voluntary	Process	Indirect	Access	All	Consumption of Fossil Fuels
Finland	2014	Finland's National Bioeconomy Strategy (2014)	Voluntary	Performance	Direct	Access	Government and Producers	Carbon Emissions
Portugal	2014	PO SEUR - Operational Program for Sustainability and Efficiency in the Use of Resources (2014)	Voluntary	Process	Indirect	Incentive	All	Natural Res. depletion
Canada	2016	Framework for clean growth	Mandatory	Process	Indirect	Incentive	Government and Producers	Carbon Emissions
Brazil	2017	National Biofuels Policy (Law 13,576)	Mandatory	Performance	Direct	Incentive	Government and Producers	Carbon Emissions
Sweden	2017	Sweden's Renewable Energy Strategy (2017)	Voluntary	Process	Indirect	Incentive	All	Carbon Emissions
European Union	2018	EU-RED	Mandatory	Process	Direct	Access	All	Carbon Emissions
Chile	2018	Global Carbon Market	Mandatory	Performance	Direct	Incentive	Government and Producers	Carbon Emissions
India	2018	Global Carbon Market	Voluntary	Process	Indirect	Incentive	Government and Producers	Carbon Emissions
Tunisia	2018	Global Carbon Market	Voluntary	Process	Indirect	Incentive	Government	Carbon Emissions
Uganda	2018	Global Carbon Market	Voluntary	Process	Indirect	Incentive	Government	Carbon Emissions
European Union	2018	EUROPEAN UNION DIRECTIVE ON BIOECONOMY 2018	Voluntary	Performance	Direct	Incentive	Government and Producers	Natural Res. depletion
Brazil	2021	2022 CARBON MARKET REGULAR FRAMEWORK	Mandatory	Performance	Indirect	Incentive	All	Carbon Emissions
European Union	2022	Domestic Renewable Heat Incentive (DRHI)	Voluntary	Process	Indirect	Incentive	Government and Producers	Carbon Emissions
New Zealand	2022	Climate Emergency Response Fund	Voluntary	Process	Indirect	Incentive	All	Carbon Emissions
France	2023	How to better include environmental assessment in public decision-making	Voluntary	Performance	Direct	Incentive	All	Natural Res. depletion

In subsequent sections (2.3.2.3.1 to 2.3.2.3.6), the results will be discussed according to each of the adapted structural elements, as outlined in Table 2.4.

2.3.2.3.1 Type of Enforcement

Mandatory policies consist of legally binding regulations with specified requirements, such as target values to be met. For instance, RenovaBio mandates a minimum percentage of biofuel participation in the fuel matrix of producers (Brazil, 2017). On the other hand, voluntary policies, as indicated by Lehman et al. (2015), are not legally binding and aim for indirect effects. An example of this is the REIPPPP in South Africa, which funds private sustainable energy projects without obligating existing producers to generate any specific percentage of renewable energy.

The observed scenario suggests a balanced approach between mandatory legal compliance and the promotion of voluntary actions. While there is a slight predominance of voluntary legislation, particularly evident in the European context, it is reasonable to anticipate significant changes in the future. This expectation stems from the goals outlined in the 2030 agenda, directly linked to Sustainable Development Goals (SDGs) 7 (Affordable and Clean Energy) and 13 (Action Against Global Climate Change), as articulated by the United Nations (UN) in 2024. Thus, intending to support renewable energy integration into the global energy matrix, the trend is for this market to transition from its current voluntary nature to acquire mandatory status soon.

2.3.2.3.2 Levers

Performance levers establish product requirements, often necessitating redesign, while process policies dictate requirements to be implemented at the company level to enhance processes (LEHMAN et al., 2015). For instance, a performance regulation like the DRHI mandates the use of renewable sources for energy generation (United Kingdom, 2022), whereas a process requirement would entail the implementation of minimum percentages of biofuels by producers, as stipulated in Decree-Law No. 117/2010 (Portugal, 2010). The division observed in this structural element closely mirrored the type of application, albeit presenting a slightly less balanced scenario.

It is paramount to underscore that many pieces of legislation incorporated control instruments covering both procedural and performance aspects, albeit with a predominant emphasis on one domain. Consequently, recognizing the necessity of addressing both dimensions is crucial for formulating more effective legislation. Understanding the importance of integrating these fronts is essential to promote comprehensive and holistic approaches within the regulatory context.

2.3.2.3.3 Use of LCA

Policies that directly establish target objectives based on Life Cycle Assessment (LCA) or Life Cycle Thinking (LCT) studies are classified as direct. Conversely, indirect policies utilize LCA data as supplementary sources during the preparation process (LEHMAN et al., 2015). For instance, RenovaBio serves as an example of a regulation that relies on LCA to calculate the impacts generated by each biofuel (Brazil, 2017), while other similar regulations, like Decree-Law No. 117/2010, employ alternative methods for impact calculation (Portugal, 2010). Although the results indicate a greater prevalence of indirect utilization, an examination of legislation enacted after 2010 reveals a more balanced scenario, suggesting an upward trend in the direct application of Life Cycle Assessments (LCA).

2.3.2.3.4 Market role

Market Access policies establish minimum requirements for products to enter the market. In the context of Market Incentive policies, promotional structures are designed for products that demonstrate greater environmental efficiency (LEHMAN et al., 2015). For instance, the Renewable Energy Law (Germany, 2010) serves as an example of market access regulation, stipulating that energy must have a renewable origin as a prerequisite for granting financial incentives. Additionally, exemplary instances of market incentive regulations include those that mandate the creation of carbon credits, directly linked to the performance of products in reducing CO2 emissions, such as Biofuel Decarbonization Credits (CBIOs) (Brazil, 2017).

As depicted in Table 2.4, there is a balanced distribution of market roles played by legislation in the global analysis. However, when focusing on legislation instituted after 2010, a more pronounced trend towards the development of legislative measures aimed at encouraging the market becomes noticeable.

2.3.2.3.5 Stakeholders

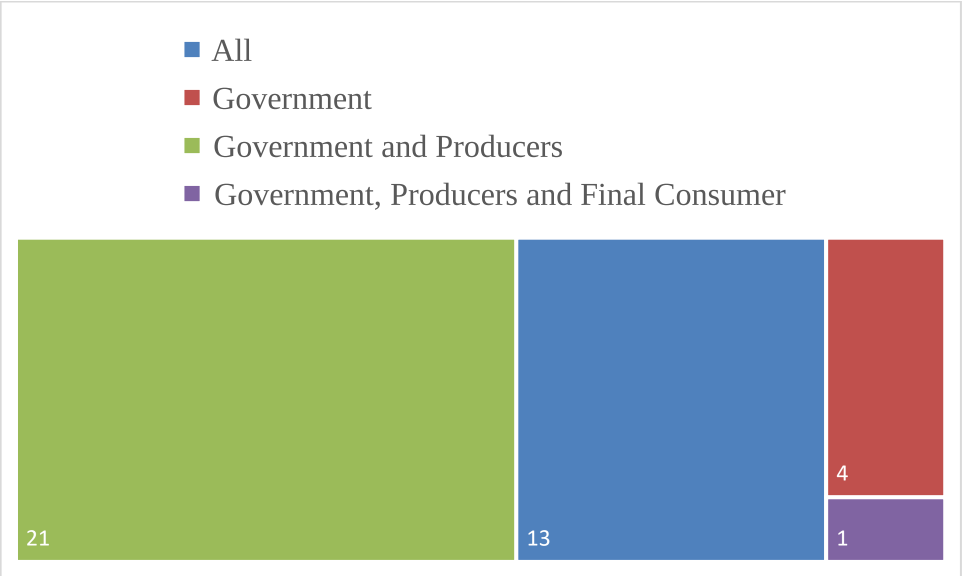
According to the definition established by the technical standard ABNT NBR ISO 31000:2018, stakeholders refer to individuals or organizations that can influence, be influenced, or be perceived to be affected by a specific decision or activity of a given organization. Within the scope of the legislative context, the following set of stakeholders was established:

Government, Producers, Distributors, Society, and Final Consumer. Each legislation had its main stakeholders identified, resulting in the visual representation presented in Figure 2.8.

In addition to the fact that all legislation includes the government as an interested party, due to its central role in the creation and application of laws, a significant presence of producers, end consumers, and distributors is noteworthy. Among these other highlighted stakeholders, producers were the most influenced, with a considerable range of regulations involving specific goals and restrictions on energy production, seeking ways to reduce the impacts of the energy matrix directly from the energy source.

Furthermore, few legislations indicate specific changes for distributors, and these changes are normally related to a minimum percentage acquisition of energy from renewable sources.

Figure 2.7 - Policies by Stakeholders



Source: Own authorship.

2.3.2.3.6 Main environmental aspect

As defined by the technical standard ABNT NBR ISO 14.040 – 14.044, environmental aspects are intrinsic elements of the activities, products, or services of an organization that can interact with the environment.

In the legislative context, particularly focusing on bioenergy incentives, a specific set of environmental aspects was delineated and utilized. This set encompasses the following elements: Reduction in Carbon Emissions (CO_2), Control of Fossil Fuel Consumption, Sustainable Use of Natural Resources, Waste Production Control, Impact on Biodiversity, and Improvement in Air and Water Quality.

The predominance of the environmental aspect associated with "Reduction in Carbon Emissions," evident in 31 of the legislations, underscores a clear prioritization of mitigating climate change. Furthermore, the attention given to "Control of Fossil Fuel Consumption" in 4 pieces of legislation indicates a targeted approach to reducing dependence on non-renewable energy sources. This approach may involve initiatives promoting energy efficiency, diversification of the energy matrix, or implementation of restrictions on excessive fossil fuel consumption, aiming at long-term sustainability. Such measures align with discussions held during the 2023 United Nations Climate Change Conference (COP28), during which the UN chief advocated for the total elimination of fossil fuel burning in the short term (UN, 2023).

Similarly, the attention devoted to "Sustainable Use of Natural Resources" in four legislations suggests a concern attributed to biodiversity conservation, ecosystem protection, and ensuring practices that prevent environmental degradation. Although direct data are not available, it is crucial to note that, overall, all legislations encompass a wide variety of environmental aspects. The three aspects highlighted in the analysis were selected due to their prominence in the regulatory texts and goals of each legislation, reflecting their predominant importance. Despite not being explicitly mentioned in any legislation, the environmental aspect related to particulate matter emissions should also be considered when placing greater emphasis on solid biofuels. This is because such emissions are highly relevant to the preservation of human health and air quality (COHEN et al., 2017).

2.3.2.4 Related Credit Markets

The majority of the legislation reviewed does not explicitly address the establishment or regulation of carbon credits. Nonetheless, certain countries have adopted distinct strategies to incentivize greenhouse gas emissions reduction, which could lead to the creation of a carbon credits market within their respective jurisdictions.

In the European context, the European Union introduced the EU-RED (2018), which implemented Renewable Energy Certificates. Each certificate is allocated for every megawatt-hour (MWh) of renewable electricity generated, representing energy production from renewable sources and resembling a form of carbon credit.

In Brazil, the National Biofuels Policy (2017) introduced CBIOs, each equivalent to one ton of carbon emissions prevented. This initiative aims to stimulate biofuels production and consumption, establishing a carbon credits market in the country. Additionally, Bill No.

412/2022 is currently under consideration in the Brazilian National Congress, seeking to comprehensively regulate the carbon market in Brazil.

Portugal, under decree law no. 117/2010, mandates producers to demonstrate achievement of a minimum target of 10% incorporation. This can be achieved by calculating Biofuel Bonds (TbB) or by purchasing these bonds from other producers. Each TdB corresponds to the incorporation of one ton of oil equivalent (Tep) of biofuels, with its value varying based on the biofuels' origin.

In Canada, the Clean Growth Framework (2016) introduced incrementally increasing carbon tax pricing, promoting carbon sequestration in forests, and advocating for the use of wood in construction, bioenergy, and bioproducts. Although not explicitly mentioning carbon credits, this approach aligns with emissions reduction strategies and could potentially lead to the creation of similar instruments.

Chile's 2018 legislation established carbon pricing instruments and anticipates the establishment of a national market for the sale of carbon emission reduction certificates by 2023.

In summary, while many legislations emphasize renewable energy and emissions reduction initiatives, few directly address a possible carbon credit market creation, with no specific tool exclusively linked to the utilization of densified biofuels.

2.3.2.5 SWOT analysis of the bioenergy sector in Brazil

An adaptation of the bioenergy SWOT matrix proposed by Catron (2013) was conducted to tailor it to the specific Brazilian scenario. This adaptation involved cross-analyzing relevant internal and external factors to identify strategic actions that could enhance the Brazilian bioenergy landscape. External factors, comprising opportunities and threats, are delineated based on their impact, ranging from 1 (small impact) to 5 (large impact), as well as the timeframe for action, categorized as short (S), medium (M), or long (L). Figure 2.8 shows the analysis.

Figure 2.8 - Brazilian SWOT analysis of the bioenergy sector

Strengths	***Weaknesses***
Large biomass generator	Potential for negative environmental consequences
Additional income generation for producers	Lack of technologies and infrastructure
Incentive for better land management	Energy consumption in the biomass densification process
Utilization of waste	CO_2 emissions during long-distance transport
Opportunities	***Threats***
Increase in fossil fuel prices (M, 3)	Political uncertainties (S, 5)
Public and governmental support (M, 3)	Competition with other energy sources (M, 5)
Creation of new technologies and infrastructures (L, 3)	Lack of private sector investment (L, 1)
Rising demand for renewable energy sources (S, 5)	Availability of raw materials (M, 3)
Potential for carbon credit generation (S, 3)	

Source: Own authorship.

2.3.2.5.1 Offensive Strategy (Strength X Opportunity)

Capitalizing on the surge in fossil fuel prices and strong public support, implement awareness campaigns highlighting the benefits of bioenergy, emphasizing biomass as a sustainable and economically viable alternative. Specifically, underscore its capacity to generate additional income for producers.

Additionally, explore new markets, leveraging the opportunity presented by northern European countries' inability to fully meet their pellet demands. Brazil, responsible for 3.3% of global pellet production in 2022, approximately 1,550,000 tons (ABIPEL, 2022), can strategically enter the international pellet market (Tavares & Tavares, 2015).

2.3.2.5.2 Confrontation Strategy (Strength X Threat)

Address political uncertainties and counter competition from other energy sources by forging strategic alliances with producers and private sector entities. Engage actively in international political dialogues to establish a robust regulatory framework and collaborate with sector stakeholders to bolster the biomass position. Invest in sustainable modes and optimize logistical strategies to minimize CO_2 emissions during long-distance transport.

2.3.2.5.3 Reinforcement Strategy (Weakness X Opportunity)

Foster partnerships with technology and infrastructure companies to address existing deficiencies and launch research and development (R&D) initiatives targeting technological innovations in biomass production and application. Capitalize on emerging technologies and abundant raw material availability. Explore potential opportunities for generating carbon credits to catalyze bioenergy adoption, thereby increasing demand substantially.

2.3.2.5.4 Defensive Strategy (Weakness X Threat)

Channel investments into research at academic institutions, focusing on the biomass and bioenergy sector, to devise strategies to mitigate potential adverse environmental impacts. Simultaneously, explore the advantages relative to other renewable energy sources. Conduct a comprehensive investigation and promote diversification of raw material sources to reduce reliance on singular sources, thereby mitigating inherent availability risks.

2.3.2.5.5 Brazilian Scenario

Brazil distinguishes itself as a nation with a highly renewable electricity matrix, with over 60% sourced from hydropower (EPE, 2022). Strategies to promote bioenergy in Brazil focus on replacing non-renewable products like coal and oil with densified biomass. Aligning with European legislation such as DRHI (United Kingdom, 2022), Brazil can leverage solid biofuels' calorific properties for internal industrial use or export to markets like Europe. Overcoming logistical challenges is a key barrier, given Brazil's vast dimensions, which can amplify environmental impacts during raw material transport, hindering the full exploitation of bioenergy opportunities.

2.3.3 Final remarks

The comparative analysis of global legislation aimed at promoting the use of biomass has shed light on the maturity of current Brazilian policies relative to various international contexts. Positively, Brazilian legislation about biofuels and transportation sector impact reduction demonstrates a high level of maturity. The progressive objectives outlined in the RenovaBio program align with those of more developed nations such as the United States and Portugal, positioning Brazil as a benchmark in this domain.

However, concerning solid biomass, while international references exist, such as the DRHI (United Kingdom, 2022), there is a noticeable absence of specific legislation incentivizing the use of briquettes, unlike pellets, which enjoy greater prominence globally. Consequently, disparities have emerged between the most advanced legislative frameworks and Brazil's current approach to promoting the use of densified biomass. Addressing these gaps necessitates a comprehensive understanding of the various types of biomass produced in the country, enabling the identification of associated impacts and energy generation potential.

Once the energy generation capacity of biomass sources is established, several incentive mechanisms can be explored. Predominantly, feed-in tariffs emerge as a commonly identified stimulus, present in nearly 20% of regulations. Under this scheme, producers generating energy from biomass may receive pricing bonuses for the energy supplied, a practice extensively utilized in European and Asian markets.

Another viable option involves the creation of a tool akin to RenovaCalc, tailored specifically to the solid biofuels sector. Nonetheless, given Brazil's relatively clean energy matrix, primarily attributed to widespread hydroelectric energy use, further research is imperative to develop the calculation methodology for such a tool, ensuring its efficacy and relevance.

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3 THE APPLICATION OF CIRCULAR FOOTPRINT FORMULA IN BIOENERGY/BIOECONOMY: CHALLENGES, CASE STUDY, AND COMPARISON WITH LIFE CYCLE ASSESSMENT ALLOCATION METHODS

Abstract: The allocation of methodological choices in Life Cycle Assessment (LCA) is a relevant issue for the Circular Bioeconomy context. The recent Product Environmental Footprint Guide from the European Commission includes the Circular Footprint Formula (CFF) as a new way to deal with energy recovery/recycling processes. This paper investigated CFF vs. other different LCA allocation methods in Brazilian briquette production. A cradle-to-gate LCA study was conducted considering 1 MJ of energy from recovered and dedicated Eucalyptus briquette production. Global Warming Potential (GWP) and Cumulative Energy Demand (CED) were selected as the impact categories to evaluate the allocation methods choice that influence the potential impacts. LCA results were compared regarding four allocation methods. Eucalyptus wood as a biomass supply scenario achieved impact results up to 4.3 kg CO_2-eq. for GWP and 0.0272 MJ-eq. for CED. The recovery wood scenario presented LCA burdens reduction by up to 206% for GWP, however a 492% increase in the CED results. CFF provided the lowest results for both impact categories. However, the CFF method still doesn’t address particular aspects of circular bioenergy systems. Biomass and bioenergy LCA require further adjustments focusing on biochemical flows in the CFF calculation procedure to lead the development of innovative circular business models.

Keywords: Circular Economy; Energy Recovery; Recycling; Life Cycle Engineering; Circular business models

3.1 INTRODUCTION

The Bioeconomy and bioenergy are two of the most pertinent issues for global sustainable development and the Bioeconomy context, as they are associated with benefits such as the minimization of environmental quality degradation and resource depletion (Pan et al., 2021; Venkatesh, 2022). Bioenergy is a promising way to valorize forest and agro-industrial biowaste widely produced around the world (Martinez-Burgos et al., 2021; Omran & Baek, 2022) In this context, biofuels can be used as substitutes for petrol or diesel in the automobile and the energy sectors; densified biomass can be used to power thermal power plants; and biodegradable wastes can play a role in energy recovery via biogas mechanisms (Bose et al., 2020). Also, biofuel popularization could drive the development of policies that would make it easier to carry out Sustainable Development Goals (SDGs) (Bhattacharya & Bose, 2022). Therefore, there is a close relationship between the use and promotion of bioenergy and the aims of Circular Bioeconomy implementation, once they are complementary in terms of maintainability and resource efficiency goals (Jain et al., 2022). Within the Circular Bioeconomy perspective, the use of solid biowaste as an environmentally friendly solution for the energy supply has become highly relevant at a global level (Koytsoumpa et al., 2021; Leong et al., 2021; Mohanty et al., 2022). One of the most promising solid biofuels to produce sustainable bioenergy are biomass briquettes (Moreno-Camacho et al., 2019; Offei et al., 2021; Yang et al., 2021).

Briquettes are high-quality fuels and have been successfully made from a variety of biomass (Dinesha et al., 2019). Sawdust and other wood by-products, a binder, and other minor additions are commonly used to produce briquettes (Olugbade et al., 2019). Problems associated with biowaste final disposal can be solved by using agricultural, forest, and industrial biomass wastes as bioenergy sources in the form of briquettes (Dinesha et al., 2019). Briquettes are frequently utilized as a fuel for home and industrial purposes because they offer several advantages for the production and transmission of energy (Rousset et al., 2011).

Biomass briquettes are regarded as renewable in terms of the environment because of the benefits in terms of the carbon cycle (Rousset et al., 2011). However, their energy use does not guarantee environmental sustainability for the phases of production, conversion, distribution, and circularity. Life Cycle Assessment (LCA) is a tool developed to analyze the environmental impacts of different systems (Dastjerdi et al., 2021; Lopes Silva et al., 2019). Its scope includes every stage of a product's life cycle, including the extraction of raw materials, manufacture, consumption, and end of life (Silva et al., 2021). An LCA technique could be used to evaluate what environmental impacts are inherent to briquettes and which are "imported" by bioenergy systems, i.e., due to systems involved indirectly as service suppliers, such as the use of fossil fuels, transportation, and infrastructure (Lopes Silva et al., 2019).

Additionally, approaches for calculating and creating indicators are needed to assess the circularity of products and processes (Ekvall et al., 2021; Hermansson et al., 2022) and the energy consumption of biofuels, including biomass briquettes. Also, the key issue for the Circular Bioeconomy context is about the complexity of allocation methodological choices in LCA (Hermansson et al., 2020; Ijassi et al., 2021). While some recycling allocation techniques are effective for technical cycles, for example, the Circular Footprint Formula (CFF), they can fall short when evaluating bioenergy systems because certain parameters cannot be easily integrated into the analysis. This is especially true for the biological cycles in the biomass and bioenergy supply. Still, few studies have analyzed this issue for a quantitative pathway (Navare et al., 2021) discussing the challenges and proposing future directions for research on better integrating the Circular Bioeconomy with the practice of LCA. Also, there are no papers published so far on the application of the CFF to investigate solid biofuels. This paper aims to contribute to filling this gap. What should be done to properly apply an energy recovery LCA method in the context of solid bioenergy (briquettes)?

The goal of this paper was to evaluate and compare the CFF and LCA recycling/energy recovery methods in a Circular Bioeconomy case study, indicating the benefits, limitations, and challenges of the environmental performance of recovered biomass briquettes in Brazil.
Hence, in Section 2 the LCA methodology and the case to be studied are described. In Section 2.2 the use of the different LCA allocation methods are presented, namely: the 50/50 method, the quality-adjusted 50/50 method, and the CFF method, as they are currently the most studied (Ekvall et al., 2020). Section 3 describes the case study results and discussions.

3.2 MATERIALS AND METHODS

3.2.1 Life Cycle Assessment

3.2.1.1 Definitions of goal and scope

According to ISO 14,044 (Standardization, 2006), the first LCA stage is the moment in which the temporal, technological, and geographical boundaries are determined. The LCA results depend on the data quality criteria, the cut-off rules, and the impact categories to be addressed. This study consists of a deep analysis of CFF as applied to bioenergy systems through the comparison with two other allocation procedures: the 50/50 and the Quality-adjusted 50/50 methods.

These allocation methods were used to calculate the LCA results for three different manufacturing scenarios, considering the LCA study from (Araújo et al., 2018) for biomass briquettes made from urban pruning activities in Brazil. The scenarios are

●Scenario 1: briquettes made of wood from a dedicated forest energy supply. Brazil is a world reference for tree plantation productivity, with high annual production volumes of wood per area and short plantation cycles (D. A. L. Silva et al., 2022). Brazilian planted forests occupy an area of 9.55 million hectares, with 78% being Eucalyptus species (IBA, 2021), used in the production of pulp and paper, wood-based panels, and for energy purposes.

●Scenario 2: briquettes made of wood waste with 50% of the heating value compared to Scenario 1. This scenario was chosen because urban pruning residues have a high moisture and ash content, which reduces the quality of the biomass. (T. C. SILVA, 2018) also analyzed the useful calorific value of biomass from urban pruning waste in Recife, Brazil, where it obtained an average value of 6.18 MJ/kg, while eucalyptus biomass has an approximate useful calorific value of 12.14 MJ/kg (Foelkel, 2015).

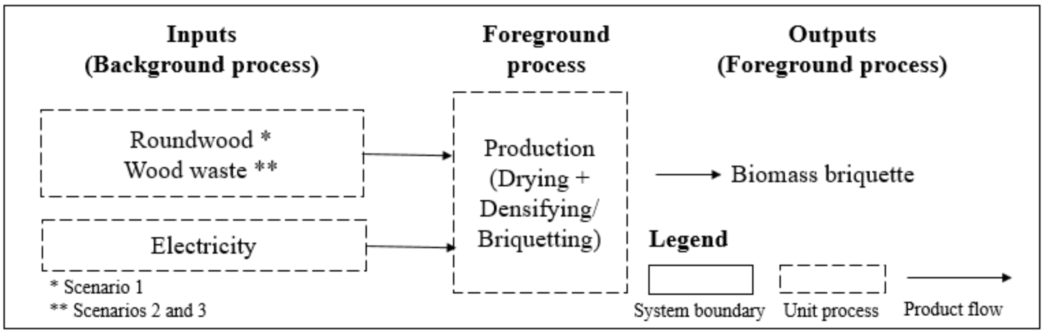
●Scenario 3: briquette production made of wood waste with the same heating value as the wood from a dedicated forest energy supply (Scenario 1). Therefore, this scenario was performed disregarding any possible difference in the efficiency of the heating value between wood and residual wood.

Beyond the allocation methods, a baseline LCA was performed for each scenario, using the avoided product approach, as implemented by (Araújo et al., 2018). The avoided product approach is a system expansion by substitution method adopted in LCA for multifunctional products and processes. System expansion in LCA refers to expanding the system boundaries by including additional functions related to the co-products (EC, 2018). Using the avoided product approach, only the impacts from the main product system's output (e.g., briquettes) are accounted for. The impacts from the remaining outputs are considered from other product systems, once these remaining outputs substitute the inputs from these product systems (Ciroth et al., 2020). In this study, the LCA results of Scenarios 2 and 3 counted with a system expansion related to the impacts avoided by processing residual wood into briquettes instead of directly landfilling it - similarly to (Araújo et al., 2018).

Scenario 1 did not count with this approach because of its linearity. By considering briquettes production with biomass taken from dedicated forests, the resulting biofuel does not substitute any other product or alternative end-of-life strategy, in a way that there are no avoided impacts to be associated with it.

A cradle-to-gate perspective was considered for all the scenarios - using an attributional LCA approach - and the system boundaries were modeled to cover the material and energy flow from the biomass supply and the production stages, including drying and densification processes for the briquetting (see Figure 3.1). The product packaging process, transport activities, and the combustion phase of the briquettes were not considered within the system boundaries under analysis. The Functional Unit (FU) was defined as 1 MJ of energy produced from the biomass briquettes.

Figure 3.1 - A general product system for biomass briquettes



Source: Own authorship

In the foreground process, drying the biomass means reducing wood moisture to 12% which is considered the ideal moisture content for the briquetting process (Lucena et al., 2013; Quirino & Brito, 1991; D. A. Silva et al., 2015) through a rotary drum dryer with a production capacity of 5.000 kg/h. Once the wood leaves the drying process, it serves as the main input for biomass briquetting, which is performed by a mechanical piston press machine (Felfli et al., 2011).

3.2.1.2 Life cycle inventory, data quality, and main assumptions

This step involves the definition of the procedures to be used for data collection and management up to the quantification of all the inputs and outputs of the product system (Bjørn et al., 2018; Rodrigues et al., 2021). The open LCA software tool version 1.10 was used to model the product systems under investigation. In Scenario 1, the biomass data supply was considered as roundwood supply from a eucalyptus-managed forest. For Scenarios 2 and 3, the biomass source was the wood waste flow (Table 3.1) as represented by t the mix of bark chips, cleft timber, wood chips, residual hardwood, and softwood inputs considered in the LCA study performed by Araújo et al. (2018).

Table 3.1 - Life cycle inventory

Flow	Unit	Quantity
Inputs		
electricity, high voltage	kWh	6.30×10^{-2}
roundwood *	Kg	1.05×10^{0}
wood waste **		
Outputs		
Biomass Briquette	Kg	1.00×10^{0}

** Scenario 1*

*** Scenarios 2 and 3*

Source: Own authorship

The difference of 0.05 kg in the mass balance from Table 3.1 relates to the water losses in the biomass drying stage. The ecoinvent 3.7 cutoff unit process database was adopted for the background datasets of electricity and wood waste supplies. When regional background data was not found on the ecoinvent database, datasets were taken from the Rest of the World (RoW) region. Roundwood background data was extracted from the 'SICV database, a Brazilian free and open-access national LCA database covering economic sectors such as agribusiness and forestry activities in the country (Souza et al., 2021).

The inventory data was converted to the UF (1 MJ-eq) based on the briquette calorific value for each scenario. The amount of energy and wood demanded by each scenario varied according to the calorific value established for the final product. For the eucalyptus (Scenario 1) and residual wood briquettes (Scenario 3) a Lower Heating Value (LHV) of 12.14 MJ/kg was considered, while for the residual wood briquettes with less efficiency (Scenario 2) the briquette's LHV was 6.18 MJ/kg.

3.2.1.3 Life cycle impact assessment and LCA interpretation of results

For the present study, all the scenarios were evaluated concerning two impact methods: the IPCC 2013 GWP 100y and the CED (v. 1.0.1, January 2015) available at the openLCA software tool. The IPCC GWP 100y is a methodology developed by the Intergovernmental Panel on Climate Change (IPCC) to quantify the Global Warming Potential (GWP) impacts from products and processes, based on the time-integrated global mean radiative forcing of a pulse emission of 1 kg of some compound relative to that of 1 kg of the reference gas, being

CO_2 (IPCC, 2015). A product's Cumulative Energy Demand (CED) represents the direct and indirect energy used throughout the life cycle, including the energy consumed during the extraction, manufacturing, and disposal of the raw and auxiliary materials (VDI, 1997). Both the impact categories, i.e., GWP and CED are commonly studied by LCA practitioners with special reference to the Energy sector (Monteiro et al., 2020; D. A. L. Silva et al., 2022). A complementary analysis of results was performed considering the uncertainty analysis of the LCA for these categories, as the life-cycle uncertainties may have a relevant influence on the LCA interpretation process [18; 44].

For the LCA interpretation of results, three allocation methods were used as described in Section 2.2. The comparative LCA results were internally normalized (Saade et al., 2021) to facilitate the LCA contribution analysis and the hotspots analysis in Section 3. A mathematical description of the CFF method and the remaining ones under investigation is given in the next paragraphs.

3.2.2 System allocation methods

System allocation is a strategy used to represent the sharing of input and/or output flows of a process/product system between a product system under study and other product systems (Standardization, 2006). Beyond the reference results obtained through LCA, three different allocation methods were calculated for all the scenarios: the 50/50 method, the Quality-adjusted 50/50 method, and the CFF.

3.2.2.1 50/50 method

According to (Ekvall et al., 2020), the 50/50 method equally splits the environmental burden of virgin material production and its final disposal between the product using this virgin material and the product where this material is lost from the technosphere. In each recycling process, the environmental burden is split equally between the product system supplying recyclable material and the product to which the recycled material is applied. The calculation of the environmental burden using this method is provided by Equation 1:

$$E = 0.5 \times [(1 - R_1) + (1 - R_2)] \times (E_V + E_D) + 0.5 \times (R_1 \times E_{Rin} + R_2 \times E_{Rout}) \quad (1)$$

where,

- E is the environmental burden (e.g., GWP, CED);
- R1 is the ratio of material in the input to the production that has been recycled in a previous system [0, 1];

●R2 is the ratio of the material in the product that will be recycled in a subsequent system [0, 1];

●EV is the environmental burdens from virgin/primary material production;

● ED is the environmental burdens from waste disposal;

●ERin is the environmental burdens from the recycling process supplying recycled/secondary material to the product;

●ERout is the environmental burdens from the recycling process accepting materials from the product.

The first summand of the equation consists of the share of the environmental burdens from both production and disposal of used virgin material, while the second summand consists of the share of the environmental burden from the usage of recycled material.

3.2.2.2 Quality-adjusted 50/50 method

This method was proposed by Detzel et al., 2016 and Allacker et al., 2017, based on the best practices approach from French Association for Normalization (AFNOR, 2011). While this method distributes the impacts due to recycling in a 50/50 way (similarly to the 50/50 method presented by Equation 1), it also includes the virgin and disposal impacts over the different products in the overall product cascade system and allows the accounting for changes in inherent material properties (i.e., the quality of the material). The formula of this method is presented by Equation 2:

$$E = (1 - R_1) \times E_V + 0.5 \times R_1 \times (E_{Rin} + E_V - E_D^*) +$$

$$+0.5 \times R_2 \times (E_{Rout} - Q_S/Q_P \times E_V^* + E_D) + (1 - R_2) \times E_D \quad (2)$$

where,

●E*D indicates the avoided ED through recycling;

●QS is the quality of the recycled material used for the investigated product [0-1];

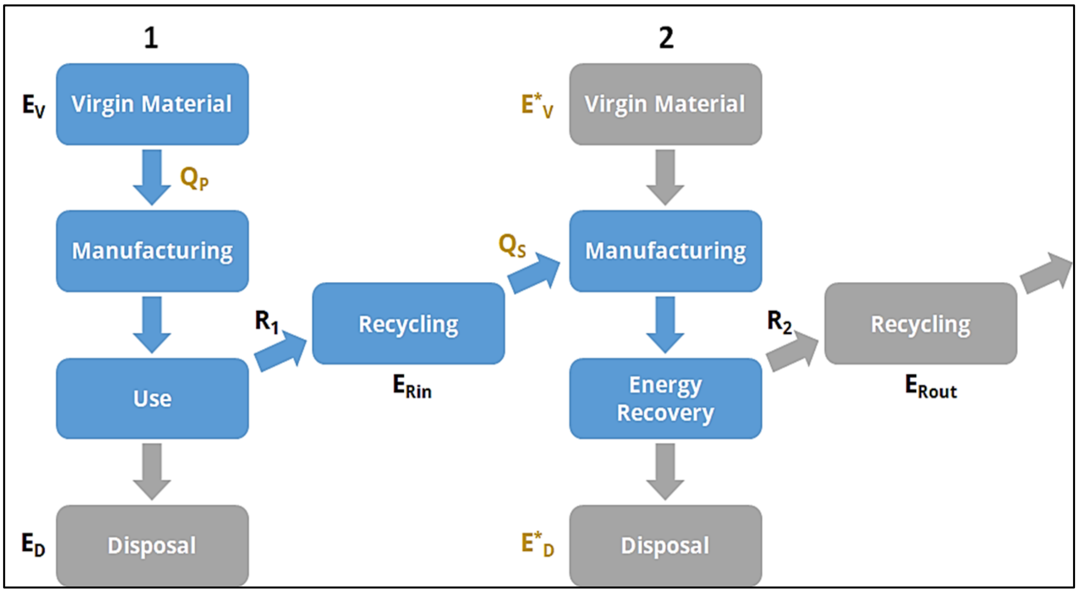
●QP is the quality of primary/virgin material used for the investigated product [0-1];

●E*V indicates the avoided EV through recycling.

The first summand of the equation consists of the environmental burden from the use of virgin/primary material only. The second summand consists of the share of the environmental burden from the usage of secondary/recycled material. The third summand consists of the share of the environmental burden from the disposal and/or new recycling of recycled/secondary material. Finally, the fourth summand consists of the share of the environmental burden from the disposal of the remaining waste.

Figure 3.2 presents the application of the 50/50 and the Quality-adjusted 50/50 methods to a system where a material is used in two products through recycling, being completely used for energy recovery after the manufacturing of the second product.

Figure 3.2 - General illustration of how the 50/50 and the Quality-adjusted 50/50 methods are applied to a hypothetical case. The gray color indicates processes and flows that are avoided through recycling. Symbols in bold black represent variables from both 50/50 and the Quality-adjusted 50/50 methods, while symbols in bold dark yellow represent the specific variables present for the Quality-adjusted 50/50 method only.



Source: Adapted from Ekvall et al. (2020).

3.2.2.3 Circular Footprint Formula

The CFF was proposed by the Product Environmental Footprint Category Rules Guidance (Version 6.3), developed by the European Commission (EC, 2018). This method accounts not only for the share of recycled material (R1) and the ratio of the material in the product that will be recycled in a subsequent system (R2), but also for the quality of recycled material entering (QSin) and leaving (QSout) the life cycle, and the balance between supply and demand for individual recycled materials - addressed by Factor A, a material-dependent factor which aims to reflect market realities (Ekvall et al., 2020). In addition, CFF also accounts for the credits and/or burdens from energy recovery processes (i.e., for heat and electricity recovery) applied during the product life cycle. Equation 3 introduces the formula for this method:

$$E = (1 - R_1) \times E_V + R_1 \times \left[A \times E_{Rin} + (1 - A) \times E_V \times \left(\frac{Q_{Sin}}{Q_P}\right)\right] +$$

$$+(1 - A) \times R_2 \times \left[E_{Rout} - E_V^* \times \left(\frac{Q_{Sout}}{Q_P}\right)\right] + (1 - B) \times R_3 \times$$

$$\times \left(E_{ER} - LHV \times X_{ER,heat} \times E_{SE,heat} - LHV \times X_{ER,elec} \times E_{SE,elec}\right) + +(1 - R_2 - R_3) \times E_D \quad (3)$$

where,

●A is a factor that represents the balance between supply and demand for recycled material [0.2-0.8];

●QSin is the quality of recycled material entering the life cycle [0-1];

●QSout is the quality of recycled material leaving the life cycle [0-1];

●B is an allocation factor of energy recovery processes that applies both to burdens and credits;

●R3 is the ratio of the material in the product that is used for energy recovery at End-of-Life [0-1];

●EER is the specific emissions and resources consumed (per functional unit) arising from the energy recovery process (e.g. incineration with energy recovery, landfill with energy recovery, etc.);

●LHV is the Lower Heating Value of the material [MJ/kg];

●XER,heat is the efficiency of the energy recovery process for heat [0-1];

●ESE,heat is the specific emissions and resources consumed (per functional unit) that would have arisen from the specific substituted heat source [0-1];

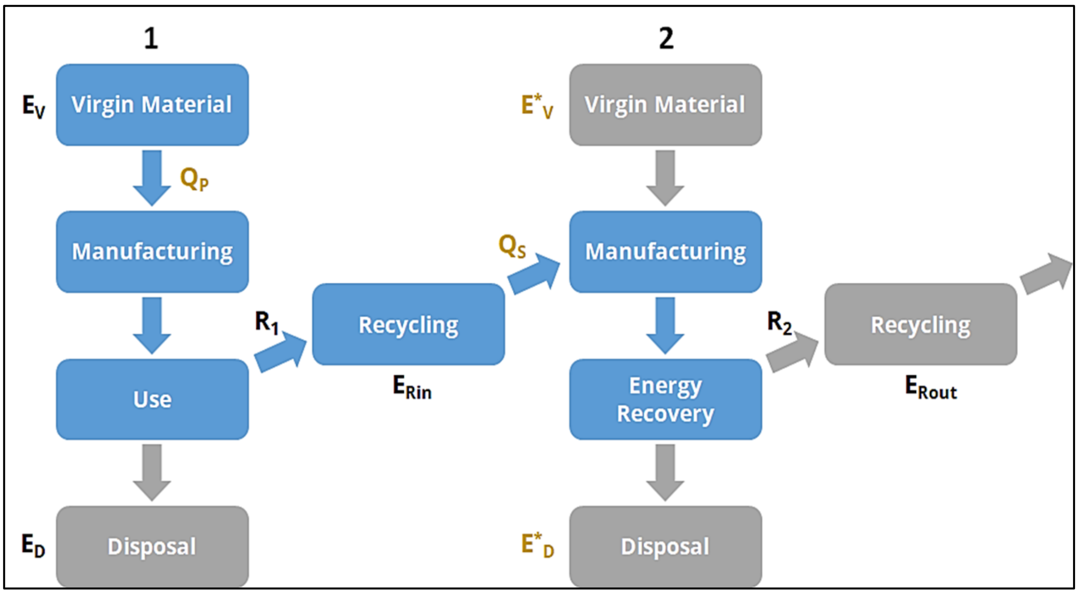
●XER,elec is the efficiency of the energy recovery process for electricity [0-1];

●ESE,elec is the specific emissions and resources consumed (per functional unit) that would have arisen from the specific substituted electricity source [0-1];

The first summand of the equation consists of the environmental burden from the use of virgin/primary material. The second summand consists of the burdens and benefits related to secondary materials input, while the third summand consists of the burdens and benefits related to secondary materials output. The fourth summand represents the energy recovery processes, for both heat and electricity purposes. Finally, the fifth summand consists of the share of the environmental burden from the disposal of the remaining waste.

Figure 3.3 presents the application of the CFF to a general system where a material is used for energy recovery after its final use.

Figure 3.3 - Illustration of how the CFF applies to a hypothetical case of a material that is used for energy recovery after being used in a product. The gray color indicates processes and flows that are avoided through recycling and therefore never take place



Source: Adapted from Ekvall et al. (2020).

3.2.2.4 Designed tests for the LCA allocation methods

A summary of the designed tests for evaluation of the LCA methods are introduced by Table 3.2, which illustrates the behavior of the methods' equations for each briquetting scenario. The null value was represented by red color in the formulas of the associated method and scenario, while the blue parameters highlight the operations that returned a non-null value, which attributed a positive or negative influence on the GWP and CED results for each scenario. The system expansion behavior, according to each scenario, can be noted on the equations used to obtain the LCA results, which were calculated as the sum of the environmental impacts related to each system input discounted by the avoided impacts due to the expanded system.

Table 3.2 - The behavior of the equations used by each LCA allocation method in the three biomass briquetting scenarios

Approach	Scenario	Equation
Avoided product	**1**	Wood Impacts + Energy Consumption Impacts for Briquetting wood - Treatment of Waste Wood on Landfill
	2	Residual Wood Impacts + Energy Consumption Impacts for Briquetting Residual Wood - Treatment of Waste Wood on Landfill
	3	Residual Wood Impacts + Energy Consumption Impacts for Briquetting Residual Wood - Treatment of Waste Wood on Landfill
50/50 method	**1**	{0.5 x [(1 - R1) + (1 - R2)] x (Ev + Ed)} + [0.5 x (R1 x Erin + R2 x Erout)]
	2	{0.5 x [(1 - R1) + (1 - R2)] x (Ev + Ed)} + [0.5 x (R1 x Erin + R2 x Erout)]
	3	{0.5 x [(1 - R1) + (1 - R2)] x (Ev + Ed)} + [0.5 x (R1 x Erin + R2 x Erout)]
Quality-adjusted 50/50 method	**1**	[(1 - R1) x EV] + [0.5 x R1 x (Erin + EV - Ed*)] + {0.5 x R2 x [Erout - (Qs/Qp) x Ev* + Ed]} + [(1 - R2) x Ed]
	2	[(1 - R1) x EV] + [0.5 x R1 x (Erin + EV - Ed*)] + {0.5 x R2 x [Erout - (Qs/Qp) x Ev* + Ed]} + [(1 - R2) x Ed]
	3	[(1 - R1) x EV] + [0.5 x R1 x (Erin + EV - Ed*)] + {0.5 x R2 x [Erout - (Qs/Qp) x Ev* + Ed]} + [(1 - R2) x Ed]
Circular Footprint Formula (CFF)	**1**	[(1 - R1) x Ev] + {R1 x [A x Erin + (1 - A) x Ev x Qsin/Qp]} + [(1 - A) x R2 x (Eout - Ev* x (QSout/QP)] + {(1 - B) x R3 x [(Eer - LHV x Xerheat x Eseheat) - (LHV x Xerelec x Eseelec)]} + [(1 - R2 - R3) x Ed]
	2	[(1 - R1) x Ev] + {R1 x [A x Erin + (1 - A) x Ev x Qsin/Qp]} + [(1 - A) x R2 x (Eout - Ev* x (QSout/QP)] + {[(1 - B) x R3 x [(Eer - LHV x Xerheat x Eseheat) - (LHV x Xerelec x Eseelec)]} + [(1 - R2 - R3) x Ed]
	3	[(1 - R1) x Ev] + {R1 x [A x Erin + (1 - A) x Ev x Qsin/Qp]} + [(1 - A) x R2 x (Eout - Ev* x (QSout/QP)] + {[(1 - B) x R3 x [(Eer - LHV x Xerheat x Eseheat) - (LHV x Xerelec x Eseelec)]} + [(1 - R2 - R3) x Ed]

Parameter description

Factor A	A balance between supply and demand for recycled material [0.2-0.8]
Ed	is the environmental burdens of the waste disposal
Ed*	indicates Ed is avoided through recycling
Erin	is the environmental burdens of the recycling process supplying recycled material to the product
Erout	is the environmental burdens of the recycling process accepting materials from the product
Ev	is the environmental burdens of virgin material production
Ev*	indicates Ev is avoided through recycling
R1	Share of recycled material [0-1]
R2	the rate of recycling of material after use in the product [0-1]
Qp	is the quality of the material delivered by the primary production [0-1]
Qs	quality of material recycled from the investigated product [0-1]
Qsin	the quality of recycled material entering the life cycle [0-1]
Qsout	the quality of recycled material leaving the life cycle [0-1]
S	the quality of the recycled material divided by the quality of virgin material [0-1]
B	allocation factor of energy recovery processes: it applies both to burdens and credits - Equals to 0 as default
R3	is the proportion of the material in the product that is used for energy recovery at EoL
Eer	specific emissions and resources consumed (per functional unit) arising from the energy recovery process (e.g. incineration with energy recovery, landfill with energy recovery, …)
LHV	lower heating value of the material [MJ/kg]
Xerheat	the efficiency of the energy recovery process for heat
Eseheat	specific emissions and resources consumed (per functional unit) that would have arisen from the specific substituted energy source. For this case, heat
Xerelec	the efficiency of the energy recovery process for electricity
Eseelec	specific emissions and resources consumed (per functional unit) that would have arisen from the specific substituted energy source. For this case, electricity

Source: Own authorship

Along with the results and discussion in Section 3, a detailed analysis of the LCA results is given regarding Table 3.2. Based on the selected LCA recycling methods, it is clear all of them are more concerned with the mass of materials flowing through the life cycle of a product. However, for biological processes in the context of the Circular Bioeconomy (Navare et al., 2021), the discussed equations do not include biochemical flows, and this may lead to some relevant research implications that will be discussed in Section 3.3.

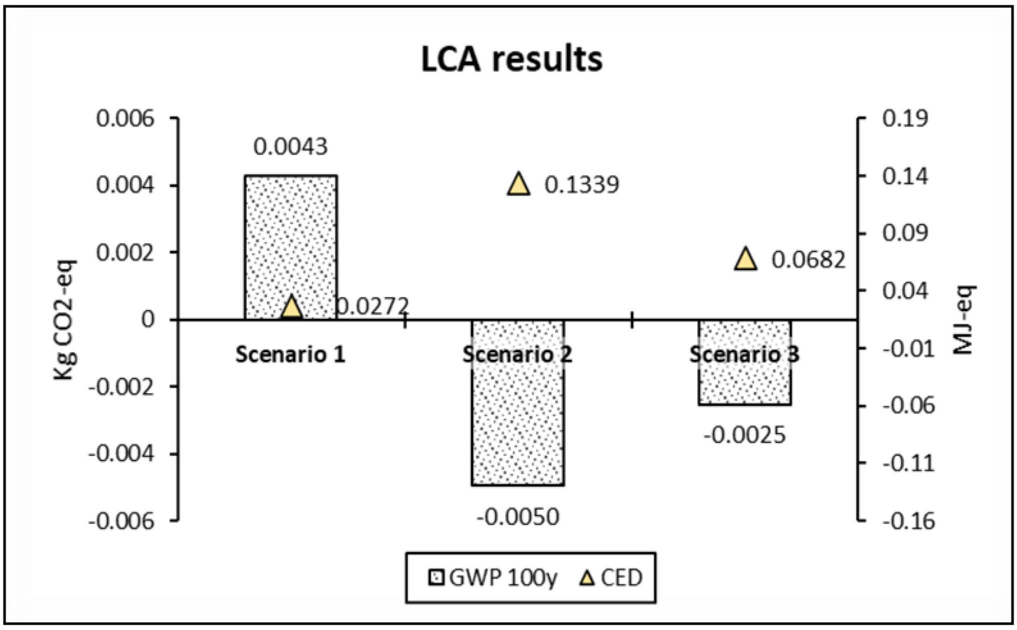
3.3 RESULTS AND DISCUSSION

The LCA results were set as the reference values for all scenarios, as a consequence of their higher robustness and complexity (ISO, 2009, 2006) when compared to the other methods. In this sense, Section 3.1 presents the LCA results overview for GWP and CED in all scenarios. Section 3.2 shows the results for the other allocation methods, also comparing them with the results of CFF. Section 3.3 discusses the results in terms of research implications and provides recommendations toward the Circular Economy in bioenergy systems.

3.3.1 Overall LCA results

The baseline LCA results obtained for all scenarios presented different behavior between the two impact categories (GWP and CED), as is illustrated in Figure 3.4:

Figure 3.4 - LCA results for the three studied scenarios.



Source: Own authorship

The GWP had negative values for Scenarios 2 and 3 due to the avoided impacts related to the final disposal of residual wood in landfills (system expansion), which surpasses the CO_2 emissions from briquetting the residual wood. In this sense, results for GWP had a relative variation of 206%, ranging from -0.005 to 0.0043 kg CO_2-eq per FU. As expected, the highest impact for GWP was noted in Scenario 1, which was modeled considering the restricted use of virgin biomass as raw material. Scenario 2 by itself had the lowest results for GWP, since it is based on a final product with approximately half of the calorific value of the other two scenarios, promoting more carbon credits through the end-of-life strategy of using residual wood as an energy source instead of landfilling it. It means that for 1 MJ of energy obtained from residual wood briquettes, Scenario 2 allows the saving of almost twice the landfilling emissions. Therefore, Scenarios 2 and 3 can be considered as good opportunities to achieve a 'net-zero' (Rampasso et al., 2021) in terms of carbon emissions toward a Circular Bioeconomy, and could contribute to reaching SDGs 7 (clean energy targets) and 13 (action against climate change) (Silva et al., 2021).

Given the energy demanded by wood treatment in landfills, the CED results were superior to zero, with results ranging from 0.0272 to 0.1339 MJ-eq (492% relative variation). Scenario 1 had the lowest results of the three scenarios followed by Scenarios 3 and 2. The behavior of CED results is a consequence of the background data taken from the ecoinvent database, which attributes higher energy demanded by wood waste obtention, instead of that associated with the same amount of wood supply. This non-expected phenomenon can be explained by more transport activities required for wood waste supply than in the virgin wood supply contributing to an increase in CED.

Also, it is important to investigate how the uncertainties contained in the data collected in the LCA may affect the reliability of the results obtained (ISO, 2006). In this sense, the Monte Carlo is a stochastic simulation technique often used in probabilistic modeling (Michiels & Geeraerd, 2020). Table 3.3 shows the LCA uncertainty analysis for the studied reference case using 1,000 iterations for the Monte Carlo simulation (GWP and CED categories).

Table 3.3 - LCA uncertainty analysis (avoided product approach)

	Global Warming Potential (Kg CO_2-eq)	**Cumulative Energy Demand (MJ-eq)**
Mean	1,06x100	1,53x10-1
Standard deviation	7,86x10-2	8,59x10-2
Minimum	8,57x10-1	3,17x10-2
Maximum	1,36x100	6,12x10-1
Median	1,06x100	1,31x10-1

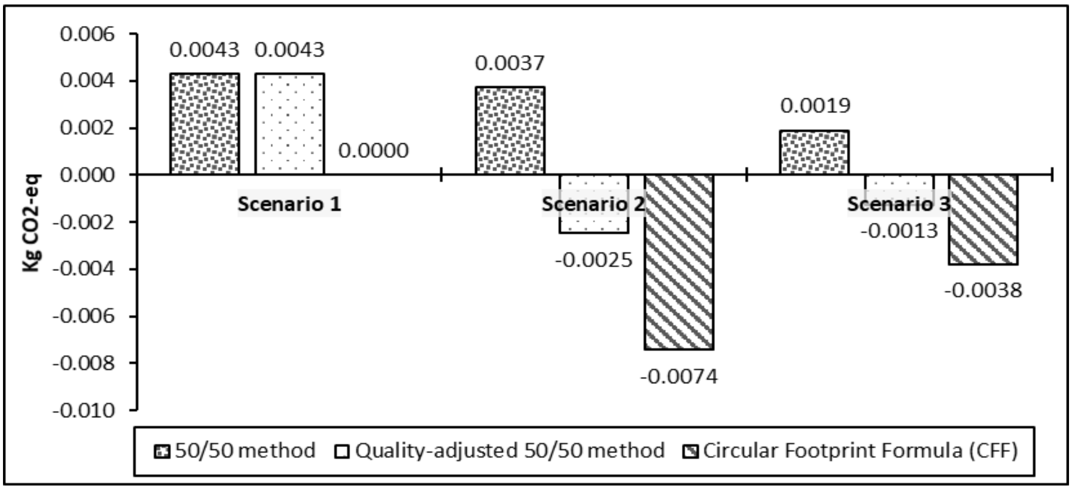
Source: Own authorship

The results show that the standard deviation value is low for both impact categories, 7,86x10-2 for GWP and 8,59x10-2 for CED, it can be concluded that the uncertainty is low, since the results showed that most values are concentrated around the mean, with a low probability of occurrence of extreme values. The uncertainty LCA results for the baseline case (avoided product approach) are within the defined 95% confidence interval in the briquette production system in both impact categories (GWP and CED). Furthermore, this result could be applied to the other three allocation methods studied (50/50, 50/50 quality-adjusted, and CFF), given the LCA results are the same differing only by the allocation method each scenario adopted.

3.3.2 Allocation method's effects on the LCA results

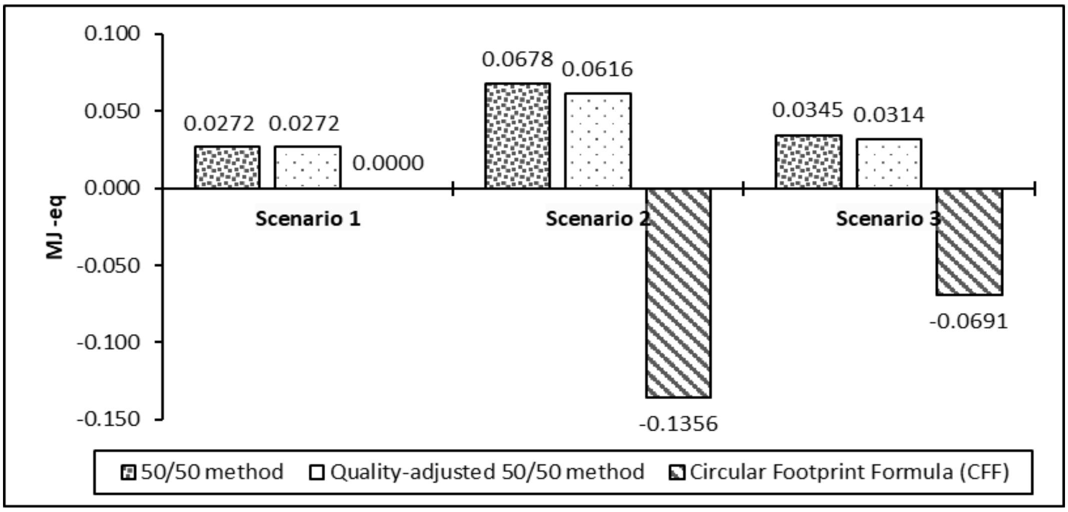
From the LCA results obtained for each scenario the GWP and CED results were recalculated using the allocation methods described in Section 2.2 and are introduced in Figures 3.5 and 3.6, respectively.

Figure 3.5 - Comparison of GWP results per FU using different allocation methods for each scenario



Source: Own authorship

Figure 3.6 - Comparison of CED results per FU using different allocation methods for each scenario



Source: Own authorship

Regarding the GWP results, Figure 3.5 shows Scenario 1 standing as the most impactful scenario for all the allocation methods. The results from the 50/50 method and 50/50 Quality-adjusted methods application were 0.0043 kg of CO_2-eq. per FU, similarly to the original results of the LCA study in Figure 3.4. This behavior was also noted in the CED results, as both the 50/50 method and the 50/50 Quality-adjusted method demanded the same amount of energy (i.e.0.0272 MJ per FU). It implies the equivalence of these two allocation methods when applied to biological cycles from virgin materials, as the value of R2 (the rate of recycling of material after use in the product) is null for both cases (see Table 3.2 again).

The results variation from Scenario 2 to Scenario 3 had the same proportion for all the allocation methods in the two impact categories (GWP and CED). Scenario 2 had approximately twice the impact values of Scenario 3, even for the negative values. This can be explained due to the similarity between these scenarios related to wood waste briquettes production, which only differ by their LHV. For Scenario 2 the amount of wood waste used to manufacture the briquette is almost twice the wood needed for Scenario 3, varying the impacts in the same proportion.

The incidence of negative values on the CFF results for Scenarios 2 and 3 points to the avoided CO_2 emissions and energy demanded by the obtention of 1 MJ of energy from briquettes. This is a consequence of the avoidance of resource consumption per FU. These resources would have arisen from the specific substituted energy source considered (Eseheat), in this case, virgin wood from Eucalyptus. This phenomenon is also observed in Scenario 2 for the quality-adjusted 50/50 method (Figure 3.5), as the requirement of a higher amount of biomass implies the avoidance of more residual wood going to landfills. The use of CFF for other biological-based systems revealed that its application to renewable Low-Density Polyethylene (LDPE) could also create an incorrect climate incentive for incineration since the recovered energy substitutes energy sources for up to 300% more climate impact. However, it can be corrected by using an allocation factor for incineration (Ekvall et al., 2021).

The environmental burdens avoided through the recycling process (Ed*) increased and, since this parameter subtracts the impacts from the recycling process (Erin), it incurred a negative result only in Scenario 2. Once Scenario 3 considers a final briquette with a higher LHV compared to Scenario 2, it demands less biomass to generate the same 1 MJ of energy used per FU. This fact reduces the avoided burdens from the landfilling process, and consequently, generates results in smaller absolute values. A similar explanation can be addressed to CED results calculated by the quality-adjusted 50/50 method (see Figure 3.5), as the sum of values for Erin and Ev surpasses the Ed*.

It is also important to highlight the null results on both impact categories calculated with the CFF method in Scenario 1. The reason for these results is the fact that the burdens from the production of virgin material (Ev) are compensated by the benefits of energy recovery from this material at end-of-life.

These recycling methods are considered good for technical cycles, although they seem to have some gaps in the evaluation of bioenergy. To cut down on waste and using resources in agriculture, Velasco-Muñoz et al. (2021) recommend some closing resource loop circular indicators. Also, Gonçalves et al. (2021) found the Cascade Factor (CF) as a potential circularity indicator for assessing biological cycles since it can either be used on full systems or in separate sectors, covering all the life cycle stages of a product and considering both closed and open-loop energy recovery of post-consumer residues. However, further studies need to be carried out to evaluate the feasibility of this application in solid biofuels.

3.3.3 Managerial/policy implications

What should be done to properly apply an energy recovery LCA method in the context of solid bioenergy (briquettes)? Some relevant research implications can be summarized:

·*General aspects of energy recovery methods for biological systems*: this is a prominent issue in CE studies. However, the same cannot be said about energy recovery in biological cycles (Velasco-Muñoz et al., 2021) because all the evaluated methods in this case study fail in some aspects. Other relevant issues should be addressed in the biological system instead of only the mass of allocated materials or energy. The CFF formula is the most complex of the evaluated methods, but even though some relevant issues in energy recovery are missing it has an essential role in bioenergy.

·*Opportunities for CFF and related literature:* the CFF and other related indicators evaluate circularity under the same baseline - with physical and biochemical issues unseparated, and with much more focus on the physical flow. For biological processes, this can be seen as a limitation because some important issues are not addressed according to (Navare et al., 2021), such as the potential cascading effects, renewability (to regenerate environment), and biodegradability (nutrient cycles). The results discussed for the briquettes case study showed negative values regarding the CFF for Scenarios 2 and 3 and negative impacts for Scenario 2 in the quality-adjusted 50/50 method (Figure 3.5). This is related to the avoidance of resource consumption (wood) per FU, although the biochemical implications of briquettes adoption are not covered by the energy recovery methods under study. Therefore, the CFF and other methods directly depend on the mass of resource consumption made available in the inventory to produce briquettes (Table 3.1). A clear opportunity for the case of biofuels would be to expand the circularity analysis by including, in a separate analysis, the biochemical parameters for the product system such as cascading effects of biomass (Gonçalves et al., 2021), and water balance (that affect biomass quality and LHV, for example). The current version of the CFF does not clearly evaluate these criteria. Therefore, circularity in biological processes would be valuable if the following set of criteria were developed (Equation 4):

$$Circularity = f\ (Physical\ flows;\ Biochemical\ flows) \qquad (4)$$

where,

● **Physical flows** could be determined by the total mass of recovered resources in the system based on cascading use of resources. This can be evaluated based on the use of indicators such as the (CF) (Gonçalves et al., 2021) and other mass-related circular indexes.

● **Biochemical flows** should be based on the renewability and biodegradability of the resources in the investigated system, and for the biomass briquettes, some relevant issues to be covered are carbon cycle and water balance. Trees and other renewable resources can provide carbon sequestration and contribute to air quality regulation and water provisioning (Liu & Bakshi, 2019). Therefore, we may consider such resources performing ecosystem restoration in the biological cycle of Circular Bioeconomy systems. Other examples of biochemical flows would be chemical balances for food and feed-based products, where nutrient cycles might have an essential role in the system's circularity performance.

A clear procedure for the implementation of Equation 4 should be developed, although the total circularity is a function of the physical and biochemical flows. The CFF, for example, has more than 10 parameters (Table 3.2), but all of them are focused on the physical flows and not analyzing, in a specific pathway, the biochemical flows of the biological cycle. The remaining recycling methods studied are in line with technical cycles but also fail in terms of biochemical flows for biological cycles. A more concise integration of CE with LCA is necessary to advance this topic from a broader perspective. Rigamonti & Mancini (2021) revealed that circularity indicators assume at some level the need to use circular inputs, recovered materials, and extending life span as relevant parameters. But this is not enough for biological systems where the biochemical flows may be the most determinant factors towards a more circular system (Navare et al., 2021; Velasco-Muñoz et al., 2021).

Ecosystems have the potential to supply a range of services that are of fundamental importance to human well-being, health, livelihoods, and survival (Millennium Ecosystem Assessment (Program), 2005). Ecosystem Services (ES) can be defined as contributions of ecosystem structure and function (in combination with other inputs) to human well-being (Burkhard et al., 2012). The biochemical flows in a circularity analysis should follow an ES perspective as the biological cycle maintains the ecosystem's capability of providing goods/services for supporting human life (Bakshi et al., 2015; Chan et al., 2006; Gopalakrishnan et al., 2016). We recommend an analysis of the demand and supply of ES for a possible new version of the CFF application. An interesting approach for this is based on the techno-ecological synergy theory proposed by Liu & Bakshi (2019) and combined with LCA to perform a case study for ethanol biofuel. We believe that Equation 5 could be used in combination with CFF results.

$$\textit{Net circularity performance} = (S - E)/E \qquad (5)$$

in which, the net circularity performance is a function of two main parameters, ‘S’ representing the biochemical flows, and ‘E’ the physical flows. ‘S’ is the natural supply of relevant ES (e.g., carbon sequestration, water provisioning, and others) for a product system's boundaries. ‘E’ represents the environmental burdens due to human activities, as previously calculated by Equation 3. Also, it is important to understand that ES representing ‘S’ are subjected to the same product system limited by Figure 3.2 to calculate ‘E’. Through a cascade model, ‘S’ and ‘E’ can be accounted for as suggested by (Rugani et al., 2019), while (Liu et al., 2020) address the valuation of ‘S’ considering the CICES© taxonomy for the categories of provisioning of resources and regulation & maintenance of climate.

This metric indicates a possible application of the concept of Equation 4 correlating the CFF within an analysis of the ecosystem's carrying capacity to obtain a net circularity performance indicator. However, it should be noted that the integration of an ES approach in LCA is not easy to put into practice because of the lack of ES in conventional LCA databases (Liu & Bakshi, 2019; Rugani et al., 2019). Also, it is important to consider the inclusion of other complementary methodologies to LCA, such as the CFF. Furthermore, in the context of bioproducts, the different methodologies can lead to conflicting results, influencing decision-making in opposing directions (Brandão et al., n.d.). However, we understand that by combining CFF with process LCA and ES in a framework, this could lead to results that can bring more circular business models.

It is essential to mention that our case study can be generalized to other companies/products where energy recovery in biofuels is a key issue, especially when calculating circularity considering not only the mass of materials and energy but also the biochemical implications in terms of carbon and water balances, for example. Finally, the novelty of Equation 5 is the use of the CFF result as ‘E’. A strong net circularity indicator would result if ≥ 0.

In terms of policy implications for circular business models, the use of Equation 5 (combined with CFF results) could be seen as a relevant input for environmental product declarations or climate declarations/policy developments because the current general rules do not consider such metrics. For example, the natural supply of ES is today not part of the general programme instructions in the international EPD® system (EPD, 2017), one of the most well-known environmental declaration programmes/initiatives. Environmental declarations are important market instruments for seeking harmonization in the environmental footprint of product communication on the international market.

3.4 CONCLUSIONS AND RECOMMENDATIONS

This study focused on the evaluation and comparison of the CFF, the 50/50 method, and the quality-adjusted 50/50 method in a Circular Bioeconomy case study, considering the environmental performance of biomass briquettes in Brazil. The results revealed a difference between the LCA results depending on the amount and source of biomass. GWP results showed the highest impacts when using dedicated wood as raw material. On the other hand, the highest results for CED were observed for the scenario of wood waste with a smaller LHV, and due to the energy demanded (avoided) from dedicated and secondary wood treatment in landfills. Regarding the allocation methods' effects on the LCA results, the application of both 50/50 methods acquired similar results, implying the equivalence between these methods. Otherwise, the null CFF results mean that in the case of solid biofuels from dedicated wood, the burdens from the virgin material supply (Ev) are nullified by the benefits of energy recovery from this material at end-of-life.

An important issue to be highlighted is the complexity of applying CFF when compared to the other allocation methods, since it involves multiple parameters regarding material quality, marketing behavior, etc. It is worth mentioning that, for energy-based FUs, the CFF's portion which represents energy recovery processes (fourth summand) must be converted from a massic-based expression to an energy-based expression, in order to avoid a double count of the material LHV, as well as a dimensional flaw.

Among the evaluated methods, the CFF was the most comprehensive LCA allocation method for evaluating the environmental performance of biomass briquettes. However, in the context of solid biofuels, there are still some important issues to be covered, specifically in biological cycles. The carbon and water balances and ES are not contemplated by the CFF and any of the remaining compared methods. Furthermore, as stated by (Ekvall et al., 2020), the CFF does not consider the waste disposal avoided by energy recovery. In this sense, a set of circular criteria for physical and biochemical flows (Equation 4) which include an analysis of the demand and supply of ES (Equation 5) could be used combined with the CFF results to obtain a net circularity performance indicator. The circular biochemical flow integration would be important to enhance more knowledge in the Circular Bioeconomy field.

It is worth highlighting that this paper is not free of assumptions and limitations, that could be overcome in future research, which should also: i) verify the effects of the allocation methods applied to solid biofuels from different biomass sources (i.e. peanut bark, coconut shell, rice husk, sugarcane bagasse, etc); ii) test other energy recovery allocation methods, including Equation 5; and iii) switch the solid biofuel to pellets and other concurrent biofuels (charcoal).

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4 THE EFFECT OF TRANSPORTATION CHOICES FOR MITIGATING CLIMATE-RELATED IMPACTS: THE CASE OF SOLID BIOFUELS EXPORTED TO EUROPE PRODUCED BY LATIN AMERICAN COUNTRIES

Abstract: There has been concern over the potential risks associated with increased exports of densified biofuels to meet the growing demands of European countries. This paper performed a Life Cycle Assessment (LCA) of the biomass pellets and briquettes produced in Brazil, Chile, Colombia, and Mexico and exported to Europe. Considering a Functional Unit (FU) of 1 MJ from pellets/briquettes in a cradle-to-product-distribution approach, eleven case studies were examined, harmonizing various technological and geographical considerations. Global Warming Potential (GWP), followed by five climate-related categories, were selected for this comparative LCA. This study revealed that no significant differences were found between the environmental footprint of pellets and briquettes. The hotspots, however, varied according to the impact category under analysis. Biomass source was the main contributor to the GWP (up to -287 g CO_2 -eq/FU), mainly due to the substantial impact of Land Use Change (LUC) during the biomass cropping stage. Sea transportation had a great influence on Acidification (up to 85%) and Ozone Layer Depletion (up to 63%), while road transportation was the main contributor to Abiotic Depletion impacts (up to 73%). In conclusion, the best way of delivering biomass pellets or briquettes to the European continent should include biodiesel replacing petroleum-based diesel consumption to achieve a 'net-zero' scenario. Also, the local consumption of pellets and briquettes is more indicated as exporting distances increase, and road transportation should be prioritized with higher payload trucks.

Keywords: densified biofuels; life cycle management; LCA; energy; bioeconomy; biomass.

4.1 INTRODUCTION

'Net-zero' attempts to balance the greenhouse gas (GHG) emissions released into the atmosphere and the offset/removed emissions. The goal of the net-zero target is to achieve a state where total GHG emissions are offset by removing or offsetting emissions, resulting in zero net contributions to climate change. It is necessary to minimize carbon emissions using low-carbon strategies such as resource conservation and bioenergy use (Droege, 2018). However, in the context of Absolute Sustainability (Liu and Bakshi, 2018), a broader list of impact categories might be used to mitigate climate-related impacts.

World demand for low-carbon energy resources, such as pellets and briquettes, has grown exponentially in recent years (Rampasso et al., 2021; Silva et al., 2022) since these biofuels are less polluting than their petroleum-based matches (Calderón et al., 2018; Silva et al., 2022). For example, the world consumption forecast for wood pellets has increased from 15 to 50 million tons between 2010-2020 and may achieve 80 million tons by 2025 (Calderón et al., 2018; Vega et al., 2024).

Pellets and briquettes are used mainly by countries that need to reduce their GHG emissions as a compliance measure from agreements signed at the Climate Conference - COP21 and the United Nations 2030 Agenda (Garcia, 2017; Garcia et al., 2018). Also, the production and use of biofuels can be seen as a driving force in emerging economies toward Bioeconomy development focused on national policies for sustainable and renewable energies (Droege, 2018; Rampasso et al., 2021).

However, agro-industrial by-products *in Natura* usually present low potential for energy use due to their undesirable characteristics, such as low energy density, low calorific value, high humidity, and irregular shape (Moraes et al., 2019). These undesirable characteristics are overcome by compacting and densifying the biomass during the briquette and pelleting processes, which aggregate more excellent commercial value to the final product. These procedures are relevant to reducing transportation costs and producing a more uniform and stable solid biofuel (Nakashima et al., 2017).

Utilizing biomass pellets and briquettes within a 'net-zero' framework presents numerous advantages for the environment and society. Not only are they renewable energy sources that contribute to a decrease in life cycle GHG emissions, but they also play a crucial role in waste utilization. Typically derived from agricultural and forestry by-products, as well as other organic waste materials (Silva et al., 2022), pellets and briquettes can reduce the environmental impact of waste disposal and foster a more circular economy.

Regarding energy efficiency, biomass pellets, and briquettes can be employed in specially designed stoves, boilers, and power plants, catering to a spectrum of industrial, commercial, and residential needs. This multifaceted application underscores their adaptability and efficacy.

Contributing to energy independence, using biomass as a local energy source aids in diversifying the energy mix and diminishing dependence on imported energy. This approach also aligns with the local economy's development, as Salvador et al. (2023) emphasized, offering opportunities for farmers and communities. The cultivation, harvesting, and processing of biomass feedstocks present prospects for job creation involving a diverse range of actors across the value chain. Overall, integrating biomass pellets and briquettes into energy strategies addresses sustainability goals and fosters economic development and waste reduction.

To the best of our knowledge, the current production of these biofuels seems predominantly geared toward meeting the electricity demands of European countries, as emphasized by Farrapo et al. (2023) and Silva et al. (2022). However, this poses a potential challenge, as the increasing distances involved in transportation can amplify environmental footprints, thereby complicating the pursuit of a net-zero economy (Tsalidis et al., 2017). To comprehensively address this concern, this paper conducts a life cycle assessment (LCA) for pellets and briquettes manufactured in diverse contexts across Latin American countries and subsequently exported to the European market. The study entails a cradle-to-product-distribution life cycle analysis, encompassing eleven case studies. The environmental footprint assessment focuses on GHG emissions and other impact categories relevant to the energy sector. The paper aims to answer the following Research Questions (RQs):

(RQ1): How do transportation choices affect the environmental footprint of Latin American pellets and briquettes exported to Europe?

(RQ2): What should be done to minimize the transportation impacts of exporting pellets/briquettes to Europe in the context of mitigating climate-related impacts?

4.2 LITERATURE REVIEW

Hakwen (2017) proposed a set of actions applicable at both micro and macro scales, from small manufacturing companies to policymakers, to attain a' net-zero' state. A pivotal strategy focuses on the energy sector, which is responsible for most of the estimated anthropogenic GHG emissions. Raworth (2018) contends that there is a need to transition to clean energy mixes and simultaneously regenerate natural capital by adopting Circular Bioeconomy solutions, for example.

Rampasso et al. (2021) and Salvador et al. (2023) advocate for the concept that a Circular

Bioeconomy centers on the development of regenerative systems, emphasizing strategies to decelerate, narrow, and ultimately close the utilization of natural resources as much as possible. In the energy sector, illustrative measures include promoting the increased use of renewable resources as feedstocks and discouraging the reliance on virgin biomass, such as wood forests, as a primary supply. In alignment with this perspective, Silva et al. (2022) elucidate that significant efforts have been directed toward designing biorefineries in recent years, focusing on recovering biomass waste as a valuable energy source. Going beyond the establishment of biorefineries and the optimization of resource efficiency, Salvador et al. (2023) assert that placing value on the local economy represents a noteworthy paradigm for the energy sector, particularly in its commitment to the use of renewable resources. All these strategies are deemed pivotal not only for fostering circular economies but also for advancing toward 'net-zero' goals.

4.2.1 Sector statistics for biomass pellets and briquettes

Among the set of energy sources, briquettes and pellets are used in various thermal applications, ranging from a bakery oven to a thermoelectric plant. However, experts report the slow development of the domestic market for pellets and briquettes in Latin American countries (Silva et al., 2022; Vega et al., 2024) by mentioning some typical problems responsible for (i) The high cost of the electricity used for production, which increases briquettes/pellets final prices; (ii) Cultural problems, since many entrepreneurs are still unaware of the advantages of using biomass briquettes and pellets; and (iii) High transport and toll costs, which make impractical long-distance shipping (Garcia et al., 2017; Garcia et al., 2018b).

South American countries produced around 608,000 tons of wood pellets, representing a 385% growth in 2017, especially in Brazil and Chile. However, that number accounted for only 2% of global pellet production in the period (Calderón et al., 2018). In this sense, there is a broad potential for exploring solid biofuels in Latin America due to the great representativeness of agriculture and forest activities in its countries (Farrapo Jr. et al., 2023; Silva et al., 2022).

It is worth highlighting that the lagging development of the Latin American domestic market for densified solid biofuels contrasts with the growing demand for pellets from Europe (e.g., United Kingdom, Italy, and Germany) and Asia (e.g., Japan, China, and Korea) countries. The optimistic forecasts of world consumption for pellets have already been reflected in the Brazilian industry, resulting in a substantial annual production increase from 2015 (75,000 tons) to 2018 (507,000 tons), pushed mainly by international demand (Calderón et al., 2018). The same was found for other South American countries, such as Chile, with an annual production of 137,400 tons (Calderón et al., 2018).

New pellet factories with high production capacity (overpassing 100,000 tons/year), all of them focusing on exportation, emerge year after year in Brazil and other Latin American countries (Matheus et al., 2021) influenced by Brazilian currency depreciation against the dollar and the euro.

Regarding briquettes, Dias et al. (2012) and Farrapo Jr. et al. (2023) report that Brazil is a major producer, employing different types of residual biomass and raw materials for their production, among them: waste from sawmills of tropical woods, açai stone, pine, and eucalyptus sawdust, coconut, coffee, peanut, and rice barks, carnauba by-products, sugarcane bagasse, cashew tree, and urban tree pruning. Small briquettes producers are concentrated mainly in Brazil's South and Southeast regions, with processing capacities ranging from 600 to 1,000 tons of briquettes per month, to take advantage of local agro-industrial waste (Fernandez et al., 2017; Moraes et al., 2019). Due to the size and processing capacity of these companies and the variability of biomass origin/supply, briquette production is highly intermittent and is often not fully accounted for by official statistics (Dias et al., 2012; Farrapo Jr et al., 2023).

Unlike briquettes, wood pellets consist of a solid commodity biofuel, which is internationally traded. Their regular and cylindrical geometry provides them with greater thermal efficiency than coal or gross biomass. They have low moisture content, allowing high energy density, resulting in greater thermal efficiency for energy conversion. In addition, this product is easily handleable and transportable, requiring little space for storage (Garcia, 2017; Moreira et al., 2021).

4.2.2 'Net-zero' challenges through the use of pellets and briquettes and climate-related impacts

In general, the current literature considers that by utilizing biomass pellets and briquettes, which are derived from responsible forestry and agricultural practices, the overall carbon impact can be minimized, contributing to 'net-zero' goals. It's important to note that the sustainability of biomass utilization depends on responsible sourcing, efficient conversion technologies, and adherence to environmental and social safeguards (Muazu et al., 2017). Additionally, the net-zero benefits depend on the entire life cycle of biomass production, processing, and use aspects to be properly managed in LCA.

One of the primary challenges in modeling the LCA of pellets and briquettes pertains to carbon sequestration in by-products as supply. When biomass is sustainably harvested, the carbon stored in the by-products left in the field has the potential to contribute to soil carbon sequestration, offering a means of mitigating the impact of climate change (Farrapo Jr. et al., 2023; Vega et al., 2024). However, there is disagreement among various LCA studies regarding the consideration of this effect as a significant land use change.

Nonetheless, according to Silva et al. (2022), numerous LCA studies do not consider carbon sequestration in by-products as a relevant factor. However, the inclusion of this aspect can yield varied LCA results and conclusions, thus influencing the assessment of climate-related impacts. Additionally, Martín-Gamboa et al. (2020) propose that harmonizing global warming and non-renewable primary energy impacts can establish a correlation between the two, providing a basis for creating net-zero solutions in the energy sector. A similar correlation may arise in the LCA of transportation logistics choices. Cleary and Caspersen (2015), along with Chen et al. (2018), emphasize the importance of accounting for GHG and other emissions in LCA. This includes emissions that can lead to acidification and particulate matter formation, among other climate-related impacts (Tsalidis et al., 2017).

Both pellets and briquettes are significant products in the Latin American region, yet there remains a scarcity of LCA studies available in the literature for this specific geographical area. Most of the publications recently found cover Brazil, Chile, Colombia, and Mexico which stand as the main producers. Despite the abundance of LCA studies in the broader energy sector, only a limited number focus on the Latin American region, with the majority concentrated in Europe (Martín-Gamboa et al., 2020).

While transportation logistics is frequently examined in LCA comparative studies (Cleary and Caspersen, 2015; Sikkema et al., 2020), current research predominantly addresses transport decisions in European contexts, as well as countries such as China and North America. Consequently, transportation logistics in the Latin American context remains largely unexplored, serving as a primary motivation for this research. Some publications have shown the relevance of this topic (Magelli et al., 2009; Pa et al., 2012) because transport (by land and sea) is a stage associated with high energy demands, mostly provided by fossil fuels, which are associated directly with an increase in environmental impacts and with the costs of solid biofuels (Paolotti et al., 2015; Magelli et al., 2009). Also, transportation choices are one of the main barriers to permitting the development of ‘net-zero’ logistical solutions (Droege, 2018; Sikkema et al., 2020).

Higher energy consumption and environmental impacts have been reported when sea freight is implemented for long transport distances (Magelli et al., 2009; Pa et al., 2012), decreasing the environmental benefits commonly associated with the use of solid biofuels (Sikkema et al., 2020). Therefore, there has been concern over the potential risks associated with increased exports of densified biofuels to meet the growing demands of European Union countries (Proskurina et al., 2016) and others, requiring more investigation on the embodied impacts from road transportation and shipping activities to the pellet/briquette environmental life cycle profile.

4.3 METHODS

To properly manage RQ 1 and RQ2, eleven case studies were modeled for the Latin American solid biofuels context, with two cases based on primary data taken from Brazilian industries, while nine of them had their inventory data taken from the literature. The execution of this exploratory research follows the LCA procedures from ISO 14040-14044 (2006).

The following paragraphs describe the LCA scope, i.e., the data sources and assumptions made on data collection and LCA modeling for the system boundaries, as well as the process of data harmonization among all the eleven case studies selected.

4.3.1 Data sources

The search gave attention to consistent datasets to build the case studies for the different types of pellets and briquettes produced in Latin America. Eleven LCA case studies (Case 1 - C1 to Case 11 - C11) were selected for the same geographical and sectorial scopes.

Secondary data were sourced through a comprehensive literature review focused on LCA studies concerning biomass pellets and briquettes in Latin America. This investigation spanned three prominent databases: Scopus, Web of Science (WoS), and SciELO. The literature review across these selected databases involved the use of various search terms, including "pellet," "briquette," "briqueta," and "briquete," to encompass potential language variations in English, Portuguese, and Spanish. Furthermore, the search criteria were refined by specifying Geographical Region (limited to Latin American countries), Period (from 2000 to 2022), Original Language, Thematic Area (excluding Health Sciences), and Publication Titles (considering all publications except those related to Food, Mining, and Humanities). Initially, 630 publications were retrieved from WoS, 405 from Scopus, and 200 from SciELO. Following this, a title screening was conducted for each database to identify publications focused on biomass pellets and briquettes, eliminating repetitions and those with unrelated topics. This process reduced the total number of publications to 113 for Scopus, 49 for WoS, and 26 for SciELO. Subsequently, an abstract screening was carried out, refining the selection to publications specifically addressing LCAs of densified biofuels in Latin America. This further narrowed down the list to 7 records chosen to represent various production cases in Brazil, Chile, Colombia and Mexico in nine case studies (C1 to C9) under diverse biomass sources and transportation logistics.

Primary data were obtained from two prominent Brazilian pellet producers situated in the south and southeast regions of the country, representing Cases 10 and 11 (C10 and C11), acknowledged as the most significant Brazilian sites for pellet and briquette production sites (Garcia et al., 2018). C10 is centered on a small producer of peanut shell pellets located in São Paulo state. The inventory data for C10 were acquired through a semi-structured interview conducted with the company's director during a technical visit in 2021. In contrast, C11 was constructed based on data from a large-scale Pinus pellet industry situated in Paraná state. The plant manager provided input and output data, along with other relevant information during a technical visit made in 2021. It is important to note that in both cases, electricity is generated through biomass cogeneration. In the case of C10, the drying process of peanut by-products was not considered, as the raw material is procured in a pre-dried state. In summary, C1 to C9 were formulated based on the selected publications, while two cases were established through primary data collections (C10 and C11). Despite originating from diverse sources, all cases yielded sufficient data to facilitate replications. Subsequently, an attributional LCA was conducted to evaluate and simulate the environmental footprints of briquettes and pellets produced in Latin America and exported to Europe..

4.3.2 Life Cycle Assesment modeling and data harmonization

- *Functional unit definition*

The Functional Unit (FU) was restricted to the production and delivery to the European market of 1 MJ of energy from pellets/briquettes produced in Latin American countries. The reference flow was defined as the mass needed to provide the FU, according to the energy efficiency conversion based on the Lower Heating Value (LHV) of each kind of biofuel. Two of the eleven cases (C3, and C11) provided the LHV information from the brazilian pine pellets mill (see on-line SM). LHV of C1 was assumed as the same to C3, and C2 calorific value was gathered from Ruiz et al. (2018). For all Chilean cases (C4, C5, and C6), Nunes et al. (2021) data were assumed as LHV, while both Colombian (C7 and C8) cases were based on Pua et al. (2020). Musule et al. (2021) provided the LHV information from Mexico (C9) while for peanut shell pellets (C10) LHV data was taken from Perea-Moreno et al. (2018).

- *Product system definition*

Cradle-to-product-distribution systems were designed as it is represented in Figure 4.1, including relevant unit processes, such as biomass supply, drying, pelletizing/briquetting process, and all the transportation flows, including the drive of raw biomass from its collecting point to the industry, as well as the exportation of the biofuels until Rotterdam port, in the Netherlands, which was considered as the final destination, since it is one of the most relevant biomass hubs in Europe (Port of Rotterdam Authority, 2015). The using phase of pellets and briquettes (i.e., burning) was not included in this study, once this paper aims to investigate the environmental profile of these products based on their productions in Latin America and their delivery to Europe.

● *Life Cycle Inventory*

All the inventory data (i.e., input/output flows) for the pelletizing and briquetting processes were taken from the reviewed LCA papers and from the contacted industries (C10 and C11), and then adjusted for the FU in Table 4.1. The background LCA datasets used to complete the comparative cradle-to-product-distribution systems included: electricity, water, thermal energy supplies, transport activities, and biomass supplies. The uncertainties linked to each of these flows were computed utilizing the Pedigree Matrix, as outlined by Saade et al. (2021), and can be found in the Supplementary Material (SM).

Regarding the biomass supply, it was considered for all cases the use of residual biomass as an input source instead of biomass from energetic crops. Except for C7 and C8, where the biomass source was palm fruit bunches from the Colombian palm oil mill, consistent with case studies by Garcia-Nunez et al. (2016) and Ramirez-Contreras et al. (2020). Also, the carbon neutral approach is followed, so in all 11 scenarios, the biogenic carbon fluxes associated with biomass burning were not accounted for in the LCA. Biomass type and data sources were chosen based on the ecoinvent database use, as detailed in the online SM. Allocation rules for biomass feed were kept as defined in the selected ecoinvent datasets (See Figure 4.2).

It is also important to highlight that just the Colombian datasets originally accounted for direct Land Use Change (LUC), while the indirect LUC was reported based on the ecoinvent database considering a 20 year span. The LUC refers to the land use conversion which generates carbon flows between terrestrial ecosystems and the atmosphere, in a way that if the carbon stocks of a biofuel crop are lower than the carbon stocks of the reference land, the land use causes CO_2 emissions (Brandão et al., 2022). For the Brazilian, Chilean, and Mexican cases, LUC data were extracted using the 'Direct Land Use Change Assessment Tool' from Blonk

Consultants (2014), and then using ecoinvent datasets as the data provider for indirect LUC accounting. Figure 4.2 shows a schematic of the biomass supply and land use modeling.

Figure 4.1 - System boundaries and data sources for each product system under investigation.

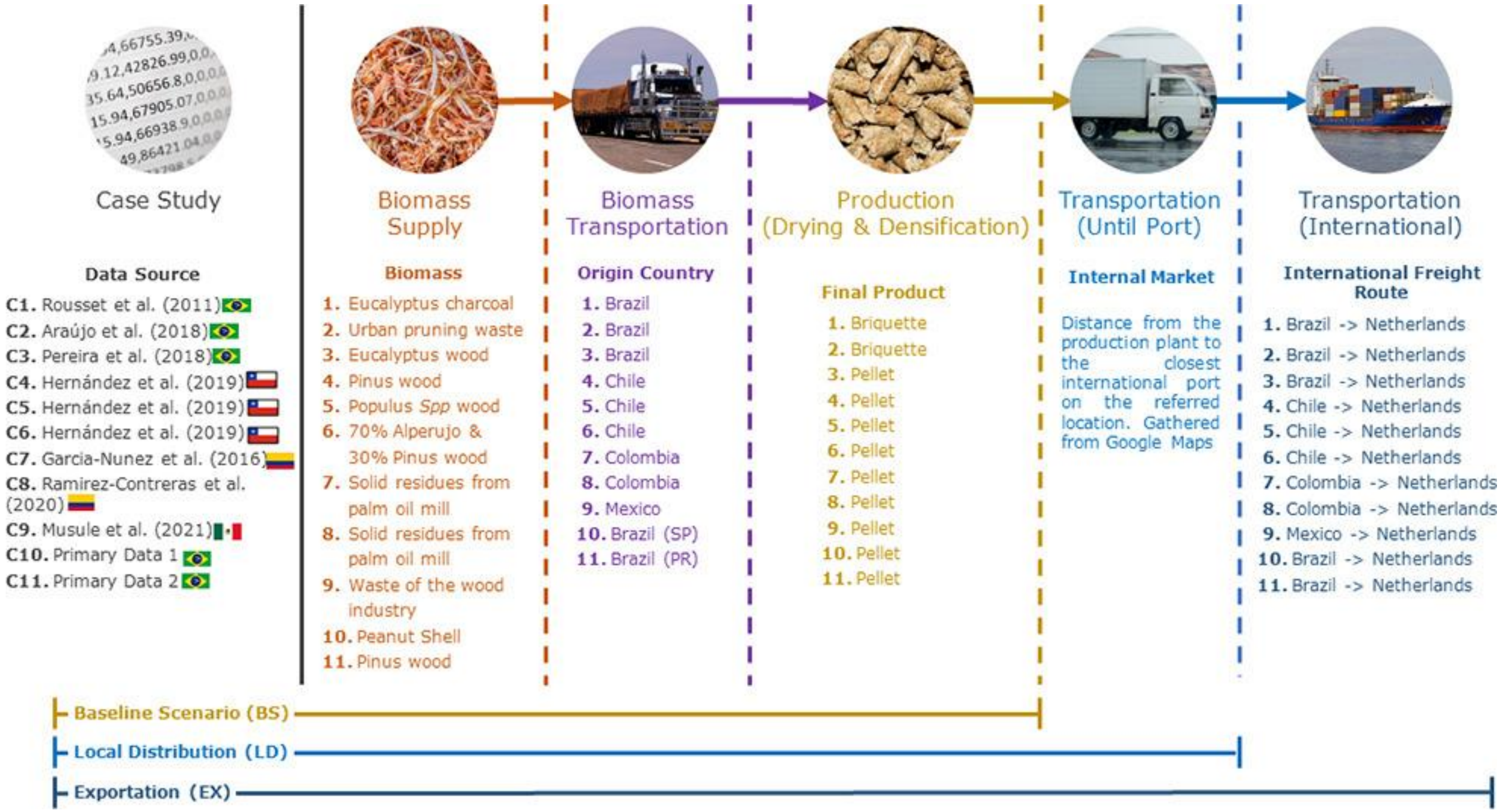


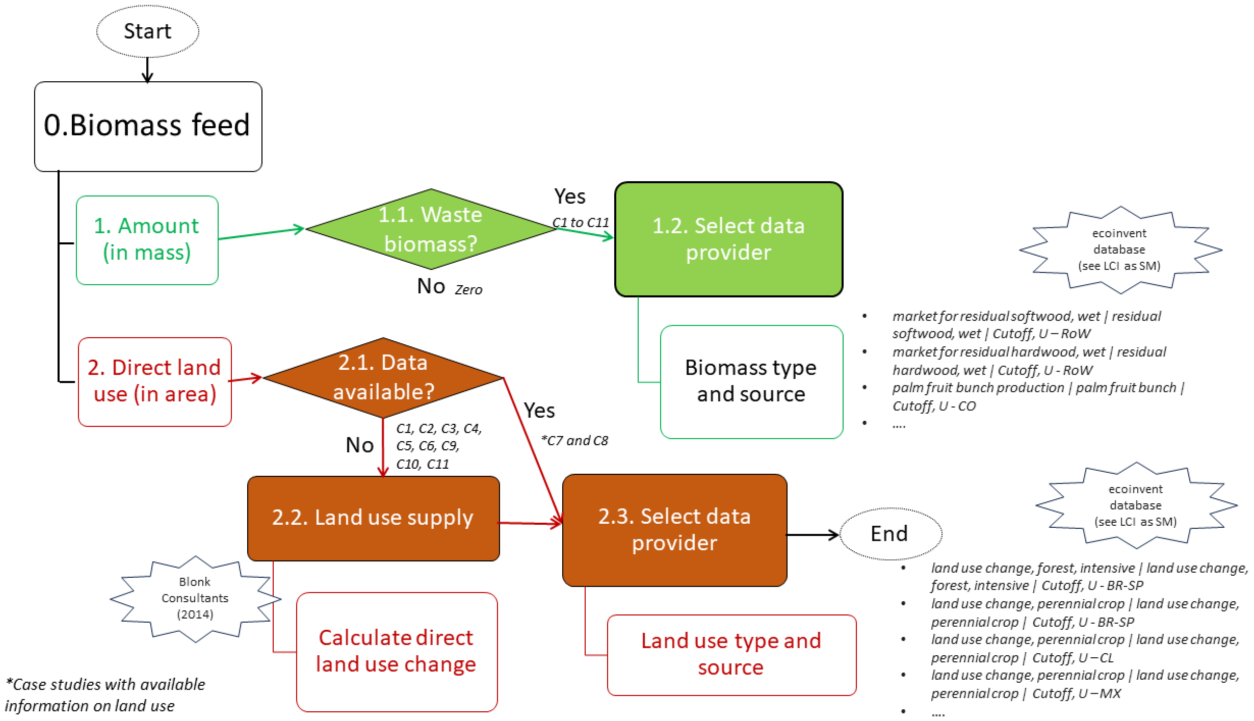
Table 4.1 - Input and output foreground flows for the selected case studies.

	INPUTS						**OUTPUTS**			
LIFE CYCLE STAGE	BIOMASS FEED		PRODUCTION (Drying and Densification)				FINAL PRODUCT, CO-PRODUCTS AND BY-PRODUCTS			
FLOW	**Raw Material [g]**	**Direct Land Use Change - LUC [cm²]**	**Electricity [kWh]**	**Water [g]**	**Diesel [mg]**	**Other**	**Solid Biofuel [FU]**	**Emissions to air [g]**	**Emissions to soil [g]**	**Co-products**
Case 1 Eucalyptus charcoal briquettes	**Charcoal** (41.73) **Starch** (4.34)	29.79	-	25.29	-	**Steam** (14.18 g) **Natural Gas** (1.57 g) **Silica Sand** (34.61 g)	**Briquettes 1 MJ (or 63.3 g)**	-	**Residual biomass** (0.95 g)	-
Case 2 Residual urban pruning waste briquettes	**Bark chips** (11.17) **Cleft timber** (11.17) **Residual hard wood** (11.32) **Residual soft wood** (11.32) **Wood chips** (11.17)	744.68	0.003	-	-	-	**Briquettes 1 MJ (or 53.2 g)**	-	-	-
Case 3 Eucalyptus wood pellets	**Residual soft wood** (263.71)	192.20	0.011	-	0.037	-	**Pellets 1 MJ (or 63.3 g)**	**Water Steam** (100.2)	-	-
Case 4 Pinus Spp Pellets	**Residual soft wood** (63.73)	15.54	0.003	-	0.042	-	**Pellets 1 MJ (or 56 g)**	-	-	-
Case 5 Populus Spp pellets	**Residual soft wood** (61.47)	51.06	0.003	-	0.040	-	**Pellets 1 MJ (or 54.5 g)**	-	-	-

Case 6 Alperujo 70% / Pinus Pellets 30%	**Residual soft wood** (18.51) **Residual hard wood** (42.14)	710.9	0.004	-	0.041	-	**Pellets 1 MJ (or 54.7 g)**	-	-	-
Case 7 Residual palm oil mill pellets	**Palm fruit bunch** (478.77)	-	-	574.53	0.478	-	**Pellets 1 MJ (or 59.7 g)**	**Water Steam** (492.42) **COD** (339.92)	**Ash** (2.48) **Sludge** (12.55) **Dust** (4.02)	**Treated POME** (235.7 g) **Palm Moisture** (98.15 g) **Electricity** (0.11 kWh) **Oils** (68.08 g) **Palm Kerneal Meal** (20.11 g)
Case 8 Residual palm oil mill pellets	**Palm Fruit Bunch** (266.31)	-	0.005	28.66	0.089	**Palm kerneal meal** (12.16 g)	**Pellets 1 MJ (or 59.7 g)**	**COD** (10.72)	-	**Palm Kerneal Crude** (12.58 g) **Treated POME** (109.76 g)
Case 9 Residual pinus pellets	**Residual soft wood** (94.46)	1,339.57	0.009	-	-	**Lubricating oil** (11.48mg) **Petrol for machines** (5.46 kJ)	**Pellets 1 MJ (or 66 g)**	**Particulates < 2.5 um** (0.025)	-	**Electricity** (0.01 kWh)
Case 10 Peanut shell pellets*	**Residual peanut shell and barks** (58.44)	4,751.2	0.009	-	0.1	-	**Pellets 1 MJ (or 58.4 g)**	-	-	-
Case 11 Pinus Pellets *	**Residual soft wood** (56.75)	13.84	0.005	-	-	**Natural Gas** (9.89 mg)	**Pellets 1 MJ (or 53.2 g)**	**Water Steam** (3.46)	-	**Residual Wood** (0.074 g)

**Case studies modeled through primary data collection in Brazil. The remaining cases were extracted from secondary data sources.*

Figure 4.2 - Decision tree for modeling and harmonizing of data for biomass supply and land use change for the eleven case studies on Latin America



- *Data representativeness*

The representativeness of all case studies was defined considering the local geographical context of each country. C3 and C11 from Brazil are the most representative ones since they consider wood pellets made from Eucalyptus and Pinus species, which fulfill more than half of the production national capacity (Garcia et al., 2016; Garcia et al., 2018). C4 is the most representative situation for Chile, as Pinus is the main biomass source for pellets production (Rocha et al., 2020). Both Colombian cases (C7 and C8) do not represent the national context, as the palm oil sector accounts for only 4% of the total energy from agro-industrial waste generation in Colombia (Sagastume Gutiérrez et al., 2020). On the other hand, C9 from Mexico can be assumed as the most representative, as wood by-products from sawmills and logging are more than 50% of the pellets production (Tauro et al., 2018).

C9 presents distinct air emissions in Table 4.1, where combustion gases are generated due to burning part of the biomass for raw material drying (where the authors measured these primary data at the study site). On the other hand, C3, C7, and C11 only exhibit the release of water steam related to biomass drying in an electric dryer integrated with a pelletizer. Other case studies, such as C2, assumed that biomass could be briquettes in its natural state (no need for drying), while the remaining studies considered only the natural drying of biomass.

- *Transportation distances*

For all cases taken from the literature, transportation data of biomass until the industry was based on the data contained in five of the seven selected publications – transportation data for C3 and C7 were gathered from Pereira et al. (2018) and Ramirez-Contreras et al. (2020), respectively, while for primary datasets, it was considered the distances according to the interviewed people at the company levels. Final product distributions to international consumers, on the other hand, were modeled considering both road and sea freight peculiarities from each case.

Calculations for road freight were based on the distances from the location of the biomass densification plants to the closest international port, for each situation. For all cases, the flows inputted on the LCA software considered 16-32 metric ton truck (Euro III) equivalent vehicles, with an exception for the raw material transportation in C2, which was modeled as a 7.5–16 metric ton truck (Euro III) equivalent vehicle according to Araújo et al. (2018).

From this standpoint, the sea freight calculations considered the distances from the international port in each case to the port of Rotterdam (Netherlands), assumed as the final point of distribution for European consumption. The distance calculations were made on the container freight shipment for all cases. Table 4.2 presents the main transportation modeling assumptions:

Table 4.2 - Transportation modeling data for each case study

Case		Road distance from biomass collecting point to industry [km]	Exportation Distances		
			International Route [-]	Road Freight Distance [km][a]	Sea Freight Distance [km][b]
1	Eucalyptus wood residue to produce charcoal briquettes	6.74	By road (Brazil) Sete Lagoas/MG → Vitória/ES By sea (International) Vitória/ES (BR) → Rotterdam/ZH (NL)	600	9,218.99
2	Urban pruning residue to produce briquettes	60	By road (Brazil) João Pessoa/PB → Suape/PE By sea (International) Suape/PE (BR) → Rotterdam/ZH (NL)	200	7,776.54
3	Eucalyptus wood pellets	6.74	By road (Brazil) Lages/SC → Itajaí/SC By sea (International) Itajaí/SC (BR) → Rotterdam/ZH (NL)	300	10,368.51
4	Pinus wood pellets	5	By road (Chile) Talca/ML → San Antonio/VS By sea (International) San Antonio/VS (CL) → Rotterdam/ZH (NL)	300	14,104.33
5	Populus wood pellets	5	By road (Chile) Talca/ML → San Antonio/VS By sea (International) San Antonio/VS (CL) → Rotterdam/ZH (NL)	300	14,104.33
6	Alperujo and pinus wood mix (70/30) to produce	56.5	By road (Chile) Talca/ML → San Antonio/VS	300	14,104.33

	pellets		By sea (International) San Antonio/VS (CL) → Rotterdam/ZH (NL)		
7	Fresh fruit Brunches to produce pellets	230	By road (Colombia)[c] Valledupar/CE → Barranquilla/AT By sea (International) Barranquilla/AT (CO) → Rotterdam/ZH (NL)	300	8,552.16
8	Fresh fruit Brunches to produce pellets	230	By road (Colombia)[c] Valledupar/CE → Barranquilla/AT By sea (International) Barranquilla/AT (CO) → Rotterdam/ZH (NL)	300	8,552.16
9	Pine wood pellets	60	By road (Mexico) Durango/ DG → Tampico/TS By sea (International) Tampico/TS (MX) → Rotterdam/ZH (NL)	880	9,610.82
10	*Peanut shell pellets	10	By road (Brazil) Itaju/SP → Santos/SP By sea (International) Santos/SP (BR) → Rotterdam/ZH (NL)	410	10,015.23
11	*Pinus Pellets	6	By road (Brazil) Telemaco Borba/PR → Paranaguá/PR By sea (International) Paranaguá/PR (BR) → Rotterdam/ZH (NL)	383	10,282.03

*[a] Road Freight Distance source: Google Maps (2021); [b] Sea Freight Distance source: SEARATES (2021); [c] Pellet origin is considered to be the same used in Case 7, in the Colombian northern region. *Cases obtained through primary data.*

In order to minimize multifunctional issues, the LCA attributional studies of C7 (Garcia-Nunez et al., 2016) and C8 (Ramirez-Contreras et al., 2020), were allocated, since the biomass processing plant, i.e., the palm oil mill produces other co-products besides pellets. For this reason, a mass allocation of 55.70% was applied to the pellet output in C7 and a mass allocation of 30.32% to pellets in C8, as these were the sole case studies where the biomass source did not originate as a residue.

- Impact categories selection

Classification and characterization steps were included during the life cycle impact assessment (ISO, 2006a, b). The ecoinvent 3.7 regionalized cutoff database was adopted as the main data source to enhance the LCA modeling for each case from C1 to C11. The LCA application was facilitated by the openLCA 1.10 software tool. For the impact assessment phase, the CML-IA baseline v4.7 method was employed (CML, 2016), focusing on six midpoint impact categories (excluding ecotoxicity and human toxicity impacts): Abiotic Depletion (ADPe), Acidification Potential (AP), Eutrophication Potential (EP), Global Warming Potential (100 years - GWP), Ozone Layer Depletion (ODP), and Photochemical Ozone Creation Potential (POCP). The selection of the CML baseline aligns with the findings of Martín-Gamboa et al. (2020) and Silva et al. (2022), where this method emerges as the most commonly used in LCAs for pellets and briquettes. Furthermore, the study took into account Cumulative Energy Demand (CED) with a focus on Overall Non-Renewable energy in the initial results. It's noteworthy that these categories employed in this study align with the international Environmental Product Declaration (EPD) platform for energy and biofuels use, specifically referring to PCR 2007:08. By adhering to the current literature and established protocols such as PCR 2007:08, the study not only ensures methodological consistency but also facilitates meaningful comparisons with other research efforts and environmental assessments in the field.

All these midpoint impact categories are deemed pertinent to achieving a 'net-zero' economy too. They have been explored in the existing literature on biofuels, including studies by Achten et al. (2010) for Jatropha biodiesel in India; Arvidsson et al. (2012) for Asian palm oil methyl ester biodiesel; Iribarren et al. (2012) evaluated the environmental performance of a biofuel production system based on the fast pyrolysis of short-rotation poplar biomass; Kim & Dale (2003) for corn, soybeans, alfalfa, and switchgrass biomass from seven states in United States; Kylili et al. (2016) studied biomass pelleting process of olive husk in Cyprus; Merchan et al. (2020) for the transportation impacts of diesel trains, electric trains and rail freight transport considering the Belgian traction mix; and Tsalidis et al. (2017) for biofuel production from torrefied wood. Therefore, considering other categories of environmental impacts beyond GWP is imperative.

While climate change is undeniably a major global concern, a truly sustainable approach necessitates the consideration of various interconnected environmental issues, as emphasized by Liu and Bakshi (2018) to avoid undesirable trade-offs. Resource depletion, in particular, stands out as an impact category that can exhibit a positive correlation with GWP results, as highlighted by Martín-Gamboa et al. (2020). In the realm of transportation logistics, shifts in GWP can have cascading effects on other environmental impact categories such as AP, ODP, and POCP, for example (Cleary and Caspersen, 2015; Sikkema et al., 2020). This interconnectedness arises from alterations in the pattern of air releases, attributed to changes in fuel consumption. Therefore, fluctuations in GWP can potentially influence the environmental impacts associated with the burning of fuels, creating a ripple effect across various aspects of air quality and atmospheric composition. A comprehensive assessment of these interrelated impacts is essential for a more nuanced understanding of the environmental consequences associated with transportation activities.

4.3.3 Life Cycle Assesment Interpretation

The environmental footprint analysis was first verified by their absolute impact values for all the impact categories (Section 4.1). A contribution analysis comparing the influence of each life cycle stage on the final impacts was performed, as well as a discussion around the main environmental hotspots (Section 4.2) observed for each of the impact categories, followed by an uncertainty analysis in Section 4.3 (Michiels & Geeraerd, 2020). The Monte Carlo simulation is one of the most usual techniques applied to the uncertainty analysis performed on LCAs studies (Guimarães et al., 2018). In this context, the validation (or lack thereof) of LCA results will be determined through the results of uncertainty analysis. Following 1,000 lognormal simulations, it will be possible to ascertain whether the LCA impact results fall within the 95% confidence interval for each impact category and case study (Saade et al., 2021).

Finally, a sensitivity analysis of transportation choices (Section 5.1) was performed on the impact categories most affected by transportation activities, so that three alternative scenarios to minimize the environmental impacts were designed:

(i) The use of biodiesel as a fuel for all transportation activities in the product systems, including sea transportation, as suggested by Noor et al. (2018). For all cases and countries, diesel consumption was replaced by biodiesel in a 1:1 ratio, considering their similar energy efficiency (Sheehan et al., 1998). Soybean biodiesel unit process was gathered for all cases in the LCA modeling since this is the only available data on Ecoinvent 3.7 database regarding biodiesel;

(ii) The use of trucks with higher load capacity (> 32 tons) for road transportation, as a potential strategy to reduce environmental impacts by optimizing the freights, according to Neves et al. (2018);

(iii) The combination of (i) and (ii) alternative scenarios.

For the impact categories, the outcomes of the three alternative scenarios were internally normalized following the approach outlined by Prado et al. (2012). This normalization was performed based on the reference LCA results, aiming to articulate the impact reduction rate as a percentage for all cases and categories within each scenario. The differences between results from primary and secondary data sources were also discussed from all perspectives.

4.4. RESULTS

4.4.1 Overall Life Cycle Assesment Results and Contribution Analysis

The overall LCA results for all the case studies and impact categories considering 1 MJ of pellet/briquette delivered to Rotterdam port from the Latin American countries are presented in Table 4.3. The highest and the lowest values are highlighted in orange and green colors, respectively. Results with negative values were also highlighted.

The results obtained for various types of densified biofuels show no significant differences. This suggests that, despite their distinct sizes, it cannot be definitively concluded whether the use of pellets instead of briquettes independently promotes environmental gains or losses. When results are categorized by country, the Chilean cases (C4, C5, C6, C9) consistently fall into intermediate positions and do not emerge as the most or least impactful cases. Notably, C9 from Mexico exhibits the highest rates of non-renewable energy demand, attributed to the extensive road distances required for transporting the final product to the departure port.

Table 4.3 - Results of the environmental impacts per FU according to the case study.

Case Study	IMPACT CATEGORY						
	ADPe (mg Sb -eq)	AP (g SO_2 -eq)	EP (g PO_4 -eq)	GWP 100y (g CO_2 -eq)	ODP (mcg CFC -11 -eq)	POCP (g C_2H_4 -eq)	CED Non-Renewable (MJ -eq)
Case 1 Eucalyptus charcoal briquettes[a]	0.395	0.115	0.049	10.219	1.373	0.378	0.464
Case 2 Residual urban pruning waste briquettes[b]	0.187	0.012	0.011	-36.070	0.258	0.001	0.094
Case 3 Eucalyptus wood pellets[c]	0.103	0.028	0.010	-30.323	0.552	0.001	0.183
Case 4 Pinus Spp Pellets[d]	0.026	0.021	0.009	1.870	0.199	0.001	0.113
Case 5 Populus Spp pellets[d]	0.025	0.020	0.008	-0.308	0.192	0.001	0.109
Case 6 70% Alperujo / 30% Pinus Pellets[d]	0.046	0.026	0.010	-76.246	0.308	0.001	0.137
Case 7 Residual palm oil mill pellets[e]	1.963	0.267	0.171	-11.610	2.276	0.004	0.251
Case 8 Residual palm oil mill pellets[f]	2.027	0.309	0.181	-7.362	2.659	0.006	0.287
Case 9 Pine wood pellets[g]	0.098	0.303	0.057	-69.484	0.492	0.012	0.515
Case 10 Peanut shell pellets[h]	0.003	0.337	2.585	-287.373	0.079	0.235	0.004
Case 11 Pinus pellets[h]	0.024	0.005	0.002	0.021	0.129	0.117	0.083

[a]Rousset et al. (2011); [b]Araújo et al. (2018); [c]Pereira et al. (2018); [d]Hernández et al. (2019); [e]Garcia-Nunez et al. (2016); [f]Ramirez-Contreras et al. (2020); [g]Musule et al. (2021); [h]Case studies gathered from primary data sourcing.

Source: Own authorship

On the other hand, the overall results for Colombian cases had the worst environmental footprint in general, with C7 and C8 figuring as the second and first cases with the highest results in two of the seven impact categories (ADPe and ODP). These results can be explained due to their multifunctional systems, where many products and coproducts are produced in addition to the biomass pellets (e.g., electricity, ash, palm oil, and palm oil mill effluent). As a result, both input (e.g., biomass supply and energy demand) and output flows (air emissions, effluents, and waste flow) tend to be higher in these systems when compared to pellet/briquette dedicated systems (Silva et al., 2022).

Two Brazilian cases (C1 and C10) had the highest impacts in the four categories (AP, EP, GWP, and POCP). The main reason for that is related to the biomass used for pellets and briquette production, which led to significant impacts on the LCAs as already discussed by Soraya et al. (2014) and Silva et al. (2022), for example.

Table 4.4 - Detailed life cycle analysis on the global warming potential impacts in terms of fossil, biogenic, and Land Use Change flows

Case Study	**Global-warming potential** impacts per FU **(g CO_2 -eq / MJ)**			
	Fossil	Biogenic	LUC	Total
Case 1 Eucalyptus charcoal briquettes	5.87	4.52	-0.17	10.219
Case 2 Residual urban pruning waste briquettes	1.80	-	-37.87	-36.070
Case 3 Eucalyptus wood pellets	5.08	0.42	-35.82	-30.323
Case 4 Pinus Spp Pellets	3.48	-	-1.61	1.870
Case 5 Populus Spp pellets	3.24	-	-3.55	-0.308
Case 6 70% Alperujo / 30% Pinus Pellets	3.99	-	-80.24	-76.246
Case 7 Residual palm oil mill pellets	10.10	0.11	-21.83	-11.610
Case 8 Residual palm oil mill pellets	9.90	0.09	-17.35	-7.362
Case 9 Pine wood pellets	1.49	-	-70.97	-69.484
Case 10 Peanut shell pellets	10.56	-	-297.93	-287.373
Case 11 Pinus pellets	0.06	0.00103	-0.04	0.021

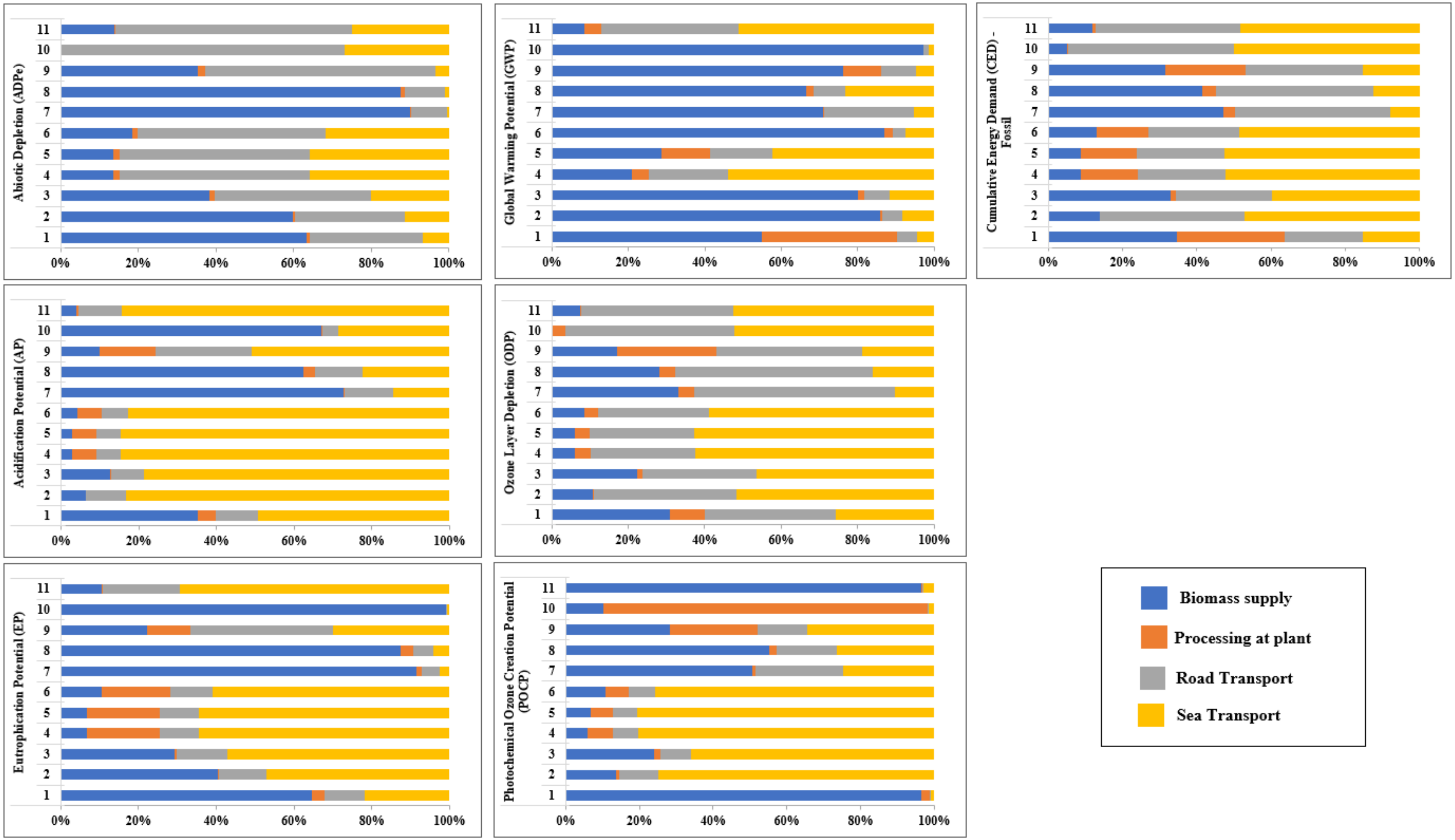
Source: Own authorship

Table 4.4 provides a comprehensive analysis of GWP impacts, delving into GHG emissions, biogenic CO_2, and LUC impacts. The GWP exhibits a close relationship with both LUC and fossil fuel utilization. For instance, in the life cycle of briquettes for C1, the substantial use of fossil fuels has resulted in the highest impacts of this nature. Conversely, LUC has played a pivotal role in generating carbon credits for the remaining cases, effectively mitigating a significant portion of GWP impacts. Notably, LUC emerged as particularly influential in the

Brazilian case, C10, with carbon stocks exceeding five times those of the Colombian case, C8, highlighting its significant contribution to the 'Net-Zero' agenda within the energy sector. In summary, the utilization of pellets and briquettes in Latin America appears to offer a positive contribution to achieving the 'Net-Zero' agenda in the energy sector, primarily attributed to the substantial impact of LUC.

Based on these overall LCA results, a contribution analysis of the impacts (in %) is illustrated in Figure 4.3. In this context, this analysis shall represent the most impactful stages in the life cycle of the pellets and briquettes produced in Latin America and exported to Europe. In view of the system boundaries defined in this study, the life cycle stages were divided as (i) Biomass supply, blue colored; (ii) Processing at the plant – pelletizing and briquetting, in orange; (iii) Road transportation, with grey color; and (iv) Sea transportation, represented in yellow.

Figure 4.3 - Relative contribution analysis (%) of each life-cycle stage considered in the system boundaries of pellets and briquettes in Latin America.



With the exception of GWP, transportation activities, both by road and sea, consistently accounted for a minimum of 50% of the total impacts across all impact categories. Generally, the impacts of transportation were intricately tied to freight distance. For instance, Figure 4.3 illustrates the predominant influence of Road Transportation (depicted in grey color) on Case 9 from Mexico, where terrestrial distances outweighed those at sea. Conversely, Sea Transportation (depicted in yellow) exerted a greater influence on the Chilean cases (C4, C5, and C6) due to the extensive distances traveled between the San Antonio and Rotterdam ports. It's important to note that the relative contributions (expressed as percentages) of sea and road transportation were influenced by the relative impacts of other life-cycle stages in each case study.

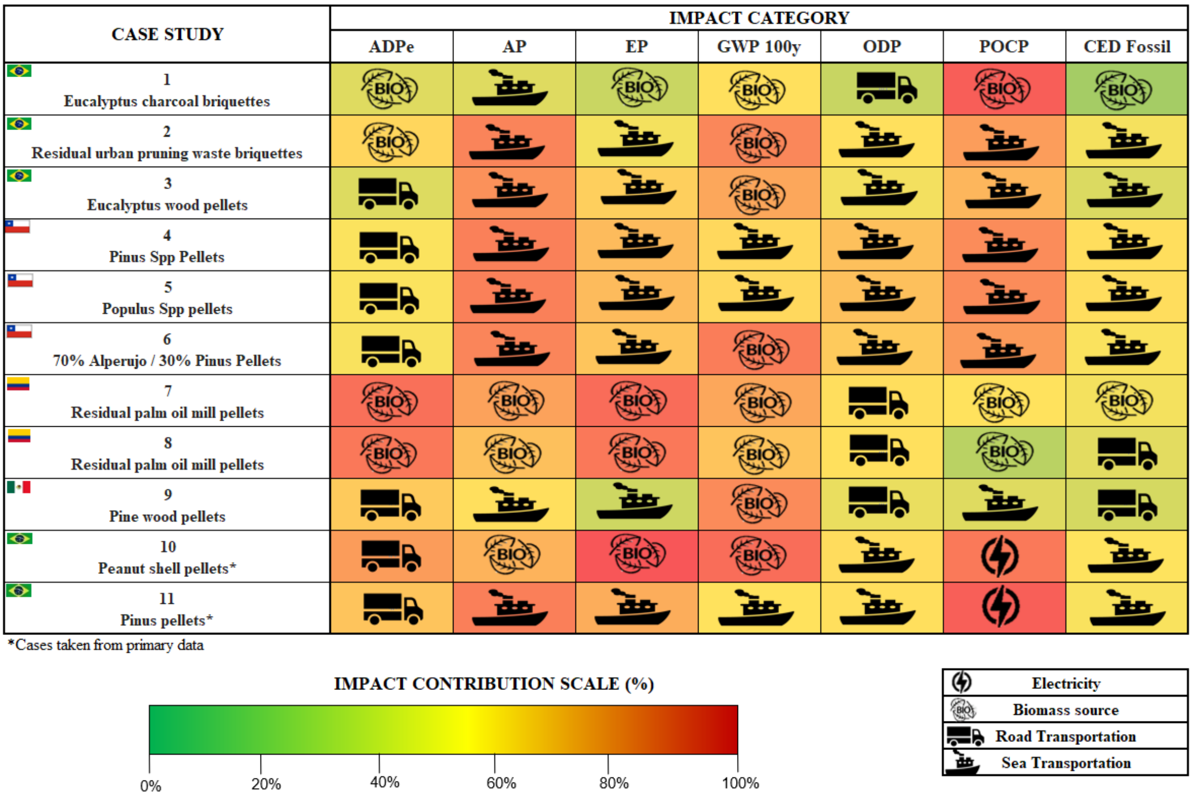
In comparison to existing literature, a focused LCA conducted by Magelli et al. (2009) on wood pellet production and distribution from Vancouver, Canada, to Stockholm, Sweden, revealed that transportation activities constituted a substantial 85.7% of all GWP impact results (with 6.0% attributed to truck/train freight and 79.7% to sea freight). These findings align with the prominent role of transportation systems observed in the cradle-to-product-distribution analysis applied to Latin American pellets and briquettes. Pa et al. (2012) also conducted a study assessing the embodied environmental impacts of transportation activities for densified biomass, specifically wood pellets. Their analysis focused on the production of solid biofuel in the province of British Columbia, Canada, catering to both local demand and exportation, extending to the port of Rotterdam, Netherlands.

4.4.2 HOTSPOT ANALYSIS

A hotspot analysis was performed in Figure 4.4. The main hotspots are represented by a collection of four different icons related to the main impact drivers identified: electricity consumption, biomass supply, road transportation, and sea transportation. In this context, the infographic illustrates the environmental hotspots and their relative contributions for all cases and impact categories under study.

A thermal scale is used to indicate the level of impact contribution for the evaluated impact category in each case. The thermal scale ranges from green (0% contribution) to red (100% contribution), indicating when the impact contribution mostly prevails over the other drivers (colors from yellow to red), for instance.

Figure 4.4 - Environmental hotspots and their relative contributions for each impact category



Source: Own authorship

Sea transportation was the main hotspot, as observed in 50% of the icons in Figure 4.4. aritime freight was the main hotspot for at least three cases, with an exception on ADPe. On the other hand, road transportation was the hotspot for at least one impact category in all case studies, except on C2. This finding can be explained by the high distances considered for road transportation, which accounted for the carry of gross biomass to the industrial processing plant, added to the impacts of the nearest exporter port distance. In general, the five impact categories seem to be more influenced by the transportation stage, as they had at least seven cases with sea or road transportation figuring as hotspots: ADPe, AP, EP, ODP, and CED. These categories were chosen to compose the sensitivity analysis in Section 5.1.

It is worth highlighting that biomass supply was the hotspot for most of the cases and impact categories for the Colombian cases (C7 and C8). The main reasons are the inefficiency of their multifunctional production systems, as they require larger quantities of raw biomass (i.e., palm fruit bunches) for the production of 1MJ of pellets; almost eight times more than in other monofunctional cases, as discussed by Silva et al. (2022). The higher demand for biomass is directly related to the increase in LUC (see Table 4.4), and consequently the increase of embodied carbon absorptions during cropping stages. Nevertheless, Case 1 also presented biomass supply as the hotspot for most cases and impact categories; however, in this case, the main reason was the use of charcoal as a biomass source and its embodied CO_2 emissions (Rousset et al., 2011).

On the following paragraphs, a more detailed analysis per impact category is provided:

Abiotic Depletion (ADPe)

The results of ADPe ranged from 0.003 (C10) to 2.027 mg Sb-eq (C8), representing a difference of 633 times between the extremist cases. Based on the findings in Figure 4.3 and Figure 4.4, it appears that this outcome is primarily influenced by two life-cycle stages: road transportation and biomass feeding. On average, these two activities accounted for 81% of the total ADPe, with a predominance of from road transportation carried out by a EURO 3 class truck. This activity contributed, on the whole, to 42% of the total ADPe, while sea accounted for only 18%. Terrestrial transportation also emerged as the hotspot for this impact category in seven out of the eleven case studies, highlighting the importance of considering environmental issues related to road transportation choices in LCAs, as pointed out by Neves et al. (2018).

Biomass is an important factor to consider when analyzing ADPe too. It emerged as the hotspot in four of the eleven case studies, with emphasis on the two Colombian cases from residual palm oil mill pellets, in which biomass source accounted for up to 90% of ADPe in C7. This significant impact of palm cultivation on ADPe aligns with the findings of Soraya et al. (2014), wherein it constituted 55% of total impacts from biodiesel processing, attributed to metal depletion associated with palm plantations.

Acidification Potential (AP)

The AP impacts to 1 MJ of Latin American pellets and briquettes delivered to Europe ranged from 0.005 (C11) to 0.337 g SO2-eq (C10), representing a growth of 67 times. This was the impact category mostly influenced by international freight performed by sea, as this life-cycle stage represented, on average, 61 % of total SO_2 -eq emissions. Sea transportation was also the hotspot in eight of the eleven case studies, which is the greatest predominance noted among all the impact categories.

The only case studies that did not face sea transportation as an AP hotspot were those C7, C8 and C10 due to the biomass sources adopted. On C10, the ammonia and nitrogen dioxide emissions to air related to peanut cultivation were the main drivers for acidification.

Eutrophication Potential (EP)

This impact category is one of the most common on the LCA of pellets, being part of more than 60% of the papers reviewed by Martín-Gamboa et al. (2020). The results for EP had the highest amplitude, ranging from 0.002 (C11) to 2.585 (C10) g PO4-eq/FU. Similar to the findings of Soraya et al. (2014), this is one of the impact categories with the highest influence on biomass supply, as this stage had an overall contribution of 43% on total EP. The results of peanut shell pellets (C10) are strongly related to the ammonia emissions due to peanut cultivation.

On the other hand, despite it being the main contribution to the overall results of EP (see Figure 4.3), there were case studies where sea transportation was the most recurrent hotspot, representing up to 65% of EP on C4 and C5.

Global Warming Potential (GWP)

According to the review performed by Martín-Gamboa et al. (2020) and Silva et al. (2022), this is the most common impact category displayed on LCA of biomass pellets and it is contained in 100% of the studies on this area. The results obtained ranged from a saving of -287.37 g CO_2-eq/FU in Case 10 to a potential total emission of 10.219 g CO_2-eq/FU in Case 1, both for the Brazilian context. Eight out of the eleven cases (C2, C3, C5, C6, C7, C8, C9, and C10) had negative values for GWP (see Table 4.4). This is a consequence of the “net-zeroed” carbon emissions contained in the background data of residual biomass due to the carbon absorption along the cropping stage.

In this context, biomass emerged as the GWP hotspot in eight cases, making an overall contribution of 61% to GWP results across the case studies. It also accounted for more than 90% of relative emissions in both C7 and C10. Given that both of these cases showed negative results for GWP, this significance indicates carbon savings (credits) resulting from the utilization of residual biomass as raw material. This outcome is a consequence of the substantial impact of LUC on carbon absorption during the cropping stages of biomass, promoting a favorable environmental profile for these biologically sourced products (Silva et al., 2022). This holds true even when considering the impacts associated with the product exportation process. This fact underscores the potential of these products as significant opportunities to achieve a 'net-zero' (Rampasso et al., 2021) in terms of carbon emissions, contributing to the advancement of a Circular Bioeconomy.

Despite biomass use being the primary factor driving the negative values of GWP, it was also the hotspot in C1, contributing to more than 50% of total carbon emissions due to charcoal use for briquette production. On the other hand, Cases 4, 5, and 11 were the only exceptions in which sea transportation was the primary hotspot, representing up to 54% of the total GWP. This occurrence was most prevalent in the Chilean Cases (C4 and C5) due to the distribution distance of 14,104.33 km for sea freight from the San Antonio port to the port of Rotterdam (Table 4.2). This distance is almost twice that considered for exportation in Cases 1, 2, and 7, for example.

Ozone Layer Depletion (ODP)

The results of ODP varied from 0.079 (C10) to 2.659 (C8) mcg CFC-11-eq/FU. In this category, both Colombian cases (C7 and C8) showed the highest impact potential. As already stated, this is the result of their inefficient multifunctional systems, which produce many coproducts in addition to the biomass pellets.

Nevertheless, the ODP was the impact category predominantly by transportation activities in the hotspot analysis (see Figure 4.4). Sea transportation emerged as the most impactful stage, serving as the hotspot in seven cases and contributing 42% to the overall ODP results. Meanwhile road transportation was the hotspot in four cases, constituting 38% of the total ODP impacts. However, as depicted in Figure 4.4, none of the case studies in Latin America were heavily influenced by transportation, with maritime freight accounting for no more than 63% in C4, and road transport having a maximum contribution of 52% in C7.

Photochemical Ozone Creation Potential (POCP)

The results for POCP are related to the chemicals creation (e.g., ozone) through the interaction of fossil fuel emissions with sunlight (Baumann & Tillman, 2004). This impact category is commonly studied for agricultural products and transport systems (Cavalett et al., 2013; Cleary and Caspersen, 2015). Results for POCP ranged from 0.001 (C5) to 0.378 (C1) g C2H4-eq/FU, as the stage of sea transportation was the most impactful, with an average contribution of 43%, mainly due to the use of fossil fuels on the product delivery to Europe. Sea transportation was the most predominant hotspot in six of the eleven cases studied (see Figure 4.4). C4 and C5 from Chile showed Sea transportation surpassing 80% of their total POCP impacts.

The biomass supply was stated as the main hotspot in three cases and corresponded for 96% of the total POCP impacts on C1, as a consequence of charcoal use as raw material for briquetting, which generates carbon monoxide high emissions. The electricity consumption was also the hotspot, for the two cases C10 and C11 of pellets in Brazil.

Cumulative Energy Demand (CED)

CED represents the direct and indirect energy used throughout the life cycle, including the energy consumed during the extraction, manufacturing, and disposal of the raw and auxiliary materials (VDI, 1997). As well as GWP, the CED is one of the most usual impact categories studied on the LCA applied to energetic sectors (Silva et al., 2022). Results for Non-Renewable CED also had a great amplitude, ranging from 0.004 to 0.515 MJ-eq per FU. Transportation activities and fuel consumption were the ones with the highest percentage contribution to the CED. Sea and road freight had an overall representativeness of 36% and 33% of all the energy demanded, respectively. In seven of the eleven cases, sea transportation was the main impact contributor, corresponding to up to 52% on C4 and C5.

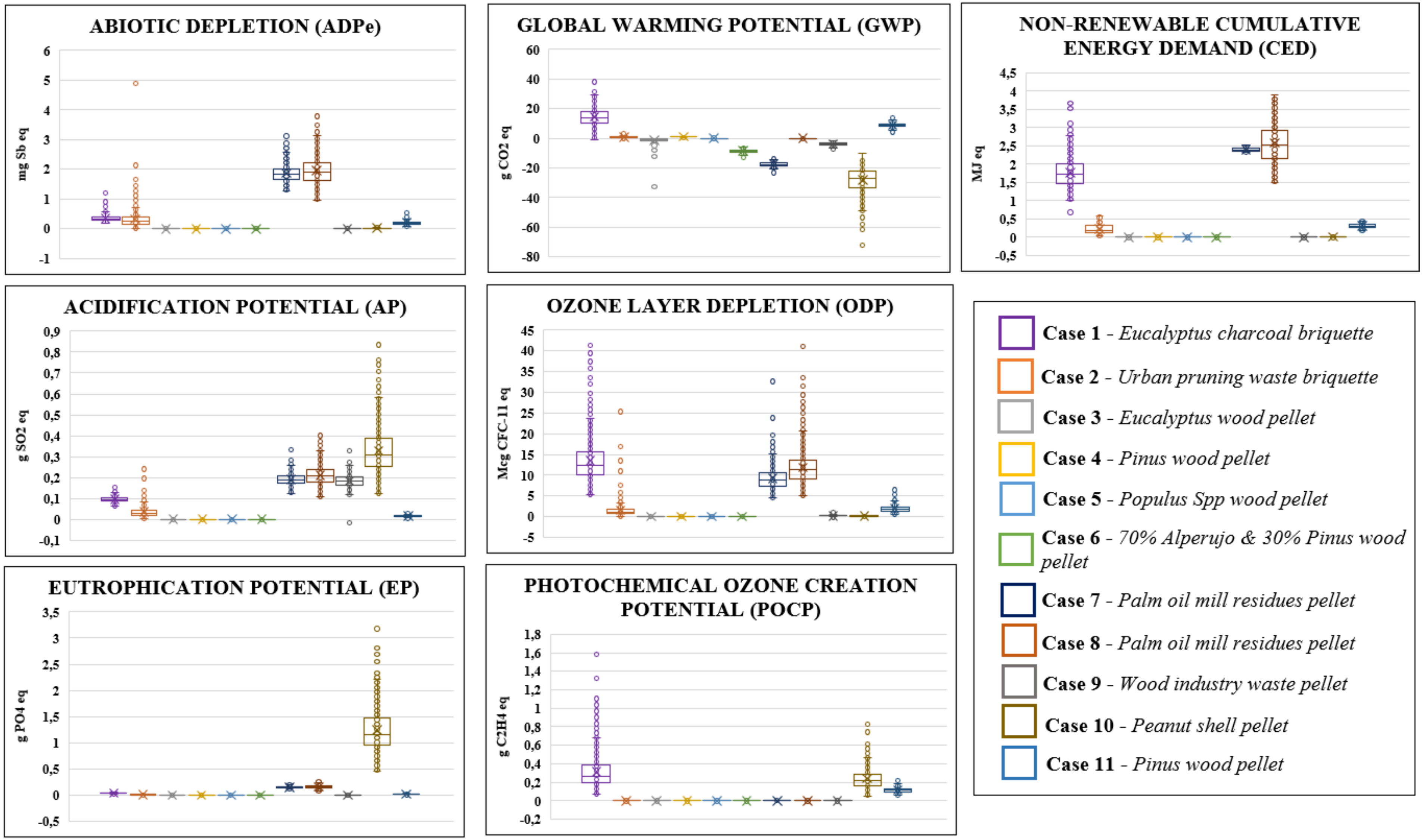
It is worth mentioning that in four of the eleven cases (C1, C7, C8, and C9) non-renewable CED values surpassed 0.25MJ-eq. It means that pellets and briquettes cradle-to-product-distribution systems may demand more than 25% of the total energy produced and delivered (e.g., 1MJ) from non-renewable sources. Despite that, results for all the cases are inferior to 1 MJ-eq, which reflects a positive energy balance for the pellets and briquettes, even if it is considered their delivery to the European market.

4.4.3 UNCERTAINTY ANALYSIS

The objective of the uncertainty analysis is to explore the uncertainties in the collected data and LCA assumptions on the reliability of the obtained results, as stipulated by ISO 14044:2006. The Monte Carlo method, a stochastic simulation technique frequently employed in probabilistic modeling (Clavreul et al., 2012; Michiels & Geeraerd, 2020) was utilized for this purpose.

The outcomes of the uncertainty analysis are depicted in Figure 4.5 using a box-plot format, categorized by their respective impact categories.

Figure 4.5 - Results of the Life Cycle Assessment uncertainty analysis for all the cases and impact categories



In general, C1, C2, C7, C8, and C10 exhibited the highest dispersion, with AP, EP, ODP, and POCP displaying smaller dispersion compared to other categories. Despite this, the simulation results did not exhibit a substantial distinction in the interquartile ranges of the box plots. Across most cases and impact categories, there was a low density of outliers exceeding the maximum and minimum control limits.

The Colombian cases (C7 and C8) recorded the highest results for ADPe and CED. In both impact categories, the results remained within the limit controls, with only a few outliers surpassing the limits for C8. C1 had the most significant impacts on GWP, ODP, and POCP, as previously discussed in section 4.1. The results of ODP and POCP displayed greater dispersion compared to the remaining impact categories, possibly attributed to the representativeness of charcoal data and associated uncertainties at the inventory level.

For the remaining categories (AP and EP), C10 had the most substantial impacts in the uncertainty analysis, while for GWP, it yielded the lowest results, indicating a greater promotion of carbon savings (credits) compared to other cases. These findings align with those discussed in section 4.1, where C10 had a more pronounced impact on AP and EP and produced the lowest results for GWP. This pattern can be attributed to the use of biomass, specifically residual peanut shells.

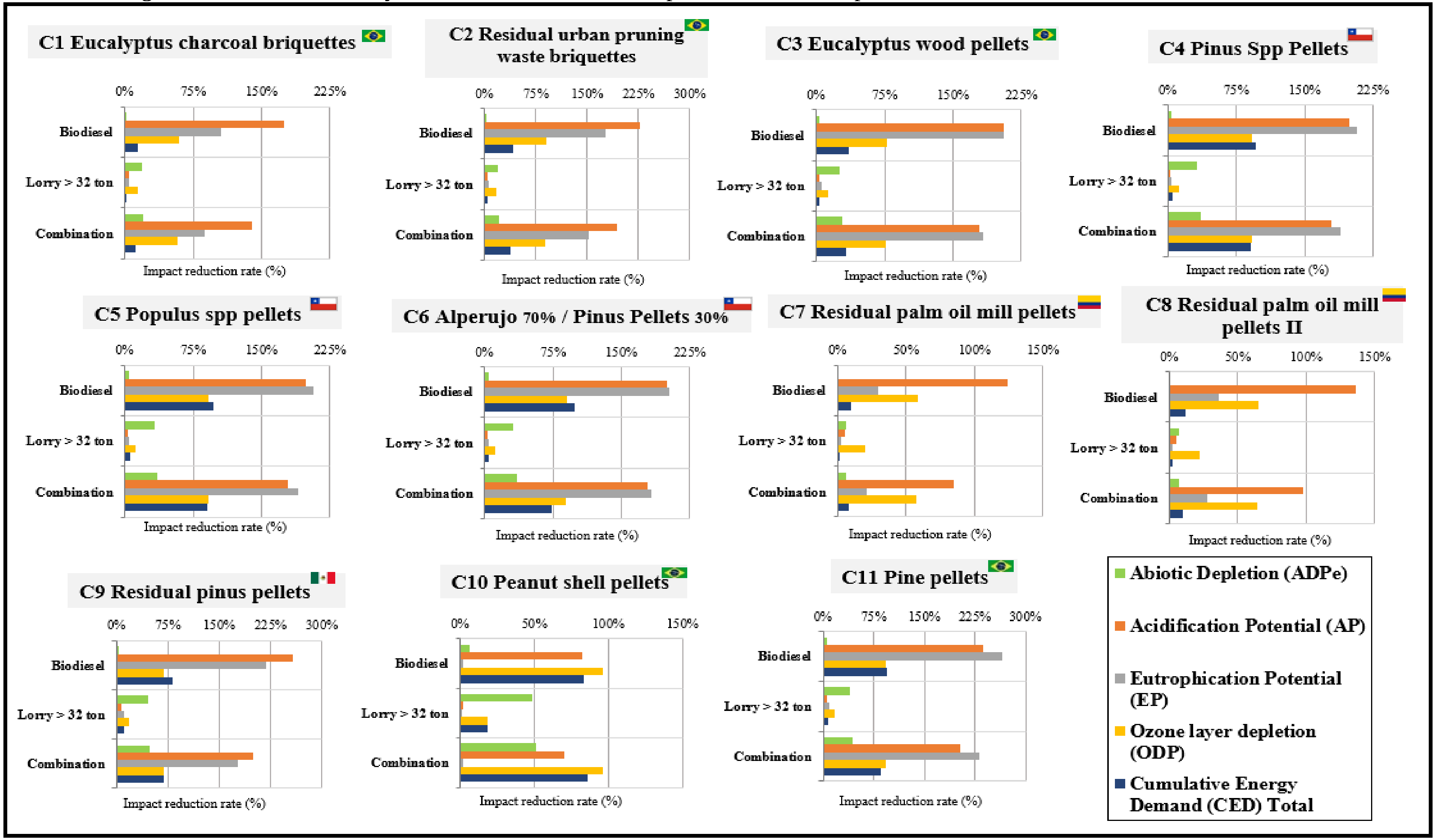
With the exception of ODP, the LCA uncertainty analysis results exhibited a similar pattern to the original LCA results in Table 4.3. Generally, for all impact categories, only a few runs exceeded the maximum and minimum control limits. This implies that, based on the uncertainty analysis, the LCA results remain consistent even for cases derived from secondary data.

4.5 DISCUSSION

4.5.1 Scenarios to mitigate climate-related impacts on transportation choices

Three alternative scenarios were designed to assess transportation choices defined as possible pathways to mitigate the environmental impacts regarding pellets and briquettes cradle-to-product-distribution systems. The outcomes of each alternative scenario were normalized as a percentage, taking into account their impact reduction rate in comparison to the reference results. Figure 4.6 shows the results of the sensitivity analysis performed for the eleven cases, assessing the impact categories mostly influenced by the transportation stage (ADPe, AP, EP, ODP, and CED).

Figure 4.6 - LCA sensitivity results for all case studies, presented as the impact reduction rate of each alternative scenario



The results indicate that the impact reduction rate for the three proposed alternative scenarios was equal to or greater than 0%, implying that all of them could potentially contribute to environmental gains when compared to the reference results. In general, the biodiesel scenario and its combination with higher payload trucks demonstrated the greatest potential for impact reduction across all categories exceeding a rate of 100% for AP and EP. This suggests that substituting petroleum-based diesel with biodiesel during the transportation stage could significantly improve the environmental footprint of pellets and briquettes, while also mitigating emissions of SO_2 and PO_4. Emissions were reduced by up to 258% (Case 9) and 265% (Case 11), respectively.

On the other hand, the scenario involving trucks with higher payload in road transportation exerted a greater influence on ADPe than biodiesel alone. The combination of these two strategies yielded the most favorable results, an impact reduction of up to 232% in Case 11. Consequently, this combination contributes to attaining a 'net-zero' reference situation across the evaluated impact categories. Interestingly, in other impact categories (excluding ADPe), the combined scenarios follow biodiesel in terms of impact reduction potential. This can be attributed to the fact that combining scenarios incorporates not only their benefits but also their limitations and associated negative impacts. From the perspective of ADPe, it emphasizes the environmental benefits of utilizing the most efficient lorries with higher payloads (over 32 tons). These findings align with the LCA conducted by Neves et al. (2019), where the use of larger lorries in road transportation is regarded as a pathway to reduce the environmental impacts throughout the product life cycle.

A potential limitation to consider in the results of biodiesel scenarios is that the soybean biodiesel unit process used in the LCA modeling pertains to the United States context, which carries different environmental impacts compared to South American soybean biodiesel. In a comparative analysis of GHG emissions stemming from U.S. soy biodiesel production versus the total GHG emissions of petroleum diesel, Chen et al. (2018) observed a notable reduction of 76.2%. Similarly, Canabarro et al. (2023) reported an average reduction of 70% in GHG emissions for Latin American countries. Despite this variance, these results underscore the considerable environmental advantages of soy biodiesel as a more eco-friendly alternative to traditional petroleum diesel, even when considering the potentially lower efficiency of Latin American biodiesel. It is important to note, however, that soybean biodiesel remains the primary type of biodiesel produced in South American countries (De Souza et al., 2022).

4.6. CONCLUSION

Based on the findings of this study, it cannot be assumed any significant environmental gains or losses when using biomass pellets instead of briquettes, for example. Therefore, we can state that these two types of biofuels are equivalent in terms of environmental profiles. A considerable variation in the LCA results was observed among the case studies for all the impact categories, as a consequence of the differences in their inventory data, mainly related to the data sources of biomass supply assumed (pinus, eucalyptus, charcoal, peanut shell, etc). The more significant variations were noted in EP, ADPe, and CED results.

Considering the overall results from each country, although being nearest to Europe than the other countries, the Colombian cases C7 and C8 were the most impactful and figured as the first and second highest LCA impacts in two impact categories (ADPe and OD) due to their residual palm oil mill biomass adopted and the inefficient multifunctional manufacturing system to produce pellets. Nevertheless, C1 and C10 from Brazil had the highest impacts for impact categories, which is a consequence of charcoal and peanut shell used as biomass sources. When results are categorized by country, the Chilean cases (C4, C5, C6, C9) consistently fall into intermediate positions and do not emerge as the most or least impactful cases. Notably, C9 from Mexico exhibits the highest rates of non-renewable energy demand.

Significantly, LUC emerged as particularly influential in the Brazilian case (C10), where carbon stocks exceeded five times those of the Colombian cases. This underscores its substantial contribution to advancing the 'Net-Zero' agenda within the energy sector. In summary, the utilization of pellets and briquettes in Latin America appears to make a positive contribution to achieving the 'Net-Zero' agenda in the energy sector, primarily due to the substantial benefits derived from LUC. The most favorable results were observed in C2 and C3 for Brazil, as they exhibited carbon savings in terms of GWP attributed to the LUC effect. Additionally, these two scenarios demonstrated low EP results and lower climate-related impacts in categories such as AC, ODP and POCP. Furthermore, C2 and C3 showed minimal impacts on resources demand (ADPe and CED).

GWP was strongly influenced by biomass, which was the hotspot in eight case studies due to the background data regarding the biomass cultivation stage. Results of GWP had negative and positive values, pointing out that pellets and briquettes could promote CO2 savings or even generate more emissions depending on some key aspects related to biomass selection. Negative results (carbon savings) were observed in eight of the eleven cases, and only the charcoal briquettes in Brazil, and the pinus spp pellets in Chile showed a non-net-zero carbon emissions. This leads to the conclusion that the use of residual biomass is the main driver to the ‘net-zeroed’ carbon emissions of these solid biofuels, even considering their delivery distances to Europe.

The exportation of solid biofuels to Europe through sea promoted the highest impact rate for all the other categories, excluding ADPe and GWP. Sea freight was the hotspot on AP, EP, ODP, POCP, and CED for at least six case studies. Even though the Non-Renewable CED exceeded 25% of the Functional Unit established in some cases, it is worth mentioning that in all the cases it was observed a positive energetic balance considering CED from non-renewable sources. In this sense, they all require less than 1 MJ of non-renewable energy to produce and deliver 1 MJ of renewable energy from pellets and briquettes. But the benefits of producing charcoal briquettes in Brazil and Colombian pellets from residual palm oil mills, may not compensate their environmental impacts in a cradle-to-product-distribution approach.

Facing that, a sensitivity analysis considering three alternative scenarios for the transportation of pellets and briquettes unveiled that the adoption of biodiesel, in lieu of petroleum-based diesel, for maritime and road freight could markedly diminish the environmental impacts related to AP, EP, ODP, and CED. Particularly noteworthy is the scenario employing higher payload trucks in conjunction with biodiesel fuel might reduce the ADPe impacts considerably, making it the most favorable alternative among those evaluated.

Decisions involving the environmental gains or losses of exporting renewable energy can be supported by this study, which is not free of limitations. Future research shall incorporate the impacts of the use phase of pellets and briquettes and a comparison between the environmental footprint of American and European solid biofuels.

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5 BIOCALC: TECHNICAL DESCRIPTION AND APPLICATION IN CARBON INTENSITY ASSESSMENT OF SOLID BIOFUELS

5.1 INTRODUCTION

Established by Law No. 13,576 of December 26, 2017, the National Biofuels Policy (RenovaBio) was created to promote the sustainable expansion of biofuel production, reduce Greenhouse Gas (GHG) emissions, and foster a market for decarbonization credits (CBIOs).

The program adopts a methodological framework based on Life Cycle Assessment (LCA) to calculate the carbon intensity of biofuels, allowing for their comparison with equivalent fossil fuels. However, RenovaBio has not yet incorporated a specific methodology for solid biofuels, such as biomass pellets and briquettes, which hinders the inclusion of these fuels in the regulated carbon market and their eligibility for CBIO certification.

In response to this gap, the BioCalc tool was developed as an extension of RenovaCalc, incorporating new solid biofuel production pathways into the program. BioCalc enables the quantification of the carbon intensity of these biofuels, providing a robust methodological foundation for their certification and facilitating their participation in the CBIO market. In this way, the tool allows solid biofuel producers to integrate into the decarbonization market, thereby increasing the competitiveness of these renewable energy sources within the sector.

Furthermore, the inclusion of solid biofuels in the national carbon market is aligned with the Brazilian Greenhouse Gas Emissions Trading System (SBCE) (Ministry of Finance, 2024). Created as a regulatory mechanism for carbon pricing in Brazil, the SBCE has the potential to enhance CBIO trading and incorporate solid biofuels into the national emissions compensation system. The implementation of the SBCE will provide a more comprehensive framework for the carbon market, enhancing the participation of various sectors in emissions reduction and contributing to the country's climate targets.

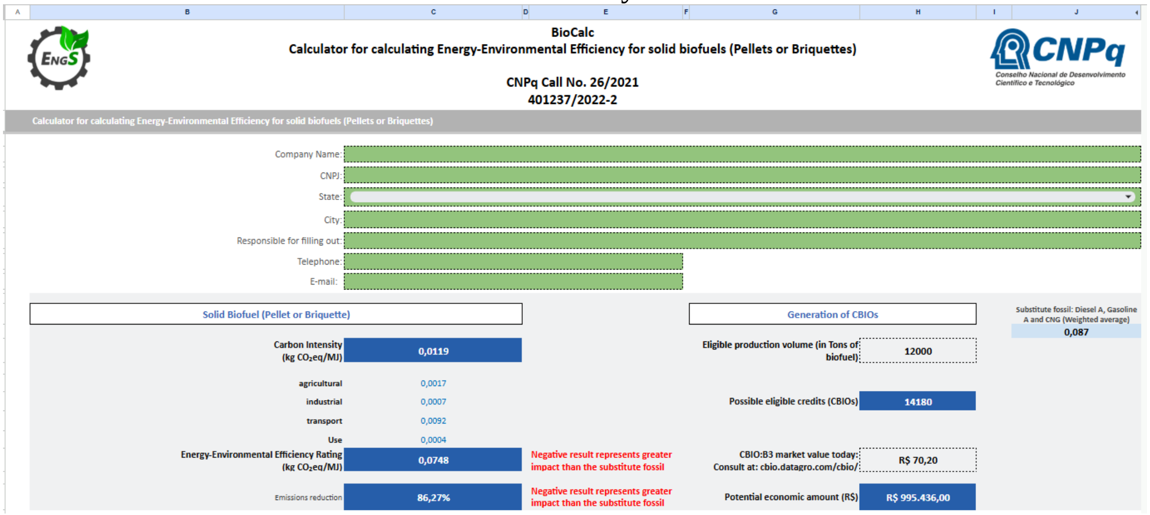
Thus, BioCalc emerges as a strategic tool for incorporating solid biofuels into both the regulated and voluntary carbon credit markets, promoting the valorization of these renewable energy sources and reinforcing Brazil's role in the transition toward a low-carbon economy.

5.2. BIOCALC AND THE CARBON INTENSITY ACCOUNTING OF SOLID BIOFUELS

BioCalc follows the methodological principles of RenovaCalc, with specific adaptations to account for the particularities of solid biofuels. The tool calculates the carbon intensity in kg CO_2 eq./MJ for each production pathway and compares the results with equivalent fossil fuels. The carbon intensity of solid biofuels directly affects the Energy-Environmental Efficiency

Score (NEEA), which, in turn, determines the potential generation of CBIOs associated with the commercialization of the quantified solid biofuel (Figure 5.1).

Figure 5.1 - Initial interface of the BioCalc tool, illustrating the user dashboard for input and visualization of carbon intensity data for solid biofuels



5.3. METHODOLOGICAL DEVELOPMENT

BioCalc adopts an approach based on attributional Life Cycle Assessment (LCA), as established by ISO standards 14040 and 14044. The methodological scope employed is cradle-to-grave, ensuring that all emissions associated with the various stages of the production chain are correctly accounted for.

To ensure consistency and reliability, data used to calculate carbon intensity are harmonized and standardized based on scientific literature and both national and international databases, such as Ecoinvent and CONAB. These data sources are aligned with the guidelines of the Intergovernmental Panel on Climate Change (IPCC) for estimating greenhouse gas (GHG) emissions.

Structurally, the methodological framework implemented in the tool encompasses the following life cycle stages: agricultural production, industrial processing, transportation and distribution, and final use (biofuel combustion), all of which are described in detail in the subsequent sections. A summary of the main methodological options and assumptions supporting the environmental performance assessment performed by BioCalc is presented in Table 5.1.

Table 5.1 - Methodological approach and assumptions for the environmental performance assessment of BioCalc

Category	Description
Approach	Attributional
Scope	Cradle-to-grave
Functional Unit	MJ of biofuel consumed
Co-product Treatment	Energy-based allocation
Data sources for upstream processes, including biomass from residues	Inventory data for upstream processes prior to the agricultural stage are sourced from the ecoinvent v.3.9.1 database. Priority was given to inventories related to Brazil (BR), followed by global (GLO) datasets. Where unavailable, Rest-of-World (RoW) inventories were used.
Land Use Change (LUC)	Emission data were obtained from the Brazilian Land Use Change (BRLUC 2.0) platform, considering average emission values ($tCO_2 \cdot ha^{-1} \cdot year^{1}$) by federal unit, based on the biomass type used for biofuel production (e.g., forestry or peanuts). Subsequently, the final emission factor (tCO_2/kg of biofuel) was calculated based on production time and agricultural yield (kg/ha), using data from the National Supply Company (CONAB) and bibliographic references provided in the modeling spreadsheet. Allocation of forestry residues was performed according to Sgarbossa et al. (2020).
Characterization Factors	GWP100, based on IPCC AR5 (2014): CO_2 = 1; fossil CH_4 = 30; biogenic CH_4 = 28; N_2O = 265

5.3.1 Agricultural phase and biomass transport to the processing facility

The agricultural stage and the subsequent transportation of biomass to the production facility represent the initial step in assessing the energy and environmental efficiency of solid biofuels. This phase comprises several subcomponents, each requiring specific data inputs.

5.3.1.1 Biomass Production

The first aspect of data collection focuses on identifying the type of biomass employed in the production process. Feedstock may originate from various sources, including forestry, agriculture, or industrial residues. Users are required to select the biomass type from a drop-down menu. This selection automatically determines two key parameters: the biomass impact factor (kg CO_2eq/kg of biomass) and its Lower Heating Value (LHV) (MJ/kg of biofuel).

Subsequently, information on biomass consumption per kilogram of biofuel must be provided to establish the ratio between input material and fuel output. Users must indicate whether this information is available by selecting “Yes” or “No.” If unavailable, the tool applies a default value predefined in the system. Conversely, when the user possesses accurate data, the field labeled “Biomass Input” should be manually completed, expressing the quantity in kg of biomass per kg of biofuel. A summary of the required data inputs for this stage is provided in Table 5.2.

Table 5.2 - Data input: Biomass production

Field	Description
Biomass type	The user must select the biomass type from a dropdown menu. This selection automatically defines two essential parameters: the biomass emission factor (kg CO_2eq/kg biomass) and the LHV (MJ/kg of biofuel).
Availability of biomass consumption data	The user must indicate whether consumption data are available by selecting “Yes” or “No” from a dropdown menu. If unavailable, the system applies a predefined default value.
Biomass input	If the user has specific information on biomass consumption, it can be entered manually.
Impact factor of selected biomass	This value is automatically filled in based on the selected biomass type.
Heating value of selected biomass	This value is automatically filled in based on the selected biomass type.
Corn starch input	Corn starch may be used as an additive in the production of briquettes or pellets. If a non-zero value is entered, the tool calculates the associated emissions.
Impact associated with corn starch consumption	This value is automatically calculated based on the corn starch input.
Impact of biomass production	Represents the total GHG emissions associated with the biomass, normalized per unit of biofuel energy (MJ). The result is expressed in kg CO_2 eq./MJ of biofuel.

Corn starch may be used as an additive in the production of solid biofuels. If the user enters a non-zero value, the tool will estimate the emissions associated with the use of this input based on the corresponding emission factor from the Ecoinvent database. Once all required data have been provided, the impact of biomass production is calculated relative to the study's functional unit. Therefore, the final result is expressed in kg CO_2 eq./MJ of biofuel.

5.3.1.2 Land Use Change (LUC)

Land use change (LUC) represents one of the most critical factors in accounting for carbon emissions associated with the biomass used for solid biofuels. The LUC impact reflects the conversion of natural or agricultural land into areas dedicated to biomass production, which can result either in greenhouse gas (GHG) emissions or in carbon sequestration, depending on the previous vegetation and the new land cover. Table 5.3 summarizes the input parameters used to calculate the impact associated with LUC.

Table 5.3 - Data input: Land use change (LUC)

Field	Description
Biomass production state	Identifies the geographic location of biomass production. The user selects the Brazilian state where the biomass was produced from a dropdown menu.
Agricultural crop	Automatically filled based on the type of biomass selected in the previous stage.
If wood residue, indicate which stage of the wood life cycle the residue originated from	Criterion for allocating biomass from wood residues. It is necessary to indicate the life cycle stage in which the residue was generated. Stages are segmented according to the classification of residues from Sgarbossa et al. (2020): branches and leaves (32.5%), bark (6.75%), sawdust (30.38%), and unspecified (23.21%).
LUC impact factor	This value is automatically filled based on the biomass production state. A negative value indicates that the land use change resulted in carbon sequestration (net CO_2 absorption), whereas a positive value indicates that land conversion led to net carbon emissions. The data were obtained from the BRLUC 2.0 platform.
Biomass allocation percentage	Automatically filled based on the selected type of wood residue.
LUC impact	Represents the final land use change impact associated with the biomass used, normalized to the production of biofuel. The result is expressed in kg CO_2 eq./MJ of biofuel.

The impact of land use change (LUC) may either increase or reduce the carbon footprint of the biofuel, depending on the previous land cover and the sustainability of the energy crop management. As such, a detailed accounting of LUC enables a more accurate assessment of the environmental feasibility of solid biofuels and may also contribute positively or negatively to the calculation of potential decarbonization credits (CBIOs).

5.3.1.3 Distance of Biomass Transport to the Processing Facility

The transportation of biomass to the processing facility is a relevant factor in the calculation of emissions associated with the life cycle of biofuels. This stage includes the logistical movement of biomass from the agricultural production site to the industrial plant where it is converted into briquettes or pellets.

The main input parameters required for this phase, along with their respective descriptions, are summarized in Table 5.4.

Table 5.4 - Data input: Biomass transport to the processing facility

Field	Description
Distance of biomass transport to the facility	Represents the distance traveled by vehicles to deliver the biomass from the production site to the industrial unit. The user manually enters the distance in kilometers (km).
Type of vehicle used for transport	Indicates the type/model of vehicle used to transport the biomass to the facility. Options include: 7.5–16t truck, 16–32t truck, >32t truck, 60m³ truck, ship, barge, and rail. Emission factors are sourced from the Ecoinvent 3.9.1 database.
Average amount of biomass transported per vehicle (auto-filled)	Represents the average biomass load transported per trip. This value is automatically filled based on the vehicle's specifications.
Transport demand (auto-filled)	Represents the transport demand in t·km (ton-kilometer). This value is automatically calculated based on the vehicle type and transport distance.
Biomass transport impact	Represents the emissions associated with biomass transport, normalized per unit of biofuel energy produced. The impact depends on transport distance, vehicle fuel consumption, and logistical efficiency. The result is expressed in kg CO_2 eq./MJ of biofuel.

5.3.2 Industrial Phase – Biomass Processing

The industrial phase of biomass processing encompasses the drying and densification steps (pelletizing or briquetting), which are essential to ensuring a solid biofuel with high energy efficiency and calorific value. During this stage, the biomass undergoes physical and energetic transformation, involving electricity consumption and industrial inputs. In some cases, cogeneration systems are used to improve process efficiency by converting part of the biomass into energy.

Sections 5.3.2.1 and 5.3.2.2 provide a detailed description of the input parameters involved in this stage.

5.3.2.1 System Data

This subsection collects information regarding the product system under evaluation, including the total annual amount of biomass processed. These values vary according to the scale of the pelletizing/briquetting plant. Additionally, the user must specify whether cogeneration is in place, i.e., whether a portion of the biomass is used for energy generation within the facility.

Table 5.5 -Key operational parameters for biomass processing systems

Field	Description
Is there energy cogeneration? (biomass used for internal energy generation)	Indicates whether the facility uses biomass to generate energy for internal consumption. The user selects “Yes” or “No.”
Amount of biomass processed (excluding biomass used for cogeneration, if any)	Refers to the total annual quantity of biomass entering the industrial process for the production of briquettes or pellets. This value is entered manually by the user in kg/year. In cases of cogeneration, the respective quantity should be excluded.
Amount of biomass consumed for cogeneration (same biomass from the agricultural phase)	If cogeneration is confirmed, this field must be filled in. It refers to the amount of biomass used to supply the energy demand of the processing stage.

5.3.2.2 Energy (Electricity and Fuels) and Manufacturing Inputs

This subsection gathers information on energy sources and materials used within the evaluated product system, all of which directly influence the carbon footprint of the solid biofuel. Inputs include electricity, fossil fuels, and biomass used in the drying and densification processes, as well as other auxiliary materials.

Table 5.6 - Energy sources and material inputs used in the industrial phase

Category	Description
Electricity	Specify annual electricity consumption according to the energy matrix. Options include: grid – medium voltage mix, grid – high voltage mix, small hydropower (SHP), biomass, wind, and solar. Data must be provided in kWh/year.
Fuels	Indicate annual fuel consumption for the manufacturing process. Options include: diesel, natural gas, LPG, gasoline A, anhydrous ethanol, hydrated ethanol, and lubricating oil. Data should be reported in liters or kilograms/year.
Other inputs	Enter annual quantities of additional materials such as wood chips, firewood, water, and silica sand.

The choice of energy sources and industrial inputs depends on the scale of the pelletizing or briquetting facility and the technology employed. Incorporating electricity from renewable sources and biomass as a fuel can significantly reduce process-related emissions, whereas the use of fossil fuels may increase the final product’s carbon footprint.

By summing the impacts of electricity consumption, fuel use, biomass combustion (when cogeneration is present), and industrial material inputs, the carbon intensity of the industrial biomass processing stage is obtained and expressed in kg CO_2 eq./MJ. A detailed accounting of these factors supports the evaluation of environmental performance and identifies opportunities for emission reduction through the use of renewable energy sources, optimized resource consumption, or technological improvements in biomass processing.

5.3.3 Distribution Phase

The distribution phase of solid biofuel includes the transport of the final product from the production unit to the consumer, either for domestic use or export. This stage is crucial in the life cycle assessment, as transport-related emissions directly impact the biofuel's carbon footprint.

Distribution may involve different logistics modes—such as road, rail, or waterway transport—depending on available infrastructure and the geographic location of the target market.

Sections 3.3.1 and 3.3.2 describe the input parameters for distribution in domestic and export markets, respectively.

5.3.3.1 Domestic Market

This section includes information regarding the commercialization of solid biofuels within the domestic market, covering the quantity of biomass transported, the average transport distance, and the type of logistical mode employed. Table 5.7 presents the input parameters used to calculate the distribution-related impact for domestic commercialization.

Table 5.7 - Input parameters for domestic distribution logistics

Field	Description
The quantity of biomass transported in the domestic market	Refers to the annual volume of solid biofuel sold within the national territory.
Transport distance from the production site to the domestic consumer	Indicates the average distance (in km) required to deliver the product to the final consumer.
Modal distribution	Specifies the percentage of the total transport distance covered by each transportation mode: rail, waterway, and road.
Type of vehicle used for road transport	If road transport is used, the user must select the type of truck from the following options: 7.5–16t truck, 16–32t truck, >32t truck, and 60m^3 truck. Emission factors are based on the Ecoinvent 3.9.1 database.

Impact of the domestic distribution phase (auto-filled)	Automatically calculated by the system based on the quantity of biomass transported and the distance traveled.
Energy transported annually (MJ/year)	Represents the total energy content of the annually distributed biofuel. This is calculated automatically based on the volume and lower heating value of the biofuel.
Domestic distribution impact (normalized)	Automatically calculated value expressed in **kg CO_2 eq./MJ transported,** based on the system's functional unit.

5.3.3.2 International Market (Export)

If the producer exports solid biofuels, specific data must be entered regarding international logistics. This process involves the shipment of the product from the factory to the port terminal and subsequently to the final market via maritime transport. Exportation represents a critical phase in the environmental assessment of solid biofuels due to the long transport distances, particularly by sea. Table 5.8 presents the input parameters used to calculate the environmental impact of export logistics.

The distribution phase is a fundamental component in calculating the environmental impact of solid biofuels, as it accounts for emissions generated during the product's transportation to the end user. By summing the impacts from both domestic and international distribution (if applicable), the total transport-related carbon footprint is obtained.

Final distribution impact calculations can be configured to reflect only domestic, only export, or both scenarios, depending on the criteria selected by the tool user. This flexibility allows for a detailed analysis of various logistics strategies and enables more informed decisions regarding efficient, low-impact transport routes.

Table 5.8 - Input parameters for international distribution logistics (export)

Field	Description
The quantity of solid biofuel exported by a container ship	Refers to the annual volume of exported products.
Distance from the facility to the nearest port terminal (Suggested tool: gov.br)	Indicates the route between the production facility and the port. Users are advised to consult the Brazilian government's website to identify the closest port and manually enter the distance in kilometers.
Modal distribution to the export terminal	Specifies the percentage of the total transport distance (to the port) covered by each transportation mode: rail, waterway, and road.
Type of vehicle used for road transport to the port	When road transport is used to reach the port, the user must select the truck type: 7.5–16t, 16–32t, >32t, or 60m³. Emission factors are based on Ecoinvent 3.9.1.
Distance from port terminal to final export destination (Suggested tool: searates.com)	Indicates the maritime distance between the port of departure and the final market. Users are encouraged to use searates.com to estimate this distance, to be entered in kilometers.
Impact of export phase (facility-to-port segment)	Automatically calculated based on the transport mode, vehicle type, and quantity transported. Result is given in kg CO_2 eq./year.
Impact of export phase (port-to-final market segment)	Automatically calculated based on the maritime distance and transported volume. Result is given in kg CO_2 eq./year.
Energy exported annually (MJ/year)	Represents the total energy content of exported solid biofuel. This value is essential for adjusting to the system's functional unit and is calculated based on volume and heating value.
Export impact (normalized)	Final calculated value expressed in kg CO_2 eq./MJ transported, adjusted to the functional unit of the system.

These values are essential for identifying emission reduction opportunities, such as adopting more sustainable transport modes (e.g., rail and waterways), using alternative fuels in road transport, or reducing the distance between production sites and consumers. Accordingly, logistics optimization can significantly contribute to reducing the carbon footprint of solid biofuels, thus improving their competitiveness in the global bioenergy market.

5.3.4 Use Phase

The use phase of solid biofuels constitutes the final stage in their life cycle, during which stationary combustion takes place to generate thermal or electrical energy. This process results in atmospheric emissions, whose magnitude depends on the specific characteristics of the biomass used.

Emissions for this phase are critical to evaluating the environmental impact of solid biofuels and comparing them with equivalent fossil fuels. The estimates are based on IPCC guidelines, which provide emission factors for CO_2 and other gases according to biomass type. Once the user selects the biofuel's biomass type, the tool automatically adjusts the emission value to reflect the material's specific characteristics. Emission factors for each biofuel type are available in Appendix I.

5.3.5 Carbon Intensity Calculation

The final calculation of life cycle emissions for solid biofuels is based on the sum of environmental impacts from the four main phases of the production process: (i) the agricultural phase and biomass transport to the facility; (ii) the industrial phase (biomass drying and densification); (iii) the distribution phase (domestic market and/or export); and (iv) the use phase (biofuel combustion). Each of these stages involves distinct sources of greenhouse gas (GHG) emissions, which are converted into a common unit—kg CO_2 eq./MJ—and summed to obtain the biofuel's final carbon intensity.

BioCalc applies characterization factors to convert various emitted gases into carbon dioxide equivalents (CO_2 eq.), using the Intergovernmental Panel on Climate Change (IPCC) coefficients (2021) for a 100-year global warming potential (GWP100) – see Table 5 in Appendix A. According to these factors, for instance, 1 kg of fossil CH_4 is equivalent to 29.8 kg of CO_2 in terms of climate impact, and 1 kg of N_2O corresponds to 273 kg of CO_2.

Emission normalization is performed directly within the calculations of each life cycle stage, ensuring that impacts are correctly allocated to the useful energy content of the produced biofuel. The final carbon intensity of solid biofuels is obtained by summing the impacts from all four life cycle stages, as expressed in Equation 1.

$$CIBiofuel = CI_{agricultural} + CI_{industrial} + CI_{distribution} + CI_{use} \quad (1)$$

Where:

$CI_{agricultural}$ = Impact from biomass production, land use change (LUC), and biomass transport to the processing facility.

$CI_{industrial}$ = Impact from electricity consumption, fuels, and material inputs used within the industrial facility.

$CI_{distribution}$ = Impact from the transportation of the biofuel to the final consumer, including both domestic and international logistics.

CI_{use} = Emissions generated from the combustion of the solid biofuel.

This result represents the total carbon footprint of the solid biofuel, expressed in kg CO_2 eq./MJ, and enables direct comparisons with fossil fuels.

To carry out the calculations described above, BioCalc automatically performs all required unit conversions to ensure consistency and accuracy of results. The conversion factors used to normalize emissions are presented in the Appendix and are based on reference values from the Ecoinvent database and characterization factors from the IPCC AR5 (2014).

5.3.6 Energy-Environmental Efficiency Score (NEEA) Calculation

The Energy-Environmental Efficiency Score (NEEA) is a key indicator used to assess the environmental performance of biofuels in comparison to their fossil fuel equivalents. It is calculated by subtracting the carbon intensity of the biofuel from that of the fossil reference fuel, thereby quantifying the emissions avoided through the use of the biofuel. The equation is expressed as:

$$NEEA = CI_{Fossil} – CI_{Biofuel}$$

Where:

NEEA = Energy-Environmental Efficiency Score (kg CO_2 eq./MJ)

CI_{Fossil} = Carbon intensity of the equivalent fossil fuel (kg CO_2 eq./MJ)

$CI_{Biofuel}$ = Carbon intensity of the solid biofuel (kg CO_2 eq./MJ)

This score quantifies the reduction in greenhouse gas emissions achieved by the biofuel compared to its fossil fuel substitute.

Selecting the appropriate fossil fuel equivalent is a critical aspect of the NEEA calculation. Due to the absence of a universally accepted substitution model for solid biofuels, three fossil fuels have been parameterized: diesel, petroleum coke, and heavy fuel oil. These fuels were selected because they represent the main fossil sources used in industrial and energy sectors, where solid biofuels could be applied. The carbon intensity values for each of these fossil fuels are presented in Table 4 of the Appendix.

5.3.7 Estimating Decarbonization Credits (CBIOs)

The generation of Decarbonization Credits (CBIOs) is one of the primary advantages of replacing fossil fuels with solid biofuels. After calculating the NEEA, which expresses the reduction in CO_2 emissions relative to the fossil reference, the next step is to estimate the potential volume of CBIOs to be issued.

To do so, the producer must input the eligible production volume (V), which represents the amount of biofuel produced (in tonnes) during the defined planning period. This value is converted into useful energy using the Lower Heating Value (LHV) of the biofuel, resulting in the total number of CBIOs that may be certified:

$$CBIOs = NEEA \times V \times LHV_{biofuel}$$

Where:

$CBIOs$ = Number of Decarbonization Credits generated (tCO_2 eq.)

$NEEA$ = Energy-Environmental Efficiency Score (kg CO_2 eq./MJ)

V = Eligible production volume (tonnes)

$LHV_{biofuel}$ = Lower Heating Value of the biofuel (MJ/kg)

The Energy-Environmental Efficiency Score (NEEA), when combined with the volume of biofuel produced, can be used for environmental certification, carbon credit generation, and regulatory incentives. In this way, the BioCalc tool contributes to enhancing both the competitiveness and sustainability of solid biofuels within the energy market by encouraging the adoption of more efficient and environmentally responsible practices. Each CBIO generated corresponds to one metric ton of CO_2 avoided, representing an effective emissions offset mechanism and an incentive for the transition toward renewable energy sources.

In addition to its environmental impact, CBIO generation can also yield economic returns for biofuel producers. BioCalc provides a direct link to the CBIO Quotation Panel (https://cbio.datagro.com/cbio/), where users can monitor the current market price of CBIOs and estimate the potential financial returns from credit trading. This functionality enables producers to evaluate not only the environmental viability of their production but also its economic attractiveness in the carbon market, supporting strategic decision-making.

The implementation of the Brazilian Greenhouse Gas Emissions Trading System (SBCE) further reinforces the potential for CBIO commercialization by integrating solid biofuels into both regulated and voluntary carbon credit markets. This system establishes a comprehensive regulatory framework for carbon pricing in Brazil, encouraging strategic sectors to adopt emissions mitigation measures (Ministry of Finance, 2024).

As a result, the integration of CBIOs into the SBCE may significantly increase demand for these assets, making them a viable economic option for companies required to offset emissions under compliance obligations or voluntary commitments. In the voluntary market, CBIOs can be purchased by companies seeking to align their operations with sustainability goals and ESG (Environmental, Social, and Governance) strategies, further expanding the financial return potential for producers.

Thus, BioCalc not only assists in quantifying the environmental benefits of solid biofuels but also supports their integration into emerging carbon markets, promoting the transition to a low-carbon economy and strengthening the role of solid biofuels as a viable and competitive alternative in the global energy landscape.

5.4. RESULTS ANALYSIS

The tool provides a results dashboard that allows users to perform automated scenario analyses. These scenarios are presented through graphical outputs that illustrate the environmental impacts associated with each life cycle stage of the biofuel. In addition, the tool enables comparative assessments of different Energy-Environmental Efficiency Scores (NEEA) based on three equivalent fossil fuels: a weighted average of diesel A, gasoline A, compressed natural gas (CNG), petroleum coke, and heavy fuel oil.

Another aspect addressed by the tool is the zero-burden assumption in the agricultural phase for residues, based on Life Cycle Assessment (LCA) principles. Finally, the tool incorporates the Circular Footprint Formula (CFF) to assess the environmental benefits of recycling and material reuse.

The following subsections provide a detailed explanation of these three analytical dimensions.

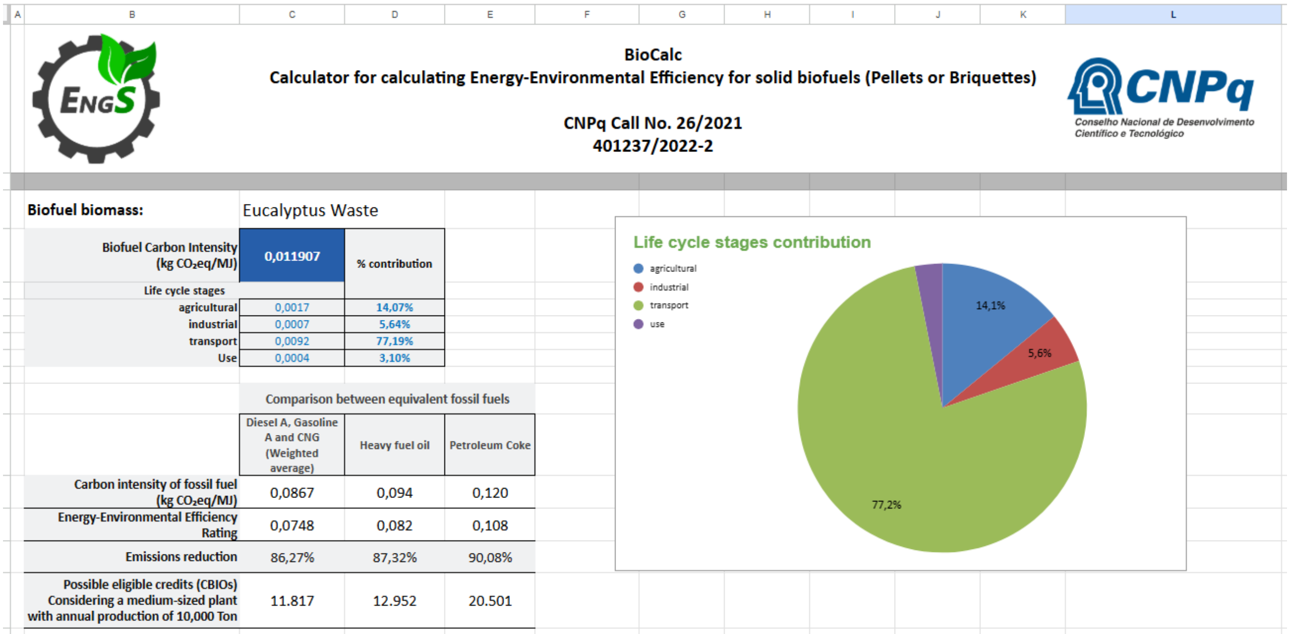
5.4.1 Life cycle stage contribution analysis

The results spreadsheet generates graphs that show the relative contribution of each life cycle stage to the overall environmental impacts of the biofuel. These stages include:

- **Agricultural production and biomass transport:** cultivation and harvesting of raw materials, and transportation of biomass;
- **Industrial processing**: conversion of raw materials into biofuel;
- **Transport and distribution:** delivery of the biofuel to domestic or international markets;
- **Final use**: combustion or application of the biofuel by the end-user.

By analyzing the percentage contribution of each stage, producers can identify critical points and opportunities for improvement. For example, if the industrial processing stage accounts for a high share of greenhouse gas (GHG) emissions, investments in cleaner technologies at this stage can be prioritized. Figure 5.2 presents a visual representation of this section of the results.

Figure 5.2 - Life cycle stage results and comparison with equivalent fossil fuels



Biofuel biomass:	Eucalyptus Waste	
Biofuel Carbon Intensity (kg CO_2eq/MJ)	0,011907	% contribution
Life cycle stages		
agricultural	0,0017	14,07%
industrial	0,0007	5,64%
transport	0,0092	77,19%
Use	0,0004	3,10%

	Comparison between equivalent fossil fuels		
	Diesel A, Gasoline A and CNG (Weighted average)	Heavy fuel oil	Petroleum Coke
Carbon intensity of fossil fuel (kg CO_2eq/MJ)	0,0867	0,094	0,120
Energy-Environmental Efficiency Rating	0,0748	0,082	0,108
Emissions reduction	86,27%	87,32%	90,08%
Possible eligible credits (CBIOs) Considering a medium-sized plant with annual production of 10,000 Ton	11.817	12.952	20.501

5.4.2 Comparison of NEEA Using Different Equivalent Fossil Fuels

The definition of an equivalent fossil fuel is critical for calculating the Energy-Environmental Efficiency Score (NEEA), as it directly influences the estimation of potential Decarbonization Credits (CBIOs). Due to the lack of a clear consensus regarding which fossil fuel solid biofuels most directly replace, BioCalc allows users to compare NEEA values based on three fossil fuel benchmarks:

- **Diesel A, Gasoline A, and Compressed Natural Gas (CNG) (weighted average):** predominantly used in road transport, serving as a reference for biofuels intended for this sector;
- **Petroleum coke:** primarily used in the cement and metallurgical industries;
- **Heavy fuel oil:** commonly applied in industrial boilers and furnaces, and often considered an alternative to solid biofuels for heat and energy generation.

By comparing the NEEA values associated with each fossil fuel, producers can assess which substitution pathway offers the greatest environmental benefit and economic return. This analysis is essential for strategic decision-making, particularly when identifying target markets or pursuing environmental certification schemes.

5.4.3 Zero-Burden Assumption for Residues in the Agricultural Phase

When a biofuel is produced from residues, such as agricultural or industrial by-products, the agricultural phase can be modeled under a zero-burden assumption in the life cycle assessment (LCA). This approach implies that emissions and environmental impacts related to the production of the feedstock are not attributed to the biofuel, since the residue would have existed regardless of its subsequent conversion into fuel.

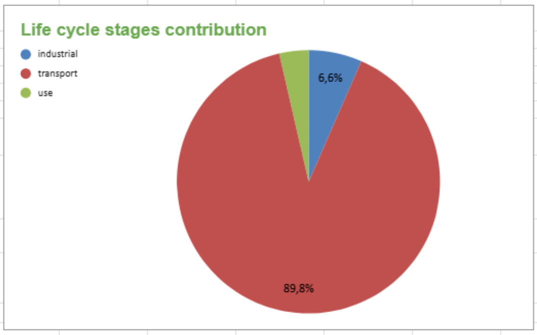
This methodological choice is supported by LCA literature, which emphasizes the importance of fair impact allocation in co-product and recycling systems. Applying the zero-burden assumption to residues significantly reduces the NEEA of the biofuel, thereby increasing the potential number of CBIOs and enhancing the competitiveness of the product within carbon credit markets. Figure 5.3 shows a screenshot of the results interface generated by the tool, illustrating how the analyzed information is structured and displayed.

Figure 5.3 - Illustration of results when applying the zero-burden assumption to residual biomass in the agricultural phase

Considering zero load in the agricultural phase, when residue

Biofuel Carbon Intensity ($kg\ CO_2eq/MJ$)	0,010232	% contribution
Life cycle stages		
industrial	0,0007	6,57%
transport	0,0092	89,83%
Use	0,0004	3,61%

	Comparison between substitute fossil fuels		
	Diesel A, Gasoline A and CNG (Weighted average)	Heavy fuel oil	Petroleum Coke
Carbon intensity of fossil fuel ($kg\ CO_2eq/MJ$)	0,087	0,094	0,120
Energy-Environmental Efficiency Rating ($kg\ CO_2eq/MJ$)	0,076	0,084	0,110
Emissions reduction	88,20%	89,10%	91,48%
Possible eligible credits (CBIOs) Considering a medium-sized plant with annual production of 10,000 Ton	12.082	13.217	17.349



5.4.4 Application of the Circular Footprint Formula (CFF)

The Circular Footprint Formula (CFF) is a methodology developed by the European Commission to quantify the environmental impacts associated with recycled content, recyclability, end-of-life disposal, and energy recovery of products. Introduced as part of the Product Environmental Footprint (PEF) initiative, the CFF provides a standardized approach for allocating environmental burdens and benefits between suppliers and users of recycled materials (Rickert & Ciroth, 2020).

Historically, the CFF emerged from the need to harmonize environmental assessment methods within the European Union, fostering a circular economy and promoting sustainable production and consumption practices. Its application enables a comprehensive life cycle analysis of materials, spanning from raw material extraction to end-of-life stages, including aspects such as recycling and energy recovery (EU4Environment, 2023).

The integration of CFF into European policies and legislation reflects the EU's commitment to sustainability and environmental impact reduction. The methodology has been widely recommended for evaluating the environmental performance of products and organizations, serving as a foundation for the development of regulatory frameworks that encourage transparency and continuous improvement in production processes.

Within the BioCalc tool, the CFF is applied to evaluate the impact of circular practices in biofuel production, considering factors such as:

- **Recycled content:** the proportion of recycled materials used in production;
- **Recyclability**: the product's potential for recycling after use;

- **Energy recovery**: the utilization of energy from waste generated throughout the product's life cycle.

The mathematical formulation of the CFF is presented in Equation 1.

$$E = (1 - R_1) \times E_V + R_1 \times \left[A \times E_{Rin} + (1 - A) \times E_V \times \left(\frac{Q_{Sin}}{Q_P}\right)\right] + $$
$$+(1 - A) \times R_2 \times \left[E_{Rout} - E_V^* \times \left(\frac{Q_{Sout}}{Q_P}\right)\right] + (1 - B) \times R_3 \times \quad (1)$$
$$\times \left(E_{ER} - LHV \times X_{ER,heat} \times E_{SE,heat} - LHV \times X_{ER,elec} \times E_{SE,elec}\right)$$
$$+ +(1 - R_2 - R_3) \times E_D$$

where,

A is a factor that represents the balance between supply and demand for recycled material [0.2–0.8];

Q_{Sin} is the quality of recycled material entering the life cycle [0–1];

Q_{Sout} is the quality of recycled material leaving the life cycle [0–1];

B is an allocation factor of energy recovery processes that applies both to burdens and credits;

R_3 is the ratio of the material in the product that is used for energy recovery at End-of-Life [0–1];

E_{ER} is the specific emissions and resources consumed (per functional unit) arising from the energy recovery process (e.g., incineration with energy recovery, landfill with energy recovery, etc.);

LHV is the Lower Heating Value of the material [MJ/kg];

$X_{ER,heat}$ is the efficiency of the energy recovery process for heat [0–1];

$E_{SE,heat}$ is the specific emissions and resources consumed (per functional unit) that would have arisen from the specific substituted heat source [0–1];

$X_{ER,elec}$ is the efficiency of the energy recovery process for electricity [0–1];

$E_{SE,elec}$ is the specific emissions and resources consumed (per functional unit) that would have arisen from the specific substituted electricity source [0–1];

By incorporating the CFF, BioCalc offers a comprehensive perspective on the environmental benefits of circular economy strategies, encouraging producers to adopt practices that reduce waste and optimize resource efficiency. This approach not only enhances the environmental performance of the biofuel but may also provide economic and competitive advantages in the marketplace.

The visual representation of the Energy-Environmental Efficiency Score (NEEA) calculated using the Circular Footprint Formula (CFF), along with its comparative analysis against equivalent fossil fuels, is presented in Figure 5.4.

Figure 5.4 - NEEA calculated using the CFF, and comparative analysis with equivalent fossil fuels

Considering the application of the Circular Footprint Formula (CFF)

Biofuel Carbon Intensity ($kg\ CO_2eq/MJ$)	**-0,013242**		
	Comparison between equivalent fossil fuels		
	Diesel A, Gasoline A and CNG (Weighted average)	Heavy fuel oil	Petroleum Coke
Carbon intensity of fossil fuel ($kg\ CO_2eq/MJ$)	0,087	0,094	0,120
Energy-Environmental Efficiency Rating	0,100	0,107	0,133
Emissions reduction	115,27%	114,10%	111,03%
Possible eligible credits (CBIOs) Considering a medium-sized plant with annual production of 10,000 Ton	15.790	16.925	21.058

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6. BIOCALC: A NOVEL LIFE CYCLE-BASED TOOL FOR QUANTIFYING THE CARBON CREDITS OF SOLID BIOFUELS IN BRAZIL

Abstract: *The increasing global demand for low-carbon energy sources has intensified interest in solid biofuels, such as pellets, particularly in regions with abundant biomass availability like in Latin America. However, methodological and regulatory challenges persist in assessing their carbon footprint and integration into carbon credit schemes. This study presents BioCalc, a novel computational tool designed as an adaptation of the RenovaCalc Brazilian model to quantify the carbon footprint of solid biofuels under a Life Cycle Assessment (LCA) framework compliant with ISO 14040/14044 standards. The tool incorporates harmonized emission factors, land use change modeling, and cradle-to-grave system boundaries to enable robust and transparent assessments. Three biomass sources—peanut shell, Pinus, and Eucalyptus—were analyzed across domestic, export, and mixed market scenarios to test the tool. BioCalc calculated carbon intensity and the potential decarbonization credits (CBIOs), applying three different methodological LCA approaches: standard attributional LCA, the Circular Footprint Formula (CFF), and the zero-burden assumption. Results revealed a substantial lifecycle reduction in carbon emissions of biomass pellets —up to 97% compared to equivalent fossil fuels—and highlighted the methodological sensitivity in the CBIOs quantification, with CFF yielding the highest economic potential. The study also evaluated national production forecasts and explored the inclusion of these biofuels in Brazil's RenovaBio and voluntary carbon markets, projecting up to USD 103.9 million in revenues under specific conditions. This research provides a policy-aligned, science-based pathway for integrating solid biofuels into regulated and voluntary carbon markets. It strengthens the case for regulatory updates to include densified biomass fuels in Brazil's decarbonization strategies and offers a replicable model for advancing circular bioeconomy principles in the global energy transition.*

Keywords: Life Cycle Assessment, RenovaBio, Decarbonization Policies, Carbon Credits, Pellets

6.1. INTRODUCTION

The accelerated global population growth, along with increasing urbanization and industrialization, poses significant challenges in developing and managing energy resources in the context of the mitigation of climate change (Ahmed et al., 2018). Consequently, countries' decarbonization targets aim to reduce greenhouse gas (GHG) emissions from conventional energy sources by transitioning to clean energy generation pathways (Chen et al., 2022; Hussain et al., 2017). Of these, low-carbon energy alternatives like solid biofuels have attracted significant attention in recent years (Rampasso et al., 2021; Silva et al., 2022). However, the use of biomass as a solid biofuel has restrictions, such as its low bulk density and difficulties in transport and storage (Bajwa et al., 2018). This motivates the use of physical-mechanical techniques like pelletizing to obtain solid fuels (i.e., pellets) with high energy content per unit volume (Muazu et al., 2017), which represent a renewable source for power and/or heating systems. Wood-based pellet consumption increased from 15 to 50 million tonnes between 2010 and 2020 and is expected to reach 80 million tonnes by 2025 (Matheus et al., 2024). These biofuels can generate less environmental impact compared to their petroleum-based counterparts (Silva et al., 2022) and provide economic benefits. For example, Quinteiro et al. (2020) determined an average of 7.25 gr CO_2-eq per MJ of heating, which contrasts sharply with 92.6 gr CO_2-eq per MJ of heavy fuel oil (Padilla-Rivera et al., 2017). Additionally, utilizing low-carbon energy sources generates economic opportunities, such as local job creation, particularly in rural areas (Walker et al., 2024).

The transition to solid biofuels has led many countries to develop and implement economic stimulus policies to promote this market (Peng et al., 2024), driven by the growing need to address the climate change crisis (Galeazzi et al., 2024). These policies include a variety of measures, such as paying a fixed price to renewable energy producers, renewable energy targets, biofuel blend mandates, and carbon pricing mechanisms (Maia & Bozelli, 2022). In this regard, Brazil has committed to addressing climate targets through its Nationally Determined Contribution (NDC), to reduce its GHG emissions by 37% by 2025 and 43% by 2030 towards carbon neutrality by 2060 (Brazil, 2020). To achieve this, a scientifically informed energy strategy based on the high-value conversion of renewable biomass takes a central role (Zhang et al., 2025).

Although there is a widespread belief that bio-based products are a better environmental alternative to their fossil counterparts, this assertion requires deeper analysis, e.g., by applying the life cycle assessment (LCA) methodology, as "bio-based" does not always imply an “environmentally friendly” alternative. LCA is a well-known methodology for quantifying the potential environmental impacts of products or services throughout their life cycle, avoiding shifting environmental burdens (ISO, 2006), and allowing quantify carbon savings and credit generation. Although the origins of LCA go back to the industrial sector, currently it is increasingly used in public policy making (Jegen, 2024), for example, in Environmental Product Declarations (EPDs) and Product Carbon Footprints (PCFs) in the construction sector (Jordan, 2021), and carbon credits in the forest (Silva et al., 2022). However, in the solid biofuels sector, different challenges require attention, such as the lack of consensus on appropriate fossil fuel baselines for biofuel comparisons, carbon credit calculation procedures and regulatory frameworks, carbon pricing mechanisms, and their contribution to decarbonization strategies.

Carbon pricing mechanisms have been primarily developed in recent years and increasingly gained relevance as strategic instruments for reducing GHG emissions (Anjos et al., 2022), fostering low-carbon technologies, including bioenergy solutions (Aguiar et al., 2024). Among the available instruments, Emissions Trading Systems (ETS)—such as the European Union Emissions Trading Scheme (EU ETS)—have incorporated certain types of bioenergy projects, particularly in the context of renewable energy promotion and compliance offsets (Backe et al., 2023; Feijoo et al., 2019). These systems establish a cap on emissions and allow regulated entities to trade carbon credits, generating opportunities for sectors that can demonstrate measurable emission reductions, such as biofuel producers.

Despite this, most existing carbon pricing frameworks were originally designed around fossil fuel-intensive sectors and liquid biofuels, often overlooking the full mitigation potential of solid biofuels, especially in emerging economies like those in Latin America (Galeazzi et al., 2024). In Brazil, recent advances such as RenovaBio have paved the way for market-based recognition of biofuels in national climate policy, yet comprehensive integration into broader carbon markets, particularly for solid biofuels, remains limited (Tiburcio et al., 2023). This underscores the need for methodological tools capable of assessing the carbon intensity and credit generation potential of solid biofuels, thereby enabling their inclusion into regulated or voluntary carbon markets (VCM) (Scully et al., 2021; Zhang et al., 2025).

The term carbon intensity denotes the amount of GHG emissions per unit of energy produced (e.g., kg CO_2eq/MJ), serving as a performance metric to evaluate fuels within decarbonization policies. In contrast, the carbon footprint reflects the total life cycle GHG emissions of a product, regardless of its energy output. While both metrics are derived from Life Cycle Assessment (LCA), carbon intensity is more suitable for energy policy tools, as it enables direct comparison between fuels and supports credit generation schemes such as RenovaBio. Conversely, carbon footprint is typically used for broader communication purposes, such as Environmental Product Declarations or organizational inventories (ISO 14040/14044; Cherubini & Strømman, 2011). In Latin America, Brazil is at the forefront of developing carbon pricing regulations (ICAP, 2025), by proposing the Brazilian GHG Emissions Trading System (SBCE, from the Portuguese translation for *Sistema Brasileiro de Comércio de Emissões de Gases de Efeito Estufa*). The biofuel sector is linked to the SBCE through the National Biofuels Policy (RenovaBio), which aims to increase the share of biofuels in the national energy matrix. In this context, RenovaCalc is a tool for calculating the carbon intensity of biofuels in a life cycle perspective, enabling the estimation of carbon credits that can be sold to fossil fuel distributors and other stakeholders (Tiburcio et al., 2023). While RenovaCalc facilitates the accounting of carbon intensity for liquid biofuels, it lacks methodological provisions and emission factors for solid biofuels and remains disconnected from broader carbon offset frameworks, particularly those associated with voluntary markets and regulated systems such as the SBCE. This limitation creates a methodological and operational gap in quantifying solid biofuels' climate benefits and supporting their economic valorization through carbon credits (Farrapo et al., 2023a; Souza et al., 2025).

To address this gap, the present research proposes the BioCalc tool —a novel computational tool developed from a life cycle perspective—to complement and extend the scope of RenovaCalc by enabling the assessment of solid biofuels within decarbonization frameworks. Specifically, this research investigates how adopting solid biofuels can influence the carbon credits market and contribute to national and international decarbonization strategies. For this purpose, three pellet production alternatives based on Peanut shells, Pinus residues, and Eucalyptus residues sources are used for testing the use of the tool. This research can permit the entrance of producers of solid biofuels into the Brazilian decarbonization market, increasing also their competitiveness, as most are classified as small- to medium-sized companies.

6.2. MATERIALS AND METHODS

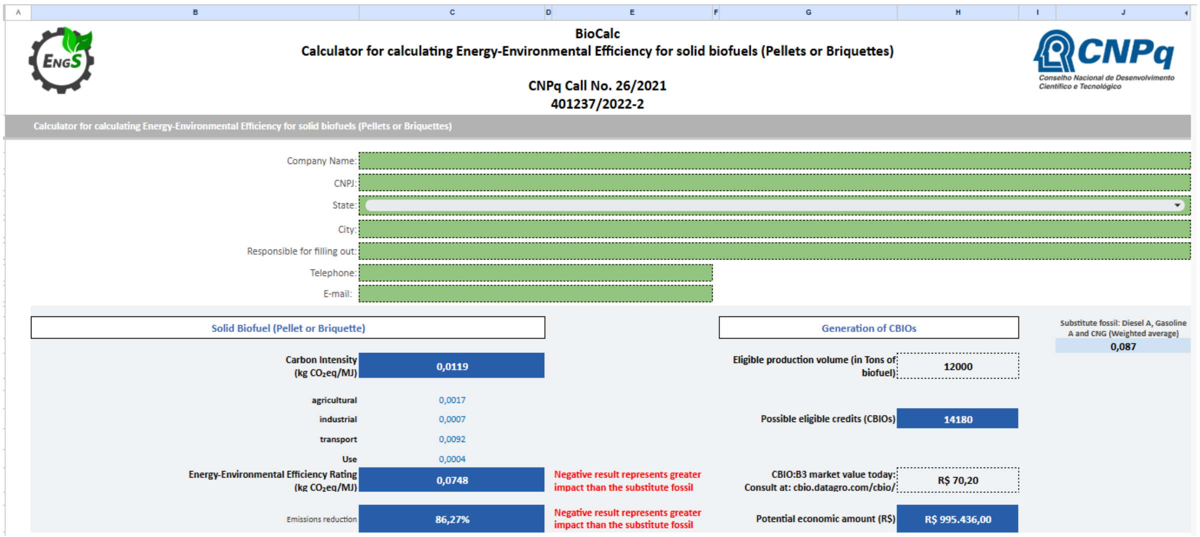
This section is described and organized as follows: 6.2.1) Development of the BioCalc tool, 6.2.2) LCA modeling: system boundaries and assumptions, 6.2.3) Comparative assessment of biomass sources and market scenarios, and 6.2.4) Integration of solid biofuels into decarbonization frameworks**.**

6.2.1 Development of the BioCalc Tool

The BioCalc tool was developed with the primary aim of incorporating the carbon intensity accounting for solid biofuels, such as pellets and briquettes, under RenovaBio requirements. Based on an attributional LCA approach in line with ISO 14040/14044 standards, BioCalc adopts a "Cradle-to-Grave" system boundary, ensuring that all emissions—from raw material production to final combustion—are rigorously accounted for.

The user interface of BioCalc is designed to facilitate the collection and standardization of input data (see Figure 1). Through intuitive dropdown menus, users select the type of biomass (e.g., peanut shell, pinus, or eucalyptus), which automatically assigns critical parameters such as the biomass impact factor and its lower heating value, derived from international databases, including ecoinvent v.3.9.1. This automation step ensures data consistency and comparability, which are essential for robust environmental lifecycle analysis.

Figure 6.1 - BioCalc – user interface overview



In addition to biomass-related parameters, BioCalc integrates detailed information on input consumption, logistic-related data (including transportation distances and vehicle types), and critical aspects of land use change (LUC). The LUC assessment is derived from the BRLUC 2.0 platform (EMBRAPA, 2021), a modeling tool designed to estimate LUC emissions in Brazil, which integrates spatially explicit data and regulatory frameworks to enhance the accuracy of carbon footprint calculations (Garofalo et al., 2022). The inclusion of LUC is particularly relevant given its substantial contribution to the overall climate impact of biofuels, as emphasized by Novaes et al. (2024), who demonstrate that neglecting LUC can result in significant underestimation of emissions in land-intensive bioenergy systems. Their findings highlight the need for harmonized tools that account for regional land dynamics and historical land occupation, especially in tropical regions with complex land use trajectories. Furthermore, Maia & Bozelli (2022) argue that incorporating LUC into environmental assessments is essential to ensuring consistency with ecosystem conservation goals and international climate commitments. These components enable the harmonization of diverse data streams and the application of IPCC (2021) characterization factors to convert emitted gases into CO_2 equivalents (in kg CO_2 eq./MJ of biofuel).

The BioCalc tool facilitates comparisons with fossil fuel counterparts by establishing a technical basis for assessing energy-environmental efficiency. A Technical Note report detailing the methodology and functionality of BioCalc is available in the supplementary material (SM). The tool can also be requested for download from the following webpage: https://www.grupoengs.com.br/en/produtos.

BioCalc automatically calculates the Energy-Environmental Efficiency Score (NEEA), an indicator that quantifies the reduction in carbon intensity (kg CO_2 eq./MJ) of a solid biofuel relative to its fossil fuel equivalent. This score serves as the basis for estimating decarbonization credits (CBIOs) under the RenovaBio framework. The corresponding equation is defined as follows:

$$NEEA = CI_{Fossil} - CI_{Biofuel}$$

Where:

$NEEA$ = Energy-Environmental Efficiency Score (kg CO_2 eq./MJ)

CI_{Fossil} = Carbon intensity of the equivalent fossil fuel (kg CO_2 eq./MJ)

$CI_{Biofuel}$ = Carbon intensity of the solid biofuel (kg CO_2 eq./MJ)

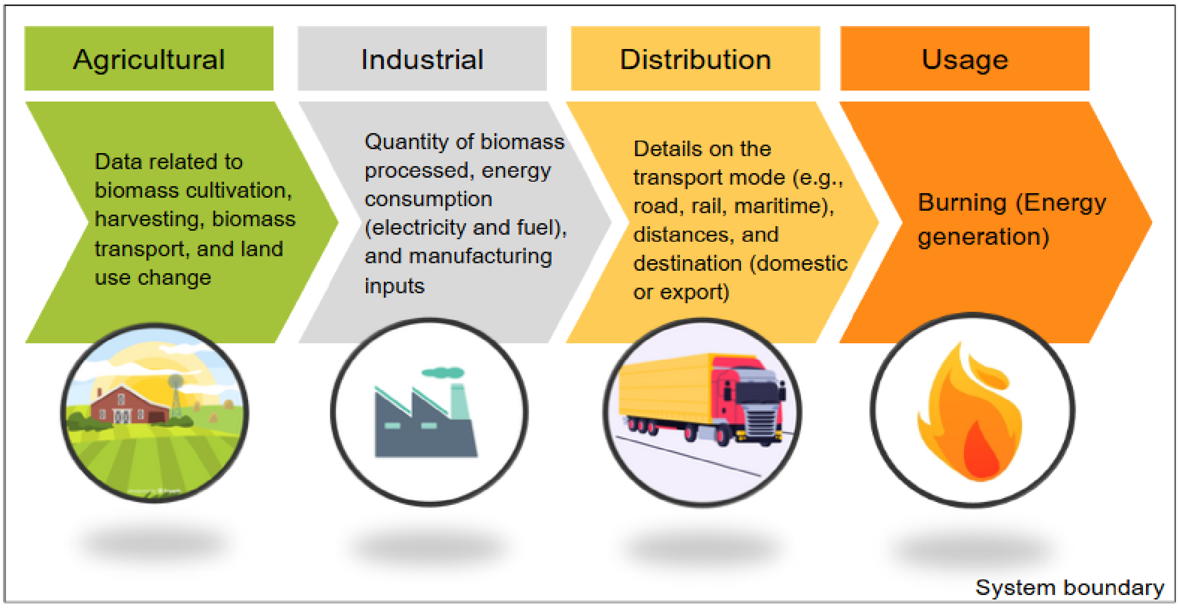
This methodological integration not only enhances the robustness of the environmental analysis of solid biofuels but also facilitates their incorporation into both regulated and VCM. The BioCalc underwent an independent third-party review conducted by EMBRAPA – the Brazilian Agricultural Research Corporation – to ensure methodological rigor and technical reliability.

6.2.2 LCA modeling: system boundaries and assumptions

The product system considered in the BioCalc tool concept is a cradle-to-grave type that encompasses all stages, including the agricultural/forest stage, industrial processing, distribution, and final use in combustion. This comprehensive approach ensures that the entire life cycle of the biofuel is accounted for in the carbon intensity calculations. Figure 6.2

illustrates the system boundary and the specific data inputs that should be entered into the tool, corresponding to each life cycle stage.

Figure 6.2 - Product system boundary and life cycle data inputs - BioCalc Tool



The biofuel feedstocks are derived from residual biomass, specifically, peanut shells, pinus, and eucalyptus wood residues, based on data from Matheus et al., (2024) for the Brazilian territory. Data inputs were categorized and modeled for each feedstock across the four life cycle stages in Figure 6.2. In the agricultural or forest stage, information included biomass cultivation and harvesting practices, short-distance transport from the collection site to the processing plant, and LUC data based on the plant location. The industrial stage covered the quantity of biomass processed, energy consumption (electricity and thermal), and manufacturing inputs used in the solid biofuel production. Distribution data encompassed transport modes (road and maritime), distances from each facility to the nearest maritime port, and the sea freight route to the final destination. The usage stage assumed combustion for energy generation as the only scenario.

Three plants strategically located in different states of Brazil were assumed. Table 6.1 details the biomass type, the road distance from the biomass collection point to the industrial plant, the plant's location (city and state, reflecting LUC context), the road freight distance to the nearest maritime Port, the maritime Port location, and the corresponding sea freight distance assumed for each case. Road transportation was modeled using a 16–32 metric ton diesel truck as standard. It is important to note that the transportation modeling assumes a one-way trip only and does not account for the empty return of the load.

Table 6.1 - Biomass supply and transportation parameters for selected solid biofuel cases

	Biomass supply	Biomass collecting point distance (km)	Plant Location (City/State)	Nearest Maritime Port (km)	Maritime Port Location	Sea Freight Distance (km)
Case 1	Peanut shell	10	Itaju/SP	410	Santos	10,015.23*
Case 2	Pinus wood	6	Telêmaco Borba/PR	383	Paranaguá	10,282.03*
Case 3	Eucalyptus wood	6.74	Lages/SC	300	Itajaí	10,368.51*

* The final export destination is designated as Rotterdam, Netherlands, based on the work done by Matheus et al. (2024).

To estimate the potential generation of eligible CBIOs, this research considered a representative production volume of 12,000 tons per year from a small- and medium-sized solid biofuel plant, a scale commonly found among national and international facilities (OECD, 2008). This production scale reflects a representative capacity within the sector, aligning with the assumptions used in the LCA modeling.

6.2.3 Comparative assessment of biomass sources and market scenarios

Three distinct market scenarios were developed to systematically assess the role of transportation in shaping the overall carbon footprint of solid biofuels and further the generation of CBIOs by the BioCalc use:

- ***Baseline Scenario (Export Scenario):*** This scenario considers that the entire biofuel production is exported. Biofuels are transported from the production facility to the nearest international maritime Port and shipped to Rotterdam, Netherlands. Rotterdam was selected as the reference export destination due to its strategic importance as a major European biomass import hub. This approach is consistent with previous life cycle assessments of biofuel supply chains, with studies such as Vera et al. (2020) highlighting the central role played by the Port of Rotterdam in facilitating biomass imports destined for Europe’s heating and energy sectors.
- ***Domestic Scenario (S1):*** This scenario assumes that the entirety of the biofuel production is destined for the domestic market. To represent the transportation emissions within this context, a fixed road distance of 100 km was considered from the production facility to the final consumer market. This assumption is consistent with previous studies that have analyzed the logistics of biomass-based energy distributions

in Brazil. Garcia et al., (2018) affirmed that the economic viability of pellet production is significantly influenced by transportation distances, noting that transporting biomass over distances greater than 200 km can render projects unfeasible due to high costs. Therefore, a 100 km distance is a conservative estimate for domestic distribution,.

- ***Mixed Scenario (S2)**:* This scenario represents a balanced biofuel distribution between domestic consumption and international export. Half of the production is allocated to the domestic market, assuming a fixed road transport distance of 100 km to the final consumer. The remaining 50% is transported to the nearest maritime Port for export to Rotterdam, Netherlands. This approach enables a comprehensive assessment of the trade-offs between local and international trade, considering both carbon footprint implications and the efficiency of energy logistics

Beyond transportation, the environmental and economic performance of different biomass sources (peanut shells, pinus, and eucalyptus wood) were also compared. These biomass sources differ in terms of carbon intensity, lower heating value (LHV), and energy conversion efficiency, factors that directly impact their net GHG emissions. The emissions associated with each biomass type are computed into BioCalc using harmonized datasets from the ecoinvent 3.9.1 LCA database, assisted by national agricultural statistics, to ensure consistency in the LCA methodology. This comparison enables an evaluation of which biomass sources offer the highest decarbonization potential and energy efficiency gains in the different market scenarios.

A crucial aspect is the comparison of the NEEA of biofuels with their fossil fuel equivalents. The standard NEEA quantifies the difference in carbon intensity between biofuels and fossil fuels, serving as a key factor for the generation of decarbonization credits (CBIOs). Given the diverse applications of solid biofuels, three fossil fuel benchmarks were selected for comparison: i) a weighted average of Diesel A, Gasoline A, and Natural Gas (GHG Protocol, 2012), ii) petroleum coke (Resolução ANP No 894, 2022) , and iii) heavy fuel oil (Resolução ANP No 894, 2022). This comparison enables an assessment of the relative carbon savings achieved through solid biofuel substitution in displacing high-carbon fossil fuels across different industrial and energy sectors.

To enhance the robustness of the environmental assessment, two alternative scenario-indicators of energy-environmental efficiency were performed: NEEA (Circular Footprint Formula - CFF) and NEEA (Zero Burden). The NEEA (CFF) was applied to quantify the benefits of material circularity and energy recovery potentials for the CBIOs generation. CFF considers the allocation of environmental burdens and the benefits related to biomass use, recycling efficiencies, and cascading material utilization, thereby providing a more comprehensive perspective on sustainability (EC, 2018). The application of CFF is particularly relevant for residual biomass sources, allowing for improved representation of carbon retention and energy recovery throughout the product life cycle (Farrapo et al., 2023). The detailed calculation of CFF use is presented in the SM. Additionally, NEEA (Zero Burden) scenario-indicator was calculated by applying a zero-carbon burden (cutt-off approach) to agricultural residues used as feedstock. While this is a common modeling choice in attributional LCAs, especially for materials such as peanut shells, sawmill residues, and forestry by-products, it does not imply the actual avoidance of emissions. Rather, it reflects an accounting convention aimed at excluding burdens from processes not directly associated with the product system under analysis (Ekvall et al., 2020). On the other hand, recent studies (Olofsson & Börjesson, 2018; Sfez et al., 2019) caution that such assumptions may omit relevant environmental impacts and should not be interpreted as delivering avoided emissions or circularity benefits, particularly when used outside of consequential LCA frameworks.

6.2.4 Integration of solid biofuels into decarbonization frameworks

This section outlines the procedure adopted to integrate solid biofuels into existing regulated and VCM frameworks, recognizing that the effectiveness of such integration is not solely technical but also institutional. As emphasized by (Leal Filho et al., 2025), successful adoption of sustainability tools in the Global South requires cohesive governance structures, regulatory alignment, and the strengthening of science-policy interfaces to ensure practical implementation and long-term impact. In this context, particular emphasis was placed on Brazil's National Biofuels Policy (RenovaBio) and the Brazilian Emissions Trading System (SBCE). The objective was to assess the potential eligibility of solid biofuels—specifically pellets—for the generation of decarbonization credits, using harmonized life cycle data and technical parameters aligned with policy requirements.

The RenovaBio program, established under Law No. 13,576/2017, employs LCA as a scientific basis to calculate the carbon intensity of biofuels and assign CBIOs proportionally to their environmental performance. Within this framework, CBIOs are traded in a regulated financial market (B3) and represent one metric ton of CO_2 equivalent emissions avoided. The BioCalc tool was used to replicate the RenovaCalc structure, enabling the quantification of carbon intensity and potential CBIO generation in different approaches for solid biofuels based on LCA modeling.

CBIO calculation is directly linked to the NEEA indicator, with higher efficiency ratings resulting in greater carbon credit eligibility. The calculation of CBIOs follows a standardized methodology (Matsuura et al., 2018) in which the NEEA score, multiplied by the annual biofuel production volume and its lower heating value (LHV), determines the total number of decarbonization credits. In this framework, one CBIO corresponds to one metric ton of CO_2 equivalent avoided. The corresponding formula is presented below.

$$CBIOs = NEEA \times V \times LHV_{biofuel}$$

Where:

$CBIOs$ = Number of Decarbonization Credits generated (tCO_2 eq.)

$NEEA$ = Energy-Environmental Efficiency Score (kg CO_2 eq./MJ)

V = Eligible production volume (tonnes)

$LHV_{biofuel}$ = Lower Heating Value of the biofuel (MJ/kg)

To assess the economic potential associated with integrating solid biofuels into Brazil's decarbonization policies, an estimation of national pellet production volumes was conducted for the period 2017-2024. Historical data from 2017 to 2020 were obtained from (Garcia et al., 2022)Figures for 2021 to 2023 were provided through a structured interview with the president of the Brazilian Pellet Industries Association (ABIPEL). For 2024, a forecasted production volume was calculated using the average annual growth rate observed between 2020 and 2023. This projection served as a reference for evaluating the revenue potential from avoided greenhouse gas emissions under different methodological approaches.

Furthermore, the estimated revenue from CBIOs was calculated based on two complementary approaches. The first used the average market price of ethanol-based CBIOs in 2024 (B3, 2025), providing a realistic estimate of the financial incentives currently available in regulated markets. The second approach was based on the average carbon pricing in the agricultural sector, as proposed by Souza et al. (2025) from EMBRAPA. For each methodological approach (NEEA, CFF, and Zero-Burden), the total number of CBIOs generated was first calculated. Then, the estimated revenue was obtained by multiplying the number of CBIOs by the corresponding unit price under each pricing scenario:

$$Estimated\ Revenue = CBIOs_{total} \times CBIO_{price}$$

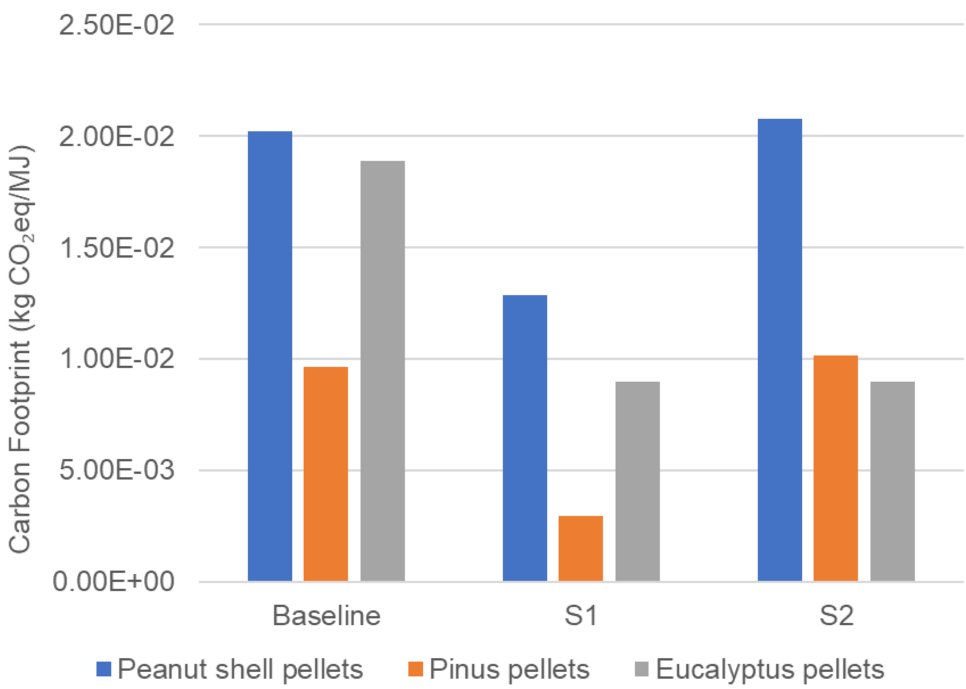
This valuation reflects an emerging policy direction aimed at internalizing the environmental costs of agricultural practices and promoting low-carbon technologies. By incorporating this alternative benchmark, the analysis broadens its applicability to future scenarios involving sector-specific carbon pricing and voluntary market participation, while also highlighting how methodological choices and market conditions influence the financial viability of solid biofuels within decarbonization frameworks.

6.3. RESULTS AND DISCUSSION

6.3.1 Carbon footprint of solid biofuels: life cycle emissions and hotspot analysis

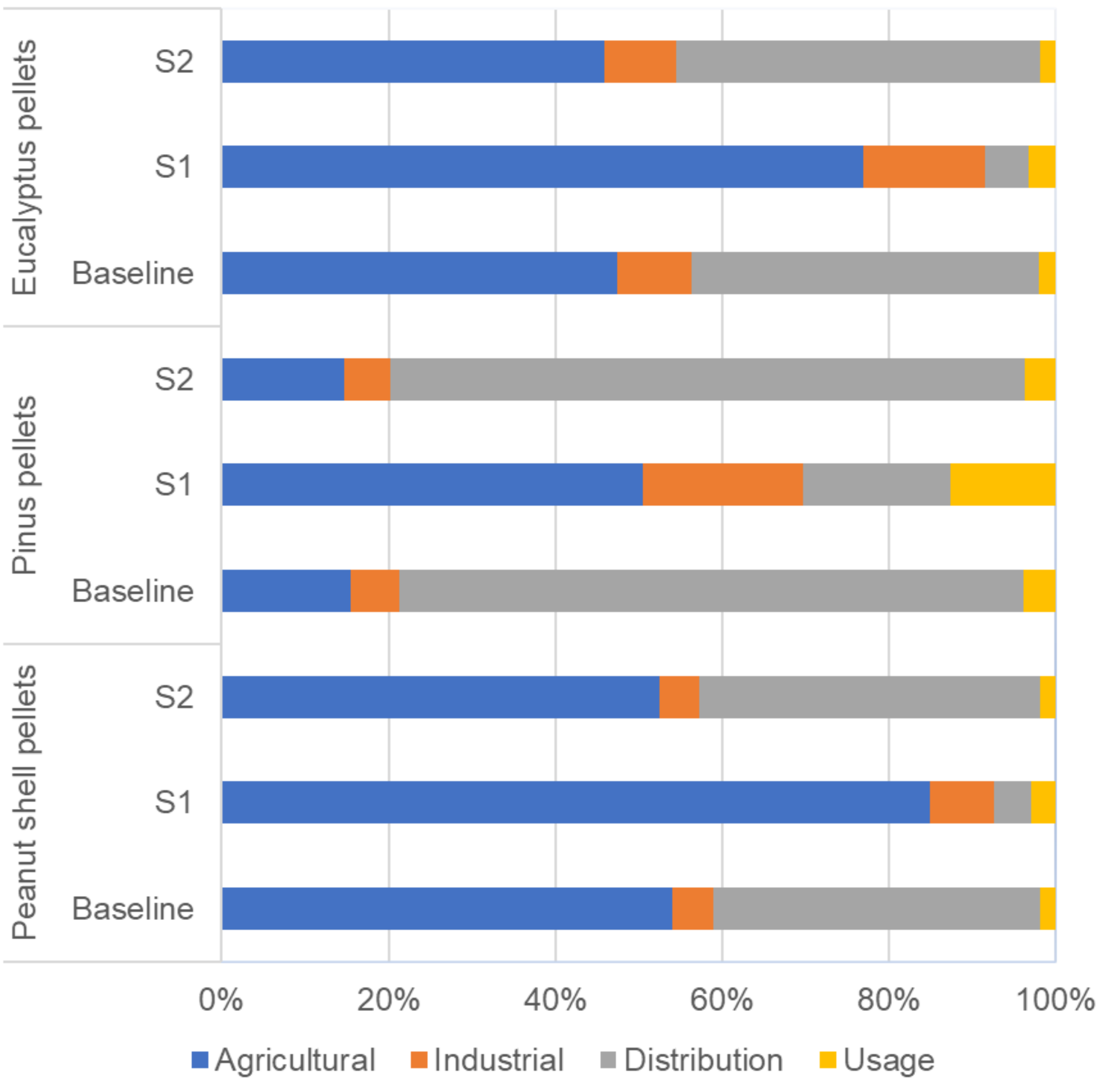
Carbon emissions from each of the biofuel's life cycle, calculated through the BioCalc tool, vary significantly according to the biomass type, production stage emissions, and logistic scenarios. The results depicted in Figure 3 highlight the differences in biofuel carbon footprint (measured in kg CO_2eq per MJ) among Peanut shell, Pinus, and Eucalyptus pellets. Peanut shell pellets showed baseline emissions of approximately 2.0×10^{-2} kg CO_2eq/MJ, decreasing to about 1.3×10^{-2} kg CO_2eq/MJ in scenario S1—a reduction of about 35%—before returning to approximately 2.0×10^{-2} kg CO_2eq/MJ in scenario S2. Pinus pellets presented the lowest baseline emissions at about 3.0×10^{-3} kg CO_2eq/MJ, which slightly increased by approximately 1% in scenario S1 and decreased by about 66% in scenario S2. Eucalyptus pellets initially exhibited baseline emissions of around 1.9×10^{-2} kg CO_2eq/MJ, decreasing significantly by approximately 53% to around 9.0×10^{-3} kg CO_2eq/MJ in both scenarios S1 and S2.

Figure 6.3 - Carbon footprint of solid biofuels by scenario and biomass source



Analyzing the contribution by life cycle phases, as shown in Figure 6.4, the agricultural phase has the most significant share for all biomass types in S1, reaching as high as 85% for peanut shells and 77% for eucalyptus. This predominance aligns with previous studies indicating that agricultural practices significantly impact biofuel emissions due to input demands such as fertilizers and fuel consumption (Padilla-Rivera et al., 2017; Silva et al., 2022). Transportation and logistics (distribution) have a higher contribution in baseline and S2, particularly for Pinus pellets, representing approximately 75-76% of emissions. Such outcomes corroborate with literature emphasizing that transportation distances significantly affect biofuel projects' environmental footprints (Garcia et al., 2018; Matheus et al., 2024).

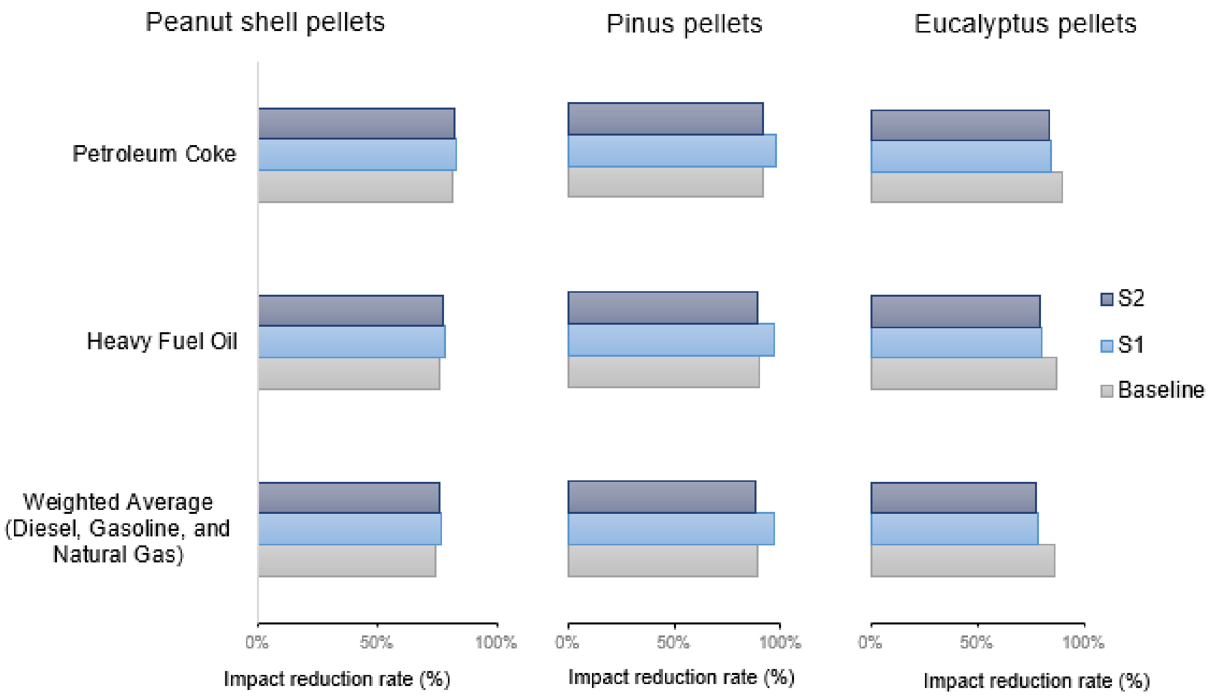
Figure 6.4 - Contribution analysis (in %) of carbon emissions of solid biofuels per life cycle phase



Usage-phase emissions accounted for less than 4% across all evaluated cases, highlighting the inherent environmental advantages of solid biofuels relative to fossil fuels. The literature widely supports this finding, documenting biomass's significantly lower carbon emissions than fossil-derived fuels (Cherubini & Strømman, 2011). For example, previous research reported wood pellet emissions from the usage phase at approximately 0.00725 kg CO_2eq per MJ (Quinteiro et al., 2020), significantly lower than heavy fuel oil emissions of 0.0926 kg CO_2eq per MJ (Padilla-Rivera et al., 2017).

Although Scenario 2 (S2) considers only 50% of the production for export, its carbon intensity (kg CO_2 eq/MJ) is higher than in the baseline scenario, where 100% is exported. This result is due to the functional unit adopted, which normalizes impacts by biofuel produced. In S2, the combination of multiple transport modes—especially domestic road transport—leads to higher emissions per unit of energy, offsetting the reduced international transport and highlighting the relevance of road modal choices in LCA outcomes.

Figure 6.5 - Emission reduction potential of solid biofuels compared to fossil fuels across scenarios

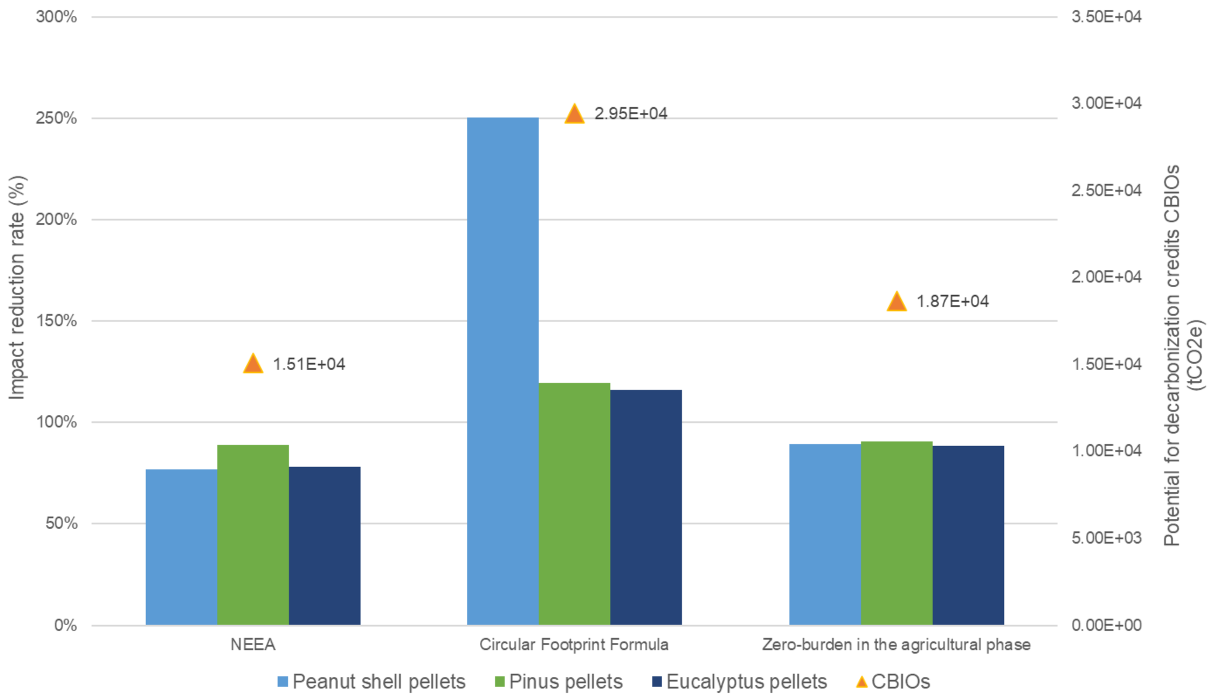


Comparative analyses between biofuels and their fossil fuel counterparts underscore significant potential for impact reduction (see Figure 6.5). This comparative assessment was performed using the Energy-Environmental Efficiency Rating (NEEA), which quantifies the relative emissions reduction of each biofuel compared to fossil fuel benchmarks. Pinus pellets demonstrated the highest impact reduction across scenarios, reaching up to 97% relative to heavy fuel oil and the average of fossil fuels (diesel, gasoline, natural gas) in S1. Similarly, peanut shell pellets and eucalyptus pellets achieved substantial reductions of up to 83% and 84%, respectively, compared to petroleum coke in their baseline scenarios. This comparison is particularly relevant for solid biofuels, which have diverse applications, ranging from industrial heating to electricity generation. Due to this versatility, there is no consensus on which fossil fuels should serve as the main reference in impact assessments. However, it is important to note that the NEEA does not exhibit substantial variation across different fossil fuel equivalents. This stability suggests that, despite the lack of a standardized baseline for comparisons, solid biofuels consistently demonstrate a significant environmental advantage in all the evaluated situations, reinforcing their role as a viable decarbonization strategy (Aguiar et al., 2024).

6.3.2 Decarbonization credit potential: methodological approaches and CBIOs estimation

The NEEA calculated for each biomass type served as a crucial determinant for CBIO generation. Higher NEEA scores directly correlated with increased eligibility for decarbonization credits. Following the methodological framework outlined in this study, the potential for CBIO generation was analyzed using three distinct approaches: (i) the calculation based solely on the standard NEEA equation(ii) the application of the Circular Footprint Formula (CFF) to the final carbon intensity result of the biofuel, and (iii) the zero-burden assumption for the agricultural phase impacts accounting. Each of these approaches provides a different perspective on emission reductions and CBIO generation potential. The main results, segmented by biomass type, are summarized in Figure 6.6, where the CBIO generation potential is averaged across all three biomasses for each approach.

Figure 6.6 - Emission reductions and average CBIO generation by methodological approach and biomass source



The NEEA-based approach yielded a reduction potential ranging from 77% for peanut shells to 89% for Pinus pellets, with eucalyptus at 78%. This reduction potential represents the relative difference in carbon intensity between each biofuel and its fossil fuel equivalent, calculated by comparing their life cycle greenhouse gas emissions per unit of energy (kg CO_2eq/MJ). These values align closely with previous studies that assessed biofuels efficiency, where similar reduction percentages were observed in LCA-based studies of wood pellets (Cherubini & Strømman, 2011; Quinteiro et al., 2020). Assuming an annual production volume of 12,000 tons —representative of small and medium-sized enterprises (SMEs), as previously outlined in the methodology section—, this approach resulted in an estimated CBIO generation of approximately 1.51×10^4 credits, representing a baseline calculation that includes the LUC impacts, where the agricultural production of biomass can result in either carbon emissions or sequestration, depending on regional land-use dynamics. As highlighted by (Garofalo et al., 2022), LUC emissions in Brazil vary significantly across states, with certain regions experiencing high emissions due to deforestation, while others promote carbon sequestration through land restoration and sustainable agricultural practices.

The CFF approach significantly altered the reduction rates, with peanut shells achieving a 250% reduction, Pinus 120%, and eucalyptus 116%. This substantial increase reflects the broader circular bioeconomy principles embedded within the CFF methodology, which accounts for material reuse, recycling benefits, and extended carbon sequestration over multiple lifecycles (Ekvall et al., 2020). The application of CFF to carbon intensity calculations resulted in significantly higher CBIOs generation of 2.95×10^4 credits. This highlights the benefits of considering material circularity in biofuel sustainability assessments, aligning with recent findings that emphasize the role of circular bioeconomy frameworks in bioenergy systems (Mola-Yudego et al., 2024).

The zero-burden approach applied to the agricultural phase demonstrated a reduction potential of 89% for peanut shells, 91% for Pinus, and 88% for eucalyptus pellets, leading to an estimated CBIOs generation of 1.87×10^4 credits. This assumption, which excludes emissions from the agricultural stage of the biomass feedstock itself, is particularly relevant in policy discussions where biofuel feedstocks are classified as waste or by-products (Silva et al., 2022b). While previous studies have demonstrated that zero-burden accounting can significantly affect carbon credit estimations, particularly in the case of agricultural residues within carbon market frameworks (Padilla-Rivera et al., 2017), its indiscriminate application in bioproduct systems warrants caution. As bio-based models gain economic relevance, residues increasingly acquire market value, becoming co-products in agricultural systems (e.g., when used for animal feed or bioenergy/bioelectricity generation). Under such circumstances, treating these materials as burden-free may lead to the systematic exclusion of important environmental impacts, such as freshwater eutrophication (FE), land use (LU), and water consumption (WC), thereby compromising the integrity of multi-criteria sustainability assessments or LCAs that go beyond carbon metrics.

Comparing these three approaches, the CFF methodology yielded the highest CBIOs generation potential due to its broader system boundary and material efficiency circularity. By internalizing avoided burdens, such as the displacement of virgin material extraction and waste disposal, the CFF approach aligns with the principles of the circular bioeconomy, fostering resource efficiency and value recovery within closed-loop systems. This characteristic is particularly relevant for solid biofuels derived from agricultural and forestry residues, as it acknowledges their role in extending biomass utility through energy recovery pathways. This perspective is reinforced by (Gonçalves et al., 2021), who highlight the importance of cascading use and material valorization strategies in supporting circular bioeconomy objectives within the forest biomass sector.

In addition, the application of CFF contributes to advancing the concept of absolute environmental sustainability, as it provides a means to evaluate the net ecological benefits of biofuel systems based on life cycle principles (Lopes Silva et al., 2025). By incorporating circularity metrics into the life cycle assessment framework, the method allows for a better alignment between biofuel production and planetary boundaries, reinforcing its role in guiding policies toward truly sustainable systems. However, the NEEA-based approach provides a more conservative and regulatory-aligned method for evaluating biofuel emissions reductions, making it more applicable for current certification mechanisms like RenovaBio. The zero-burden assumption, while reflecting real-world practices in specific policy contexts, remains subject to debate due to its dependency on regulatory definitions of biomass residues (Feijoo et al., 2019).

These findings underscore the importance of methodological choices in biofuel sustainability assessments. The significant variance in CBIOs generation highlights the need for harmonized criteria in carbon credit calculations, particularly for solid biofuels, where different usage scenarios complicate direct comparisons with fossil fuel baselines. Future research should focus on integrating these methodologies within regulatory frameworks to ensure consistency and maximize biofuels' environmental and economic benefits in the carbon market.

6.3.3 Enabling solid biofuels in climate policy: economic potential and regulatory integration

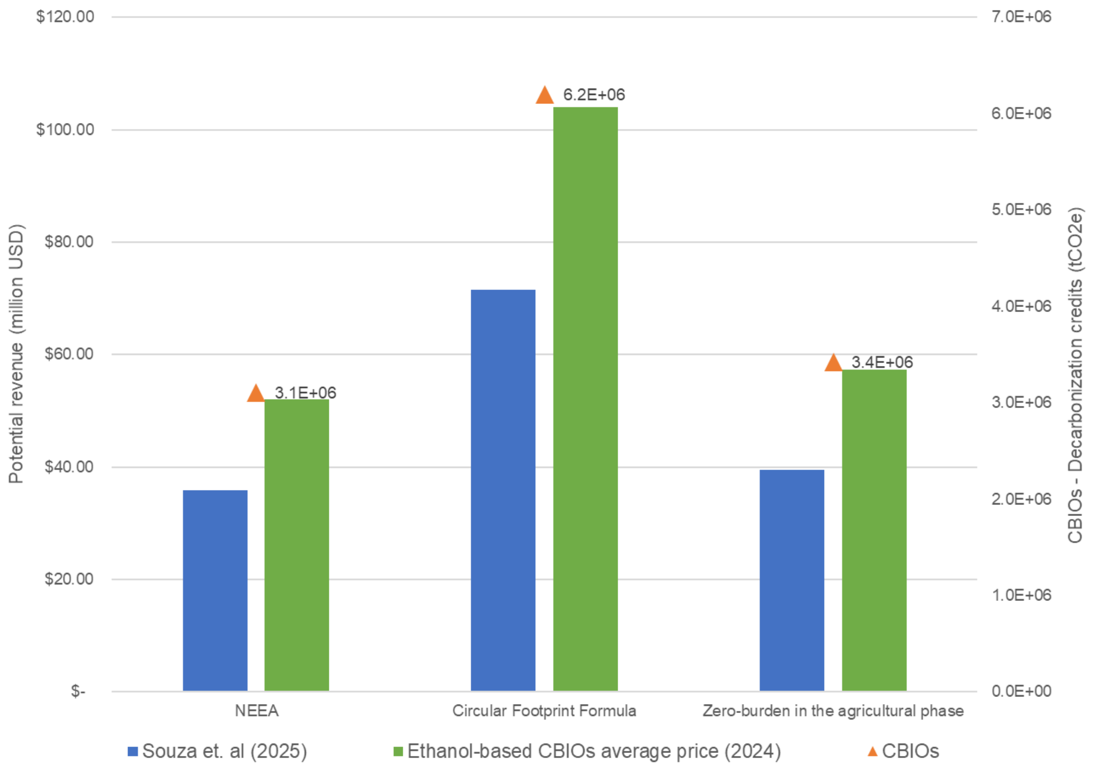
Recent data on pellet production in Brazil, detailed in Table 2, reflect a notable supply expansion over the period 2017–2023. Between 2017 and 2020, annual increases ranged from 7.9% to 38.1% (Garcia et al., 2022). Subsequent years, based on ABIPEL (Brazilian Association of Pellet Industries) records, showed even more substantial growth: 31.7% from 2020 to 2021, 43.5% from 2021 to 2022, and 29.0% from 2022 to 2023. A projected 27.9% increase was estimated for 2024 using the average growth rate observed during this recent period, forecasting a production volume of approximately 2.56 million tons. This sustained trend suggests a growing national capacity to support solid biofuel markets with both domestic and export potential.

Table 6.2 – Historical and projected pellet production volumes in Brazil (2017–2024)

Year	Production volume (mTon)	Source
2017	0.47	Garcia et. al (2022)
2018	0.51	Garcia et. al (2022)
2019	0.70	Garcia et. al (2022)
2020	0.82	Garcia et. al (2022)
2021	1.08	ABIPEL
2022	1.55	ABIPEL
2023	2.00	ABIPEL
2024	2.56*	*Forecast

When assessing the potential economic return from avoided carbon emissions (Figure 6.7), the impact of the methodological choices for NEAA calculation becomes even more evident. The estimation incorporated not only the unit prices per decarbonization credit under two pricing benchmarks— (Souza et al., 2025)—but also the total number of eligible CBIOs generated for each methodological approach to estimate NEEA. The CFF approach, which accounted for 6.2 million tCO_2e in credits, produced the highest revenue potential: approximately USD 71.5 million under the agricultural carbon pricing scenario and USD 103.9 million using the ethanol-based CBIO benchmark index. The standard NEEA, which yielded 3.1 million tCO_2e, resulted in revenue estimates of USD 35.8 million (Souza et al., 2025) and USD 52 million (ethanol benchmark). Meanwhile, the zero-burden assumption to the agricultural stage, with 3.4 million tCO_2e, generated intermediate returns of USD 40 million and USD 58 million, respectively. These updated pictures point out the economic relevance of methodological assumptions in quantifying emission reductions and the significant economic potential of solid biofuels as a decarbonization strategy. However, the variance in outcomes underscores the influence of methodological assumptions on credit quantification. This aligns with earlier findings that emphasize the role of harmonized and transparent carbon accounting practices to avoid discrepancies in market mechanisms (Feijoo et al., 2019).

Figure 6.7 - Estimated revenue from avoided emissions and CBIOs under different methodological approaches



Despite the absence of a dedicated regulatory pathway for solid biofuels in current Brazilian decarbonization programs, such as RenovaBio, these results highlight a compelling case for their inclusion. Solid biofuels present distinct advantages: high substitution potential for fossil fuels in industrial and energy sectors, compatibility with waste-based feedstocks, and scalability in the national context. As emphasized by Aguiar et al., (2024), expanding the scope of eligible technologies and feedstocks can support greater decarbonization while leveraging Brazil's comparative advantages in biomass production. Also, the VCM presents additional opportunities for solid biofuels. The Brazilian VCM (IBMVC, 2025) aims to scale high-integrity carbon credits, facilitating Brazil's and global net-zero commitments. Pellet producers can access to this market by generating verified emission reductions, attracting investments, and fostering sustainable practices.

Regarding the energy dynamics of ethanol production, the expansion of corn ethanol in Brazil has led to increased energy demand at biorefineries, which rely heavily on both thermal and electrical energy to power fermentation, distillation, and drying stages. Despite achieving a 24% reduction in energy inputs between 2005 and 2019, corn ethanol plants still consume approximately 25,000 BTU per gallon of ethanol produced (Gerrior et al., 2022). Within this context, pellets derived from biomass residues such as corn stover or regionally available feedstocks represent a viable substitute for fossil fuels in supplying this thermal demand. Integrating pellets into the energy matrix of ethanol facilities—especially during high-load processing periods—would reduce dependence on fossil-derived energy and enable further emission reductions to increase CBIOs generation. This substitution could also be eligible for carbon credits in RenovaBio and under VCM while aligning with circular bioeconomy strategies by reinserting residual biomass into the same productive chain that generated it.

Furthermore, the development of a robust pellet sector may provide transformative opportunities for small and medium enterprises involved in biomass harvesting, processing, and distribution. By generating and selling carbon credits, these companies could diversify their revenue streams, invest in cleaner technologies, and promote sustainable land use practices. In socio-economic terms, this transition is likely to generate jobs, support skills development, and improve livelihoods in rural areas, aligning with broader goals for inclusive development (Silva et al., 2024).

In summary, integrating solid biofuels into Brazil's decarbonization policies—including participation in VCM and the use of biomass residues from corn ethanol production—presents a multifaceted opportunity. It supports emission reduction targets, fosters economic growth, and promotes social development, particularly among small companies and rural populations. Regulatory adaptation and methodological standardization will be essential to unlock this sector's full potential to contribute to Brazil's decarbonization agenda.

6.4. CONCLUSION

This manuscript addressed critical methodological and policy-related gaps in the integration of solid biofuels into carbon credit markets through the development and application of the BioCalc tool. By adapting the existing RenovaCalc model to solid biofuels and applying a life cycle assessment framework, this research demonstrated the technical feasibility, environmental relevance, and economic potential of including pellets in decarbonization strategies for Brazil. BioCalc enabled the quantification of carbon intensity and the eligibility for decarbonization credit generation, offering a standardized and transparent methodology applicable to regulatory and VCM perspectives.

The results showed that solid biofuels—especially those derived from residual biomass such as forestry and peanut shells residues—present a substantial capacity to reduce greenhouse gas emissions, reaching impact reductions of up to 97% compared to fossil fuels in certain scenarios. Furthermore, the comparative evaluation of three methodological approaches (NEEA, Circular Footprint Formula, and Zero-Burden) revealed significant variation in the estimated decarbonization potential and associated revenues, ranging from approximately USD 35.8 million to USD 103.9 million per year, depending on the biomass source and CBIOs calculation method. These discrepancies underscore the importance of methodological harmonization to ensure fair, transparent, and effective carbon accounting within emerging biofuel credit systems.

Beyond methodological contributions, this study offers relevant insights into policy development. The current regulatory framework in Brazil, while advanced in liquid biofuels, lacks dedicated provisions for solid biofuels. The evidence presented supports the urgent need to expand RenovaBio and the Brazilian Emissions Trading System to incorporate densified biomass fuels. The findings also highlight the synergies between bioenergy deployment and the principles of the circular bioeconomy, including waste valorization, cascading biomass use, and regional socioeconomic development.

Additionally, the proposed BioCalc tool can serve as a valuable decision-support mechanism for small and medium enterprises, public authorities, and private investors by providing robust, policy-aligned data on carbon mitigation outcomes. In particular, the integration of pellets into ethanol production chains—replacing fossil-based thermal energy sources—presents a concrete opportunity to enhance energy circularity and reduce lifecycle emissions within Brazil's biofuel industry.

In sum, this research contributes to the scientific and practical foundations for expanding the role of solid biofuels in climate mitigation policies. It proposes an actionable framework for credit generation based on transparent and replicable LCA methods, strengthens the alignment between environmental policy and circular economy principles, and reinforces the strategic relevance of Latin American biomass resources in the global energy transition. BioCalc contributes to this by offering a regionally adapted method for integrating solid biofuels into decarbonization markets.

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FINAL CONSIDERATIONS

This project was designed to develop a life cycle-based methodological framework and computational tool capable of quantifying the carbon intensity and decarbonization credit potential of solid biofuels, specifically pellets and briquettes, produced in Latin American countries (LAC). Grounded in the principles of the Circular Bioeconomy and Life Cycle Assessment (LCA), the central objective was to adapt and extend the logic of the RenovaCalc system to the context of densified biomass fuels, considering their unique technological routes, feedstock characteristics, and logistical configurations.

In alignment with this objective, the research successfully delivered both conceptual and practical outcomes. The study began by identifying a critical gap in the regulation and quantification of solid biofuels within national and international carbon market frameworks. Through a comprehensive bibliographic and legislative review (Chapter 2), the research mapped 37 policies from five continents, revealing that while liquid biofuels are widely regulated, solid biofuels remain largely overlooked, especially in LAC. This finding justified the need for a methodological instrument tailored to their characteristics and policy recognition.

Methodologically, the thesis provided robust evidence that the choice of LCA modeling assumptions, including allocation methods, waste treatment strategies, and circularity principles, substantially affects the estimated carbon intensity of solid biofuels. Chapter 3 highlighted that the Circular Footprint Formula (CFF), although offering a harmonized framework aligned with European Commission guidelines, may underestimate environmental burdens in specific cases due to limited consideration of biochemical flows. Conversely, conventional allocation methods can lead to over- or underestimation of emissions depending on the input-output structure of the production system.

Chapter 4 contributed a regionalized analysis by modeling transport-related emissions in biomass export chains from LAC to Europe. The results demonstrated that transport can represent up to 30–40% of the total Global Warming Potential (GWP) in some scenarios, particularly when intermodal chains are inefficient or dependent on fossil-intensive modes. These findings underscore the need to include logistical variables when designing credit attribution systems or establishing national decarbonization targets.

Chapters 5 and 6 constituted the core technical contribution of the thesis, the development and validation of BioCalc, a novel computational tool designed to estimate the carbon intensity of densified biofuels and simulate their credit generation potential based on avoided emissions. The tool was parameterized based on the structure of RenovaCalc and adapted through a modular architecture that allows the inclusion of additional impact factors, circularity metrics, and regional datasets. Case studies modeled with BioCalc demonstrated that the carbon intensity of solid biofuels varies significantly depending on the methodological approach and specific production conditions. These differences led to substantial variations in the estimation of decarbonization credits, with total avoided emissions ranging from approximately 3.1 to 6.2 million tCO_2e per year. When converted into financial terms using current carbon pricing benchmarks, the potential revenue associated with these credits was estimated between USD 35.8 million and USD 103.9 million annually. These findings underscore the considerable economic implications of methodological choices in carbon accounting and reinforce the importance of transparent and harmonized frameworks for credit generation.

The original contributions to the field of environmental engineering and sustainable energy policy are threefold. First, it fills a methodological gap by adapting an LCA-based quantification approach to a class of biofuels not currently covered by major carbon crediting systems. Second, it integrates policy analysis and technical modeling, offering a rare interdisciplinary perspective that bridges regulatory frameworks and LCA modeling tools. Third, it introduces BioCalc, a flexible and replicable tool that can be applied in policy design, credit validation, or market simulations involving solid biofuels.

From a practical perspective, the findings of this thesis provide technical inputs for potential future inclusion of solid biofuels in programs like RenovaBio or the Brazilian Emissions Trading System (SBCE). The quantification of avoided emissions and credit generation potential offers concrete economic insights for producers, policymakers, and market agents. Also, the research provides a transparent basis for sustainability certification schemes and voluntary carbon market participation.

From a theoretical standpoint, this work advances the application of Circular Economy principles in LCA and contributes to ongoing discussions about methodological harmonization in environmental footprinting. It critically evaluates the suitability of emerging metrics (e.g., CFF) in non-European contexts and proposes adjustments that can make such methods more robust and globally applicable.

However, the research also presents limitations that must be acknowledged. The case studies, although representative, were geographically limited to Brazil and based partially on secondary data, which may not capture all regional production specificities. Additionally, the modeling did not include social or health-related impact categories, which are increasingly relevant in sustainability assessments of bioenergy systems. The current version of BioCalc focuses exclusively on climate-related impacts, and its scope could be expanded in future iterations to include water, resource depletion, and biodiversity indicators.

Based on the outcomes and identified gaps, the thesis recommends several directions for future research. These include (1) expanding the geographical scope of BioCalc applications to other Latin American countries; (2) integrating dynamic data updates for energy matrices and emission factors; (3) coupling the tool with socio-economic impact modules; and (4) testing its application within real carbon market operations, such as pilot projects in the SBCE or in the voluntary credit sector. It is also recommended that further work be conducted to define standardized methodological rules for solid biofuels within international climate frameworks, particularly under the emerging carbon market mechanisms established by Article 6 of the Paris Agreement, which are intended to succeed the former Clean Development Mechanism.

In conclusion, the findings presented offer substantial contributions to the advancement of solid biofuels as a legitimate and quantifiable solution for climate mitigation. By integrating robust life cycle modeling, policy analysis, and computational innovation, the work sets a precedent for how methodological transparency and circular economy principles can enhance the environmental and market visibility of solid bioenergy systems. It delivers not only a practical tool for carbon credit estimation but also a strategic framework for positioning solid biofuels within the broader context of sustainable energy transitions.

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APPENDIX

Table 1 - Life cycle emissions of inputs and other upstream processes

Input	Unit	Emission factor (kg CO_2 eq./unit)	Data source
Biomass (production)			
Pinus residue	kg	2,51E-02	ecoinvent 3.9.1
Eucalyptus residue	kg	2,51E-02	ecoinvent 3.9.1
Eucalyptus charcoal	kg	1,76E+00	ecoinvent 3.9.1
Peanut shell	kg	6,66E-01	ecoinvent 3.9.1
Virgin eucalyptus	kg	1,04E-01	ecoinvent 3.9.1
Virgin pine	kg	4,22E-01	ecoinvent 3.9.1
Corn starch	kg	1,20E+00	ecoinvent 3.9.1
Biomassas (combustão)			
Pinua residue	kg	1,97E+00	IPCC (2006)
Eucalyptus residue	kg	1,97E+00	IPCC (2006)
Eucalyptus charcoal	kg	1,88E+00	IPCC (2006)
Peanut shell	kg	1,74E+00	IPCC (2006)
Virgin eucalyptus	kg	1,97E+00	IPCC (2006)
Virgin pine	kg	1,97E+00	IPCC (2006)
Eletricity			
Grid electricity – medium voltage mix	kWh	5,02E-01	ecoinvent 3.9.1
Grid electricity – high voltage mix	kWh	1,29E-01	ecoinvent 3.9.1
Electricity – SHP	kWh	3,67E-02	ecoinvent 3.9.1
Electricity – biomass	kWh	1,10E-01	ecoinvent 3.9.1
Electricity – wind	kWh	1,38E-04	ecoinvent 3.9.1
Electricity – solar	kWh	8,01E-02	ecoinvent 3.9.1
Fuel (production)			
Diesel	litro	7,96E-01	ecoinvent 3.9.1
Natural gas	Nm³	3,35E-01	ecoinvent 3.9.1
LPG	kg	7,22E-01	ecoinvent 3.9.1
Gasoline A	litro	1,31E+00	ecoinvent 3.9.1
Anhydrous ethanol	litro	1,23E+00	ecoinvent 3.9.1
Hydrated ethanol	litro	6,07E-01	ecoinvent 3.9.1
Wood chips	kg	3,65E-01	ecoinvent 3.9.1
Firewood	kg	2,60E-02	ecoinvent 3.9.1
Fuel (combustion)			
Diesel combustion	litro	2,64E+00	IPCC (2006)
Natural gas use	Nm³	1,53E+00	IPCC (2006)
LPG use	kg	2,93E+00	IPCC (2006)
Gasoline A combustion	litro	2,25E+00	IPCC (2006)
Anhydrous ethanol combustion	litro	1,79E+00	IPCC (2006)

Hydrated ethanol combustion	litro	1,70E+00	IPCC (2006)
Wood chips combustion	kg	1,97E+00	IPCC (2006)
Firewood combustion	kg	1,97E+00	IPCC (2006)
Industrial inputs			
Water	litro	2,37E-05	ecoinvent 3.9.1
Lubricating oil	kg	1,51E+00	ecoinvent 3.9.1
Silica sand	kg	3,58E-02	ecoinvent 3.9.1
Transporte			
Truck transport 7.5–16t	tkm	9,37E-02	ecoinvent 3.9.1
Truck transport 16–32t	tkm	9,80E-02	ecoinvent 3.9.1
Truck transport >32t	tkm	6,11E-02	ecoinvent 3.9.1
Truck transport 60 m³	tkm	6,11E-02	ecoinvent 3.9.1
Ship transport	tkm	9,52E-03	ecoinvent 3.9.1
Barge transport	tkm	3,50E-02	ecoinvent 3.9.1
Rail transport	tkm	3,34E-02	ecoinvent 3.9.1

Table 2 – Emission rate for Land Use Change (LUC)

State (UF)	Taxa de emissão		
	Pinus (tCO_2\kgPinus)	**Eucaliptus (tCO_2\kgEucalipto)**	**Peanut (tCO_2\kgAmendoin)**
Acre	0,00E+00	0,00E+00	1,62E-04
Alagoas	0,00E+00	0,00E+00	0,00E+00
Amapá	7,72E-03	2,62E-03	1,00E-04
Amazonas	0,00E+00	0,00E+00	0,00E+00
Bahia	-5,90E-04	-2,00E-04	0,00E+00
Ceará	0,00E+00	0,00E+00	1,95E-04
Distrito Federal	-1,19E-03	-4,04E-04	1,49E-04
Espírito Santo	-3,40E-04	-1,15E-04	0,00E+00
Goiás	-2,09E-03	-7,09E-04	4,01E-04
Maranhão	8,73E-03	2,96E-03	0,00E+00
Mato Grosso	-2,29E-03	-7,77E-04	9,26E-04
Mato Grosso do Sul	-2,65E-03	-8,99E-04	2,43E-04
Minas Gerais	3,80E-04	1,29E-04	1,42E-04
Pará	1,22E-02	4,15E-03	1,71E-04
Paraíba	-4,43E-03	-1,50E-03	1,59E-03
Paraná	1,00E-05	3,39E-06	6,87E-05
Pernambuco	-4,06E-03	-1,38E-03	1,30E-04
Piauí	-1,45E-03	-4,92E-04	4,58E-05
Rio de Janeiro	3,79E-03	1,29E-03	1,52E-04
Rio Grande do Norte	0,00E+00	0,00E+00	0,00E+00
Rio Grande do Sul	5,00E-04	1,70E-04	0,00E+00
Rondônia	1,58E-02	5,36E-03	1,56E-04
Roraima	1,12E-02	3,79E-03	5,81E-04
Santa Catarina	1,47E-03	4,99E-04	0,00E+00
São Paulo	-4,80E-04	-1,63E-04	1,41E-04
Sergipe	-3,09E-03	-1,05E-03	1,74E-04
Tocantins	9,16E-03	3,11E-03	2,00E-04

Fonte: BRLUC 2.0

* Production time and yield of each crop based on data from CONAB (2024).

Table 3 - Emission factors for biofuel combustion in boilers

Solid biofuel	**kg** CO_2 **eq/MJ**	**Reference**
Pinus pellet/briquette	0,000369	IPCC (2006) apud RenovaCalc
Eucalyptus pellet/briquette	0,000369	IPCC (2006) apud RenovaCalc
Eucalyptus charcoal	0,119052	ecoinvent 3.9.1
Peanut shell pellet/briquette	0,000373	ecoinvent 3.9.1
Virgin eucalyptus pellet/briquette	0,000369	IPCC (2006) apud RenovaCalc
Virgin pine pellet/briquette	0,000369	IPCC (2006) apud RenovaCalc

Table 4 – Carbon intensity of equivalent fossil fuels

Equivalent fossil fuel	**Total carbon intensity of substitute fuel (kg CO_2 eq./MJ)**	**Reference**
Weighted average: Diesel A, Gasoline A, and CNG	0,0867	GHG Protocol, 2012
Petroleum coke	0,120	Resolução ANP nº 894/2022
Heavy fuel oil (HFO)	0,094	Resolução ANP nº 894/2022

Table 5 – Lower heating value (LHV) of biomass sources

Biomass source	LHV		Reference
	g/MJ	MJ/kg	
Pine residue	53.19	18.8	Matheus et al. (2024)
Eucalyptus residue	63.29	15.8	Matheus et al. (2024)
Eucalyptus charcoal	63.29	15.8	Matheus et al. (2024)
Peanut shell	58.48	17.1	Perea-Moreno et al. (2018)
Virgin eucalyptus	63.29	15.8	Farrapo Jr. et al. (2023)
Virgin pine	53.19	18.8	Farrapo Jr. et al. (2023)

Table 6 – Global warming potential (GWP) of greenhouse gases

Greenhouse gas	GWP kg CO_2eq/kg	Reference
CO_2 – Fossil carbon dioxide	1,0	AR6 (IPCC, 2021)
CH_4 – Fossil methane	29,8	AR6 (IPCC, 2021)
CH_4 – Biogenic methane	27,2	AR6 (IPCC, 2021)
N_2O – Nitrous oxide	273,0	AR6 (IPCC, 2021)