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PROGRAMA INTEGRADO (UNESP, USP E UNICAMP) DE PÓS-GRADUAÇÃO EM BIOENERGIA

INITIATIVES TO DECARBONISING THE BEVERAGE AND FOOD PACKAGING VALUE CHAIN: THE CARTON PACKAGE CASE

JULIANA CAMPOS AMORIM

Rio Claro – SP
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Tese apresentada ao Instituto de Pesquisa em Bioenergia de Rio Claro, Universidade Estadual Paulista, como parte dos requisitos para obtenção do título de Doutor em Ciências.

Orientador: Prof. Dr. Humberto de Jesus Eufrade Junior

Co-orientador: Prof. Dr. Saulo Philipe Sebastião Guerra

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ABSTRACT

The increase in greenhouse gas (GHG) emissions, such as CO_2, CH_4, and N_2O, since the Industrial Revolution has raised global temperatures and intensified extreme weather events. Agrofood systems account for approximately 31% of these emissions, and the growing demand for food due to population growth underscores the need for mitigation efforts. The food production chain encompasses pre- and post-production stages, as well as the packaging industry. An example of sustainable packaging with significant environmental attributes is the carton package, composed of approximately 75% paperboard, 20% polyethylene, and 5% aluminum. It has a high renewable content and an established recycling process. In terms of emissions, only 1% originate from direct operations, while 31% are generated during the production of the materials used in the packaging, and 7% come from its final disposal. To enhance the sustainability attributes of carton packaging, the objective of this thesis was to explore decarbonization strategies within its value chain, specifically: (1) in the raw materials used to produce the packaging, particularly the paper, by investigating carbon sequestration in *Eucalyptus spp*. forest plantations; and (2) in the end-of-life phase, focusing on the recycling process byproducts. Since 75% of carton packaging is composed of paper derived from eucalyptus and pine fibers, Chapter 1 focused on alternatives to enhance carbon sequestration in eucalyptus plantations, analyzing data from 448 planting plots in Brazil and Australia through a multivariate analysis. In Australia, *Eucalyptus* species grow slowly in their early years and accelerate after 5–10 years, while in Brazil, carbon accumulation peaks between 4–6 years and then declines. Carbon stock showed a stronger correlation with elevation and precipitation than temperature in both regions, highlighting the need for localized management strategies. Chapters 2 and 3 investigated the recycling process of carton packaging, seeking alternatives for the plastic-aluminum residue currently sent to landfills. Chapter 2 characterized the residue, highlighting its potential for energy recovery, with a useful heating value of 15.76 MJ/kg after 60 days of covered drying and an optimal degradation range between 400°C and 550°C. Classified as non-hazardous (Class II A), the residue is viable as Refuse-Derived Fuel (RDF) and for biochar production via pyrolysis. Chapter 3 explored the pyrolysis of the residue at temperatures between 450°C and 750°C, including co-pyrolysis with 75% wood chips from *Eucalyptus urophylla* × *Eucalyptus grandis*. Co-pyrolysis at 750°C significantly enhanced the biochar's properties, increasing fixed carbon content and useful energy (27.30 MJ/kg), while also providing nutrients such as calcium, magnesium, and potassium, showing potential use for agricultural applications. The findings underscore co-pyrolysis as a sustainable strategy for waste valorization. This study contributes to decarbonization strategies in the carton packaging value chain, aiming to reduce GHG emissions both at the beginning of the chain, during raw material production, and at the end, in the recycling process.

Keywords: eucalypt plantations, carbon accumulation, carton package, pyrolysis, bioenergy.

RESUMO

O aumento das emissões de gases de efeito estufa (GEE), como CO2, CH4 e NO2, desde a Revolução Industrial, tem elevado a temperatura global e provocado eventos climáticos extremos. Os sistemas agroalimentares respondem por cerca de 31% dessas emissões, e a crescente demanda por alimentos devido ao aumento populacional exige esforços para reduzi-las. A cadeia produtiva alimentícia inclui etapas de pré e pós-produção, além da indústria de embalagens. Um exemplo interessante de embalagem com fortes atributos de sustentabilidade é a embalagem cartonada, composta por aproximadamente 75% de papel cartão, 20% de polietileno e 5% de alumínio, com alto conteúdo renovável e um processo de reciclagem consolidado. Em relação às emissões, somente 1% provêm da operação direta, enquanto 31% são gerados no processo produtivo dos materiais que compõe a embalagem, e 7% das emissões em sua destinação final. Para potencializar os atributos de sustentabilidade da embalagem cartonada, o objetivo desta tese foi explorar estratégias de descarbonização em sua cadeia de valor, mais especificamente (1) nas matérias-primas utilizadas para produzir a embalagem, em particular na produção de papel, buscando compreender o acúmulo de carbono na madeira de plantações florestais de *Eucalyptus* spp.; e (2) na destinação final embalagem, nomeadamente nos resíduos produtivos do processo de reciclagem. Como 75% da embalagem cartonada é composta por papel, que é produzido a partir das fibras de eucalipto e pinus, o Capítulo 1 focou em alternativas para potencializar a captura de carbono em plantios de eucalipto, analisando dados de 448 parcelas de plantio do Brasil e da Austrália, em uma análise multivariada. Na Austrália, as espécies de Eucalyptus crescem lentamente nos primeiros anos e aceleram após 5-10 anos, enquanto no Brasil a concentração de carbono atinge o máximo entre 4-6 anos e depois declina. O estoque de carbono mostrou maior correlação com elevação e precipitação do que com a temperatura em ambas as regiões, evidenciando a necessidade de estratégias de manejo localizadas. Os Capítulos 2 e 3 investigaram o processo de reciclagem de embalagens cartonadas, buscando alternativas para o resíduo gerado no processo de reciclagem do plástico-alumínio, que hoje é destinado a aterros. O Capítulo 2 caracterizou o resíduo, destacando seu potencial para recuperação energética, com poder calorífico útil de 15,76 MJ/kg após 60 dias de secagem em local coberto, e degradação ideal entre 400°C e 550°C. Classificado como não perigoso (Classe II A), é viável como Combustível Derivado de Resíduos (CDR) e para produção de carvão através da pirólise. O Capítulo 3 investigou a pirólise do resíduo entre 450°C e 750°C, incluindo co-pirólise com 75% de cavacos de madeira de *Eucalyptus urophylla x Eucalyptus grandis*. A co-pirólise a 750°C melhorou significativamente as propriedades do carvão, aumentando o teor de carbono fixo e a energia útil (27,30 MJ/kg), além de fornecer nutrientes como cálcio, magnésio e potássio, destacando seu potencial uso para aplicações agrícolas. Os resultados evidenciaram a co-pirólise como estratégia sustentável para valorização de resíduos. O presente trabalho contribui com estratégias para a descarbonização da cadeia de valor das embalagens cartonadas, visando reduzir as emissões de gases de efeito estufa tanto no início da cadeia, na produção da matéria-prima, quanto no final, no processo de reciclagem.

Palavras-chave: plantações de eucalipto, captura de carbono, embalagem cartonada, pirólise, bioenergia.

SUMÁRIO

GENERAL INTRODUCTION

Since the industrial revolution in 1850, the amount of greenhouse gases into the atmosphere, such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (NO_2) has increased considerably, leading to an increase in the average global temperature and the occurrence of extreme and unpredictable weather events, known as climate change (SHIVANNA, 2022). The global average surface temperature has been warmed by 1.09°C compared to pre-industrial levels, and the last four decades were the warmest ones since 1850. If the emissions rate remains the same, the global temperature can rise by 2.7°C until 2100 (MASSON-DELMOTTE *et al.*, 2021).

As climate change is a global issue, its solution involves actions that countries must take jointly. A series of global meetings called Conference of Parties (COPs), organized by the UNFCCC (The United Nations Framework Convention on Climate Change), has been realized, and international treaties have also been signed over the years (MARTINE; ALVES, 2019).

The main treaty was the Kyoto Protocol, signed in 1997, which established the responsibility of developed countries that contribute more to greenhouse gas emissions to mitigate and reduce their emissions (OKEREKE, 2010). Regarding the global meetings, a total of 25 COP meetings have been held, and the 21st Conference of Parties (COP 21), held in Paris in 2015, was the only one to achieve any meaningful action on climate change (MARTINE; ALVES, 2019). The Paris Agreement, signed in December 2015 and binding as of November 2016, established that the global average temperature should be well below 2°C, being 1.5°C the safer limit, above pre-industrial levels (IPCC, 2021).

Besides that, the Sustainable Development Goals (SDGs), established by the United Nations, were adopted in 2015, involving 17 goals and 169 targets dealing with a wide range of issues, including environmental protection and climate change (MARTINE; ALVES, 2019). Specifically, SDG number 13, with the goal "Take urgent action to combat climate change and its impacts," has specific targets to implement the commitment undertaken by developed countries that are parties to the UNFCCC towards the goal of jointly mobilizing US$ 100 billion per year from 2020, from all sources, to meet the needs of developing countries, in the context of significant mitigation actions; and fully operationalize the Green Climate Fund by capitalizing it as soon as possible (CAMPBELL *et al.*, 2018).

In 2019, human activities contributed to 54 billion tonnes of carbon dioxide equivalent (CO2eq) emissions to the planet. Within this total, agri-food systems accounted for 17 billion tonnes CO_2eq, corresponding to approximately 31% of the overall emissions (FAO, 2021). The most recent projections from the United Nations showed that the global population will reach approximately 8.5 billion by the year 2030, 9.7 billion by 2050, and 10.4 billion by 2100 (UNITED NATIONS, 2021). The disparity between the quantity of food produced in 2010 and the quantity required to fulfil anticipated demand by 2050 is about 7,400 trillion calories, equivalent to a 56% increase in global food demand.

The projected difference between the annual GHG emissions expected from agriculture and land-use change in 2050 is estimated to be 15 gigatons of CO_2e. To keep global warming below 2°C above pre-industrial temperatures, the target of 4 gigatons of CO_2eq has been set as agriculture's proportional contribution; the estimated gap is 11 gigatons of CO_2e (SEARCHINGER *et al.*, 2019).

Besides the agricultural production, the food system includes both pre- and post-production processes, which encompass the transportation, industrial activities, storage, and food consumption (ROSENZWEIG *et al.*, 2020). In this sense, there are several transformation domains within food systems that can contribute to bridging the emissions gap, including decarbonizing the food supply chain by implementing measures to mitigate emissions in retail, transportation, fuel usage, industrial processes, waste management, and packaging within the food industry (UNEP, 2022). In May 2023, 5,667 companies have established or committed to developing science-based targets, that comprise well-defined business actions to reduce GHG emissions, being 355 of them from the food and beverage sector and 148 from the containers and packaging sector (SBT, 2023)

The packaging industry in Brazil has increased over the years, presenting positive results in production for the third consecutive year. It grew by 3.9% in 2022, before the growth of 3.11% in 2021 and 0.5% in 2020. It reached the gross value of physical packaging production of R$ 123.2 billion, generating 244,836 job positions in 2022. Besides that, direct exports had revenues of USD 738.1 million, and imports moved a total of USD 648.4 million (ABRE, 2023).

Paper and cardboard packaging stand out with 34% of the sector, followed by plastic (33.6%) and metallic (20.8%). Food and beverage packaging are the primary users (ABRE, 2023). Food and beverage packaging is fundamental to protecting food quality and safety from environmental, physical, and chemical factors and extending a product's shelf life (BUMBUDSANPHAROKE, 2019). The design of this type of packaging, including the selection of the material, is essential to satisfy the food protection and reduce environmental impacts (GHENAI, 2012).

In this sense, one type of packaging that deserves attention is the carton package, an aluminum–kraft paper–plastic laminate packaging, used for milk, plant-based beverages, juice, nectars, and other beverages and foods (SIDDIQUI, 2020). Composed for approximately 75% of paperboard paper, 20% of polyethylene, and 5% of aluminum (SIDDIQUI, 2020), this aseptic packaging allows products to have a shelf life of at least 3-6 months without refrigeration, facilitating its distribution and storage (REJEESH, 2023). And besides protecting food, this packaging features key sustainability attributes, such as high renewable content and a validated recycling process (TETRA PAK, 2021).

The results of a meta-analysis on selected studies indicate that beverage cartons have a significantly lower global warming potential (measured in gram CO_2 equivalents) compared to PET bottles, single-use glass bottles and reusable glass bottles. On average, beverage cartons have a median of 83 g CO_2eq per liter, while reusable glass bottles have a median of 100 g CO_2eq per liter, PET bottles 156 g CO_2eq per liter, and single-use glass bottles have the highest median of 430 g CO_2eq per liter (WOHNER; TACKER, 2020).

Beverage cartons outperform mainly due to their efficient packaging and transportation, as well as their predominant use of renewable materials. However, it is essential to acknowledge that the analyzed studies showed considerable variations in multiple parameters, such as the modeling of biogenic carbon, assumptions about recyclability, and recycling rates (WOHNER; TACKER, 2020).

One of the largest producers of this type of packaging disclosed in its sustainability report that only 1% of its GHG emissions comes from its own operation, while 31% comes from the purchased materials and other upstream, including the emissions of the raw materials, and 7% from the end-of-life emissions, which comprises the final destination of the packaging (TETRA PAK, 2023).

The objective of this thesis was to further explore the sustainability attributes of the carton package by identifying opportunities to reduce the carbon emissions throughout the value chain, helping to promote a climate resilient economy in Brazil. Strategies to reduce emissions will be studied (1) upstream, in the raw materials used to produce the package, particularly in paper production, seeking to understand the accumulation of carbon in wood from forest plantations of *Eucalyptus spp*.; and (2) downstream, in the packaging end of life, focusing in the productive residues of the recycling process.

Chapter 1 will focus on carbon reduction alternatives for the raw materials used in the package. As 75% of the carton package is composed of paperboard, which is made from a mix of wood fibers from eucalyptus and pine trees in approximately a 50:50 mass proportion, carbon reduction efforts should be centered on that. Eucalyptus trees provide short-fiber pulp, which enhance absorption and softness. Pine trees, on the other hand, yield long-fiber pulp, which confer strength and durability (FOELKEL, 1975). Therefore, this chapter will be intended to understand the major drivers of carbon accumulation in eucalypt plantations, since by adopting best practices at this stage, carbon emissions reduction will be happening from the beginning. As eucalyptus is originally from Australia, this chapter brought comparisons between Brazilian and Australian eucalyptus plantations, enabling the adoption of broader strategies, beyond the Brazilian scope.

Chapter 2 will focus on the end-of-life stage of the carton package, exploring strategies to improve the recycling process and reduce GHG emissions. Currently, the plastic-aluminum residue generated during the recycling process is sent to landfills, representing an untapped opportunity for sustainability gains. This chapter will investigate the characterization of this residue, analyzing its physical, chemical, structural, and thermal properties to identify its potential for energy recovery. By understanding the composition and behavior of this material, alternative uses such as Refuse-Derived Fuel (RDF), contributing to a circular economy and minimizing environmental impacts.

Chapter 3 will delve deeper into the potential valorization of the plastic-aluminum residue through pyrolysis, a thermal decomposition process. The chapter will examine pyrolysis at various temperatures, including co-pyrolysis with wood chips from *Eucalyptus urophylla* × *Eucalyptus grandis*, to assess the properties of the resulting biochar. The findings from this chapter will demonstrate how co-pyrolysis can enhance biochar properties, increasing its energy content and nutrient availability. By focusing on this innovative approach, Chapter 3 will highlight how waste valorization at the end-of-life stage can significantly contribute to decarbonization efforts and sustainable waste management.

FINAL CONSIDERATIONS

This work has outlined pathways to be taken concerning the decarbonization of the carton package value chain. In Chapter 1, it was observed that the increase in carbon capture in *Eucalyptus* spp. plantations is strongly influenced by rainfall, mean annual temperature and elevation, highlighting the need for locally adapted forest management considering a relationship between multiple variables. By enhancing carbon sequestration, emissions reduction in the paper production chain occurs from the outset, with positive impacts on sustainable forestry practices. In Chapters 2 and 3, strategies for valorizing the waste generated during the recycling process of carton packaging were examined. With a recycling rate of 39.1% and high renewable content, this improvement in the recycling process further contributes to the circular economy perspective and the sustainable attributes of packaging. In Chapter 2, the great potential of the waste generated by the packaging for energy recovery was identified, with favorable carbon and volatile content and low environmental risk, suggesting its use as Refuse-Derived Fuel (RDF). In Chapter 3, the results showed that the pyrolysis of the waste generated in the recycling process is feasible, and co-pyrolysis at 750°C significantly improved the biochar properties, increasing fixed carbon content and energy retention (UHV = 27.30 MJ/kg). Furthermore, the charcoal generated provided essential nutrients, such as calcium, magnesium, and potassium, making it suitable for agricultural applications. These results highlight co-pyrolysis as a sustainable strategy for waste valorization, contributing to increased soil organic carbon (SOC) levels and advancing decarbonization efforts.

As a suggestion for future work, co-pyrolysis at other temperatures (450°C and 550°C) could be evaluated, including altering the percentage of *Eucalyptus urophylla* × *Eucalyptus grandis* wood chips (25%, 50%, and 75%) to determine which configuration most favors the application of the waste, whether for energy recovery or agricultural use as biochar. Furthermore, it is crucial to analyze the form of aluminum element is available in the soil with the application of biochar, as well the the gases generated during the pyrolysis process, focusing on their composition and potential environmental impacts. This analysis is essential for ensuring environmental safety and advancing the understanding of the process as a sustainable waste valorization strategy.

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