UNIVERSIDADE ESTADUAL PAULISTA
"JÚLIO DE MESQUITA FILHO"
INSTITUTO DE PESQUISA EM
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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

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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.

Drivers of carbon stock in eucalypt plantations: A multivariate analysis and prediction models for Australian and Brazilian experiments

(Article submitted to the journal New Forests, with formatting preserved in this Chapter 1)

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Abstract

To understand the drivers of carbon uptake in eucalypt plantations in Australia and Brazil, we conducted a multivariate analysis using data from 448 planting plots, considering factors such as longitude, latitude, elevation, age, rainfall, temperature, and carbon stock. Brazil and Australia were chosen because Brazil hosts extensive eucalyptus plantations, while Australia, the tree's native region, offers a unique basis for comparison. Our findings revealed that Brazilian eucalyptus plantations exhibited a higher average carbon stock compared to Australian ones, with values of 9.89 MgC $ha^{-1}yr^{-1}$ and 5.91 MgC $ha^{-1}yr^{-1}$, respectively. Additionally, for every 100 mm yr^{-1} increase in rainfall, there was a mean carbon stock increase of 0.744 MgC $ha^{-1}yr^{-1}$ in Brazil and 0.356 MgC $ha^{-1}yr^{-1}$ in Australia. Rainfall, mean annual temperature and elevation showed a strong correlation with carbon stock in the multivariate analysis for both countries. The observed variations in species compositions across the dataset underscore the importance of implementing tailored management strategies to optimize carbon uptake in eucalyptus plantations. These findings provide valuable insights for enhancing carbon sequestration in eucalyptus planting sites, contributing to more effective climate change mitigation effort.

Keywords: principal component analysis; GAM models; carbon uptake; stemwood biomass.

1.1 Introduction

Despite ongoing discussions highlighting the complexities of forest plantations for climate change mitigation (Soimakallio et al. 2022; Peng et al. 2023; Kirschbaum et al. 2024), these debates address various aspects, including their carbon sequestration potential, environmental and social impacts, sustainability over the long term, comparisons with alternative strategies such as natural forest restoration, and the regional versus global applicability of plantation approaches. Even with these considerations, upstream strategies for climate change mitigation continue to promote the use of forest plantations worldwide.These strategies include the valorization of engineered wood products in urban buildings to replace steel and concrete (Mishra et al. 2022), the retention of carbon in harvested wood products or their use for bioenergy to replace fossil fuels (Gustavsson et al. 2017), and their diversification into many products, such as chemicals and biomaterials (Stafford et al. 2020; Dessbesell et al. 2020; Maximo et al. 2022).

Significant shifts in climate patterns and the occurrence of extreme and unpredictable weather events (Masson-Delmotte et al. 2021; Shivanna 2022) have raised concerns about the productivity and, consequently, the carbon sequestration capacity of forest plantations in both exotic and native locations (Gilson and Maguire 2021; Elli et al. 2020; Ryan et al. 2020). Furthermore, the emergence of pests and diseases in a forest matrix concentrated on a few commercial species makes the scenario even more alarming for meeting the demands of the forest-based industry (Pawson et al. 2013; Silva et al. 2019).

Planted forests occupy 290 million hectares worldwide, with *Eucalyptus* being one of the most widely planted genera, spanning 95 countries and more than 22.57 million hectares (FAO 2020; Zhang and Wang 2021). Originally from Australia, Tasmania, and other islands in Oceania, eucalypt was introduced to Brazil in the 19th century or earlier. However, it was only at the beginning of the 20th century, when the first scientific studies comparing eucalypt with some native species confirmed its adaptability, that commercial plantations began to meet the demand for railway sleepers and charcoal from the Paulista Railroad Company (Mora 2000).

Australia has 101 million hectares of native eucalypt forest, representing 77% of the native forest area, and 0.92 million hectares of commercial eucalypt plantations.

Most commercial plantations consist of *Eucalyptus globulus* and *Eucalyptus nitens*, managed for pulp logs on a ten to fifteen-year rotation (ABARES 2018). In Brazil, eucalypts are the most abundant planted trees, covering 7.6 million hectares, which represents 76% of the total plantation area of 9.94 million hectares. These plantations are primarily located in the states of Minas Gerais (29%) and São Paulo (13%) in the southeast region, and Mato Grosso do Sul (15%) in the Midwest region (Iba 2023). These regions have higher temperatures compared to those in Australia. The most commonly used planting densities in Brazil range between 1,100 and 1,700 plants per hectare, with rotation cycles of five to seven years (Eufrade Junior et al. 2016). The main species are *Eucalyptus urophylla* (Silva et al. 2019), either as pure species or in hybrid combinations, especially with *Eucalyptus grandis*. The primary commercial uses are for pulp and paper, wood-based panels, charcoal, and solid wood products (IBA 2023).

Carbon stock in plantations can be influenced by various factors, including species, silvicultural practices, and environmental conditions (Silveira et al. 2002). Among environmental characteristics, critical factors include temperature, soil type, elevation, relative humidity, and rainfall (Stape et al. 2004; Binkley et al. 2017; Pérez-Cruzado et al. 2011; Gatto et al. 2010; O'Brien et al. 2003). Technical and silvicultural factors such as species, stand density, and age also play a significant role (Pérez-Cruzado et al. 2011; Cook et al. 2014; Campoe and Binkley 2020).

It is crucial to deepen our understanding of the factors that enhance the carbon uptake performance of forest plantations. Conducting a systematic literature review on this topic is essential, as it consolidates current knowledge and identifies gaps in existing research, providing a foundation for targeted interventions in forest management. Recording information on species, stand structure, and growth is fundamental for planning and implementing silvicultural practices and managing forest resources (Bettinger et al. 2017; Müller et al. 2019). Therefore, this study aims to examine how the variables across these planting plots interact with carbon stock and to assess whether these relationships vary between two specific locations: Brazil and Australia. The choice of these countries is strategic—Brazil, where this study is conducted, has extensive eucalyptus plantations, while Australia is the native region of the eucalyptus, offering a unique context for comparative analysis.

1.2. Material and methods

1.2.1. Literature Search and study area description

The search was conducted on scientific databases and open research institute reports, encompassing publications from January 1989 to April 2021. Brazilian studies were sourced from indexed journals in the Scopus database, using the search terms "carbon sequestration," "carbon stock," "carbon uptake," "carbon accumulation," "eucalypt plantation," and "Brazil," considering articles in both English and Portuguese. The Brazilian studies considered planting ages ranging from 1 to 10 years (de Jesus and Brouard 1989; Bernardo et al. 1998; Fernandez et al. 2000; Stape et al. 2004; Hubbard et al. 2010; Marsden et al. 2010; Stape et al. 2010; Campoe et al. 2012; Campoe et al. 2013; Le Maire et al. 2013; Ribeiro et al. 2015; Silva et al. 2015a, b; Campoe et al. 2016; Eloy et al. 2016; Binkley et al. 2017; Castro et al. 2017; Ribeiro et al. 2017; Viera et al. 2017; Simetti et al. 2018; Dos Santos et al. 2019; Viera and Rodríguez-Soalleiro 2019; Eufrade-Junior et al. 2020; Lima et al. 2020; Rocha et al. 2020; São José et al. 2020; Valadão et al. 2020; Watzlawick et al. 2020; Araujo et al. 2021; Dai et al. 2021; Eufrade-Junior et al. 2021). For Australian contributions, data were obtained from large open forestry research reports (Johnson and Stanton 1993; Lee et al. 2011a), focusing on planting plots with a relatively good latitude overlap with Brazil, considered planting ages ranging from 4 to 21 years. Figure 1 shows all the locations where planting plots were identified in the articles studied. In the same location, more than one experiment may have been conducted.

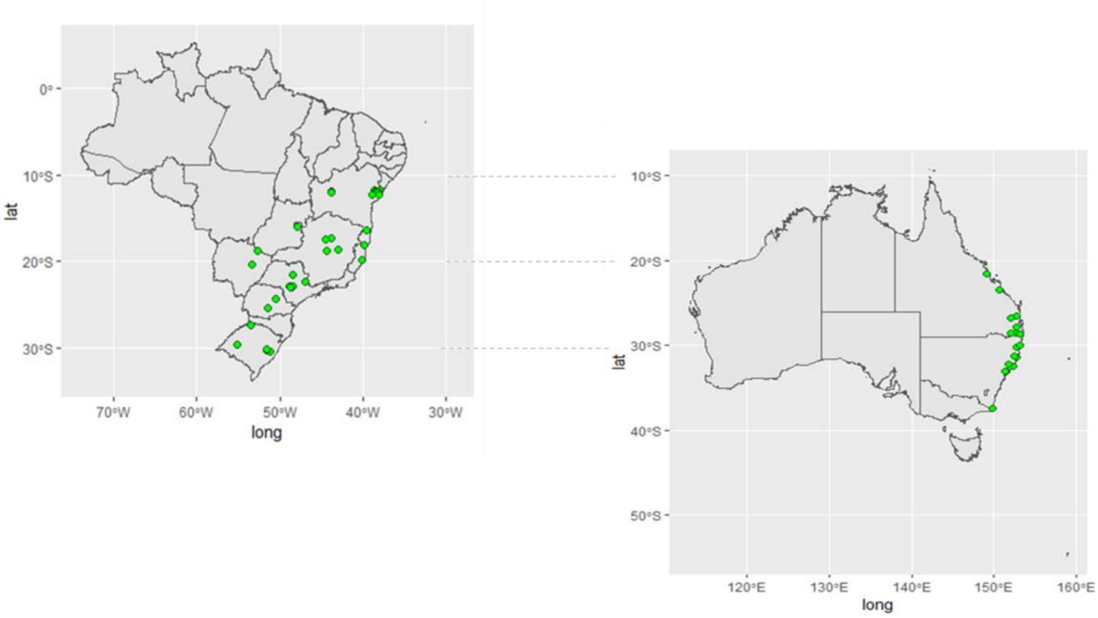


Fig. 1 Brazilian and Australian planting plots locations.

A total of 164 planting plots were evaluated across eight Brazilian states: Bahia, Distrito Federal, Espírito Santo, Minas Gerais, Mato Grosso do Sul, Paraná, Rio Grande do Sul, and São Paulo. These planting plots spanned 24 sites and included 12 different Eucalyptus species and hybrids. The most representative were *Eucalyptus grandis*, *Eucalyptus grandis* × *Eucalyptus urophylla*, and *Eucalyptus camaldulensis*, as they appeared in the highest number of planting plots across the evaluated locations. For Australia, the study presented data from 284 planting plots conducted in two states: New South Wales and Queensland, across 18 sites with 38 *Eucalyptus* species. The most representative species were *Eucalyptus saligna*, *Eucalyptus pilularis*, and *Eucalyptus agglomerata*.

1.2.2. Data Records

Data records are reported in a sheet with 449 rows and 15 columns. Each row represents an individual planting plots within a publication, meaning that the same publication may contain multiple experiments. The columns represent the reference, location, and variables considered in the PCA analysis. The spreadsheet can be found in Appendix A. The variables were divided into four categories, as detailed below:

- Environmental Variables:
  - "Latitude," "Longitude," and "Elevation" were directly reported in the articles, and in a few cases, they were obtained through the name of the closest city.

  - Temperature: refers to the mean annual temperature.
  - Rainfall: denotes the mean annual precipitation.
  - Soil order: represents the soil classification according to the World Reference Base for Soil Resources (FAO 2014).
- The tree-size variables include:
  - Species/hybrids: Reports the names of eucalypt species (cultivars) as detailed in the paper.
  - Age: Refers to the age (in years) of the eucalypt plantation.
  - Diameter at Breast Height (DBH): The dendrometric measurement of the trunk or bole diameter at 1.3 meters of a standing tree, reported in centimeters.
  - Height: The height of the tree in meters.
- Wood Properties:
  - Wood Basic Density: The density of the wood. For papers that do not present this information (9.4% of the dataset), a density of 450 kg m^{-3} was assumed for Brazilian planting plots, based on the average obtained from literature reviews in this country. For Australia, the basic density was according to the species as presented by Dadswell (1972).
  - Carbon stock: The average carbon stock of the wood as a percentage. Literature generally uses a carbon content of 50% for eucalypt wood to convert biomass to carbon. In this study, we adopted 45% based on the average obtained from all literature review articles.
- Forest Stand Variables:
  - Stand Density: Measures the stocking of a stand of trees based on the number of trees per unit area.
  - Mean Annual Increment (MAI): This study investigates this variable in depth. For studies that already provided this information (16% of the dataset), it was directly utilized. To estimate the annual carbon sequestration in wood where technical information was unavailable, it was calculated by multiplying the mean annual increment (MAI), age, wood basic density, and wood carbon content.

1.2.3. Data Analysis

To understand the main drivers of carbon stock in *Eucalyptus* plantations, we selected the variables of interest filled out in the worksheets for both countries. Pearson's correlation test (R) was used to identify correlated quantitative variables in the dataset. This test measures the strength of a linear relationship between two variables (Rodgers and Nicewander 1988). When R = 1, the two variables are perfectly positively linearly correlated, meaning Y increases as X increases; when R = 0, there is no linear relationship between the variables; and when R = -1, they are perfectly negatively linearly correlated, meaning Y increases as X decreases (Iñigo et al. 2012). Since temperature was strongly correlated with latitude and longitude, and the latter was particularly different between Brazil and Australia, we opted to use only the local elevation of each planting plots as the geographical dimension. The diameter at breast height, height, age, and stand density were used to estimate the mean annual increment (MAI) in articles that did not present this information. The MAI and wood properties (basic density and carbon concentration) were then used to calculate the carbon stock. Therefore, the statistical analysis was performed with four quantitative variables: elevation, temperature, rainfall, and carbon stock.

To fully understand the analyzed phenomenon, we employed multivariate statistical techniques using principal component analysis (PCA) to characterize the measured variables and their interaction with supplementary categorical variables, such as the countries (Australia and Brazil) and their respective *Eucalyptus* species. Additionally, we utilized a gamma regression model with cubic splines to observe the relationships among these variables with carbon stock over time. This model, known as a Generalized Additive Model (GAM), allowed us to visualize the partial effects of these variables on the mean response in carbon stock.

1.3. Results

1.3.1. Database Evaluation

Table 1 summarizes the main characteristics of each country. For many variables, such as elevation and stand density, the ranges across the two countries were similar. However, Australia exhibited a greater range of ages. *Eucalyptus camaldulensis*, *Eucalyptus dunnii*, *Eucalyptus grandis*, and *Eucalyptus saligna* were found in both countries.

Table 1. Mean, Standard Deviation (SD), and Range of the quantitative variables of the reviewed countries.

Country	Variable	Unit	Mean	SD	Range
	Rainfall	mm yr^{-1}	1,200.81	281.95	507.00 – 1900.00
	Temperature	°C	18.76	4.10	12.92 – 27.50
	Latitude	°	-30.66	3.09	-21.60 – -37.40
	Elevation	m	341.81	260.09	15.00 – 1,070.00
Australia	Age	yr	12.86	4.79	4.00 – 21.00
	Wood Basic Density	kg m^{-3}	674.17	78.17	512.59 – 897.03
	Stand Density	trees ha^{-1}	1,026.35	351.52	215.84 – 2,500.00
	Mean Annual Increment	m^3 ha^{-1} yr^{-1}	16.26	16.85	0.10 – 70.08
	Carbon stock	Mg C ha^{-1} yr^{-1}	5.91	4.99	0.10 – 23.52
	Rainfall	mm yr^{-1}	1,341.33	266.92	640.33 – 2,050.00
	Temperature	°C	21.33	2.23	17.50 – 25.60
	Latitude	°	-20.70	4.41	-11.78 – -30.39
	Elevation	m	575.66	303.04	5.00 – 1,098.00
Brazil	Age	yr	5.93	1.83	1.00 – 10.00
	Wood Basic Density	kg m^{-3}	457.69	26.32	384.00 – 500.00
	Stand Density	trees ha^{-1}	1,363.85	481.04	404.00 – 2,469.00
	Mean Annual Increment	m^3 ha^{-1} yr^{-1}	33.06	15.22	1.80 – 75.70
	Carbon stock	Mg C ha^{-1} yr^{-1}	9.89	3.82	0.41 – 20.70

In general, Brazilian *Eucalyptus* plantations exhibited a 67% higher average carbon stock compared to Australian ones, averaging 9.89 MgC ha^{-1} yr^{-1} in Brazil and 5.91 MgC ha^{-1} yr^{-1} in Australia. The highest annual wood carbon values were found in *Eucalyptus longirostrata* and *Eucalyptus pilularis* plantations in Australia, and *Eucalyptus grandis* × *Eucalyptus camaldulensis* and *Eucalyptus grandis* plantations in Brazil.

Figure 2 presents the correlogram illustrating Pearson's correlations to understand the relationships between carbon stock (carbon_ha_year), longitude (long), latitude (lat), elevation (elev), age, temperature (temp), and rainfall (rain). Data from Australia and Brazil were analyzed separately, revealing the following correlations: (i) in Australia, carbon stock showed positive correlations with latitude (0.26), elevation (0.28), temperature (0.05), age (0.48), and rainfall (0.14); (ii) in Brazil, carbon stock had a positive correlation only with rainfall (0.27), while latitude (-0.20), elevation (-0.17), and temperature (-0.04) were negatively correlated (Figure 3). Although Pearson's correlations generally showed low values for carbon stock in both countries, which was expected due to the extensive and heterogeneous nature of the database, a strong correlation was noted among temperature, latitude, and longitude (Linacre and Geerts 1997).

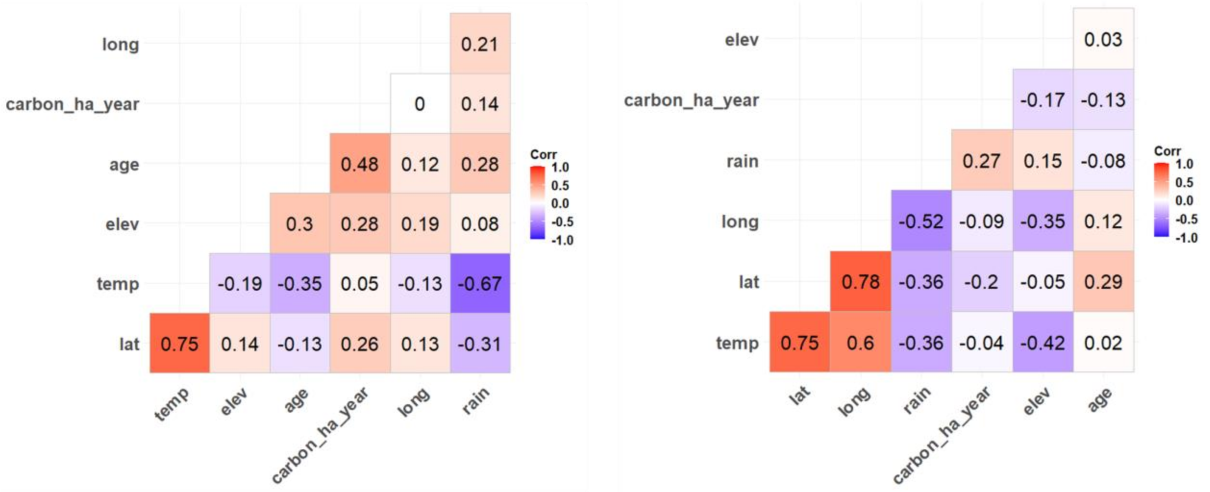


Fig. 2 Pearson correlation among evaluated variables (longitude, latitude, age, elevation, temperature, rainfall and carbon stock). The correlogram on the left displays the results of the Australian planting plots and the correlogram on the right displays the results of the Brazilian planting plots, respectively. Negative correlations are displayed in blue and positive correlations in red color. Color intensity are proportional to the correlation coefficients. In the right side of the correlogram, the legend color shows the correlation coefficients and the corresponding colors.

The Pearson correlation was used as an exploratory analysis; however, it did not allow for an in-depth examination of the interactions between variables across these planting plots in relation to carbon stock. Consequently, it was necessary to proceed with a multivariate analysis.

1.3.2. Principal Component Analysis (PCA)

Principal Component Analysis (PCA) is a pivotal tool for understanding complex datasets by simplifying them while retaining essential information. This study employs

PCA as an exploratory mechanism to uncover the intrinsic relationships among the variables under investigation. By revealing the internal data structure within a reduced-dimensional space, PCA facilitates the identification of patterns, clusters, and outliers, offering valuable insights for further analysis and decision-making processes.

Table 2 displays the contribution percentages of each variable — elevation, temperature, rainfall, and carbon stock— obtained from the PCA analysis. The variation explained by the first two components is sufficient to comprehend the data behavior and their respective structures. Consequently, we performed a joint analysis for both countries and separate analyses for Australia and Brazil. Figure 4 illustrates the PCA results discriminated by country. The first Principal Component (PC1) and the second Principal Component (PC2) account for 30.9% and 39.6% of the total data variability, respectively.

Table 2. Contribution (%) of the variables in PCA in the Australian and Brazil planting plots.

Variables	PC1	PC2	PC3
Australia + Brazil			
Elevation	19.155	14.790	65.355
Temperature	23.655	37.950	0.868
Rainfall	45.018	2.335	12.673
Carbon stock	12.172	44.925	21.104
Australia			
Elevation	9.977	35.545	50.222
Temperature	42.810	8.879	2.395
Rainfall	43.294	4.316	9.550
Carbon stock	3.919	51.389	37.834
Brazil			
Elevation	26.653	23.372	17.631
Temperature	42.329	1.159	0.769
Rainfall	29.238	16.074	43.398
Carbon stock	1.781	59.394	38.220

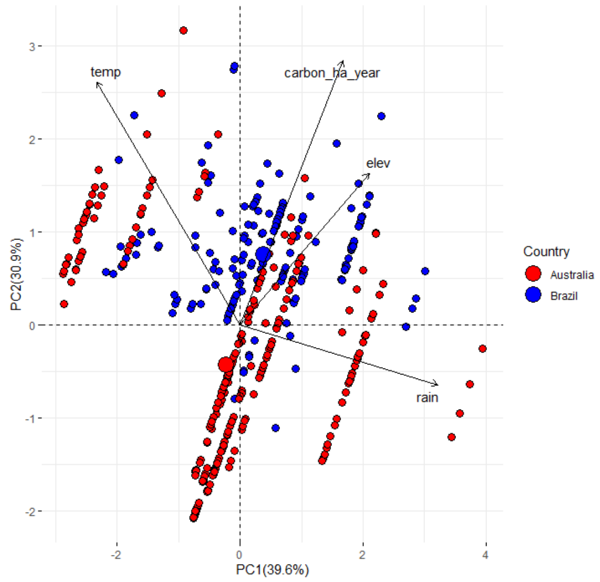


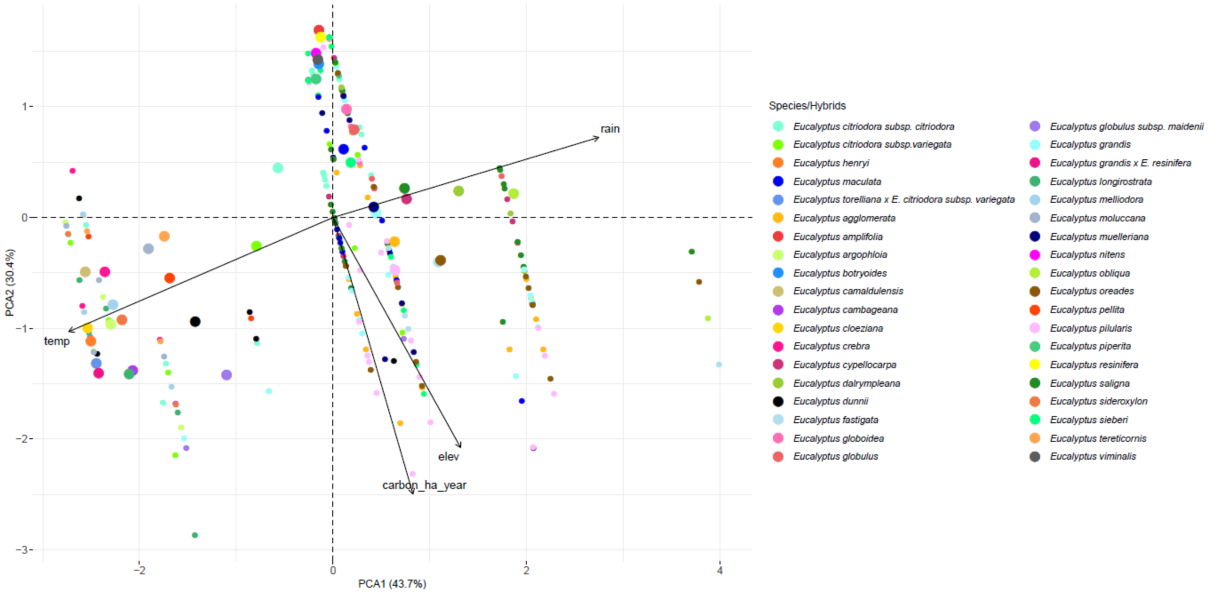
Fig. 3 Principal component analysis (PCA) of the contributing variables (elevation, temperature, rainfall and carbon stock) discriminating by country in color red Australian planting plots and in color blue Brazilian planting plots, respectively. X and Y axes represent the first and second factors of the PCA, respectively. The percentage of variation explained for each principal component is indicated in parentheses.

The major contributions of variables for the Australian and Brazilian planting plots were rainfall in Principal Component 1 (PC1) and temperature and carbon stock in Principal Component 2 (PC2) (Table 2). Notably, PC2, positioned on the y-axis, included variables more closely related to carbon sequestration. It showed a positive correlation with elevation and temperature, with the strongest relationship observed with elevation (Figure 3).

It is observed that, although the planting plots share some species such as *Eucalyptus camaldulensis*, *Eucalyptus dunnii*, *Eucalyptus grandis*, and *Eucalyptus saligna*, the analysis reveals the presence of two distinct groups based on the countries, leading to separate analyses. The first two principal components (PCs) were selected for the PCA, accounting for 74.1% and 72.2% of the variance in the Australian and Brazilian planting plots, respectively. For these analyses, only variables with a contribution of ≥ 15.0% were considered (Figure 4).

For Australia, the first principal component (PC1) explained 43.7% of the total data variation, while the second principal component (PC2) accounted for 30.4% of the residual variation. In Brazil, PC1 and PC2 explained 41.2% and 31.0% of the total data variation, respectively. In both countries, PC1 exhibited a negative association with temperature and rainfall, indicating that higher temperatures were observed in areas with lower rainfall. Regarding PC2, which was most related to carbon stock and elevation, Australian eucalypt plantations showed a strong positive association between these variables. In contrast, Brazilian plantations displayed a correlation between carbon stock and rainfall, rather than with elevation (Figure 4).

(i)



(ii)

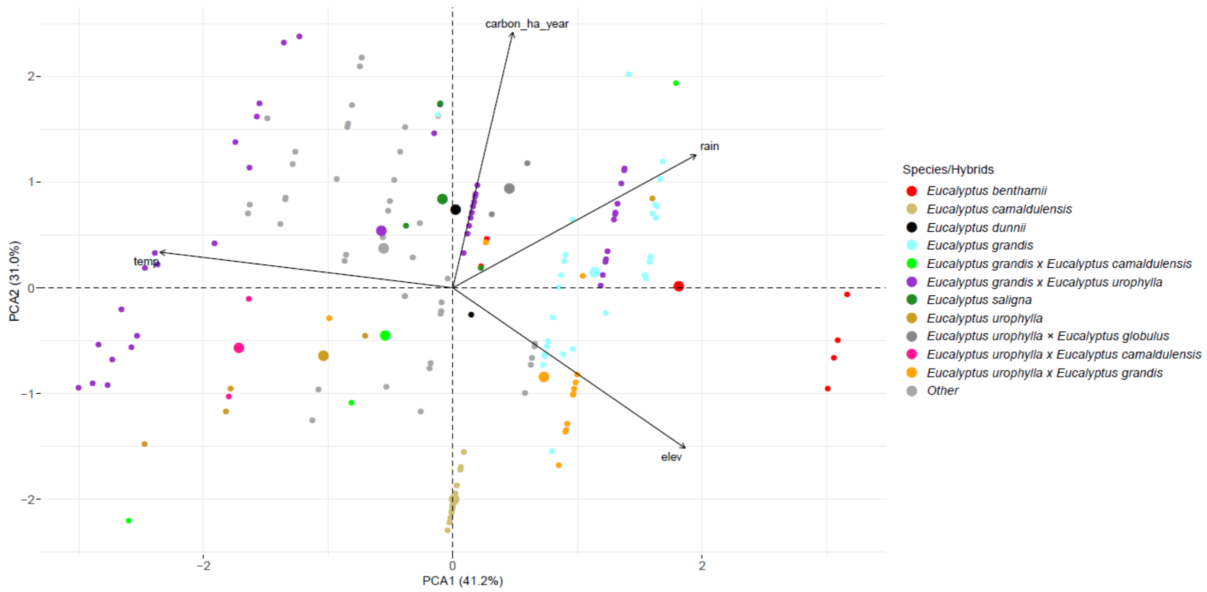


Fig. 4 Principal component analysis (PCA) of the contributing variables (latitude, elevation, temperature, rainfall and carbon concentration) discriminating by species for Australian (i) and Brazilian (ii) planting plots. X and Y axes represent the first and second factors of the PCA, respectively. The percentage of variation explained for each principal component is indicated in parentheses.

Regarding the species/hybrids, it is observed that *Eucalyptus pilularis* planted at higher elevations promoted greater carbon stock in Australia. Conversely, *Eucalyptus urophylla* × *Eucalyptus grandis* planted in high-elevation regions in Brazil exhibited lower carbon stock values. Additionally, *Eucalyptus saligna* demonstrated significant carbon stock, which was associated with increased precipitation.

1.3.3. Generalized additive models

The trend of the main variables, fitted using generalized additive models to predict the carbon stock in *Eucalyptus* plantations, is presented in Figure 5.

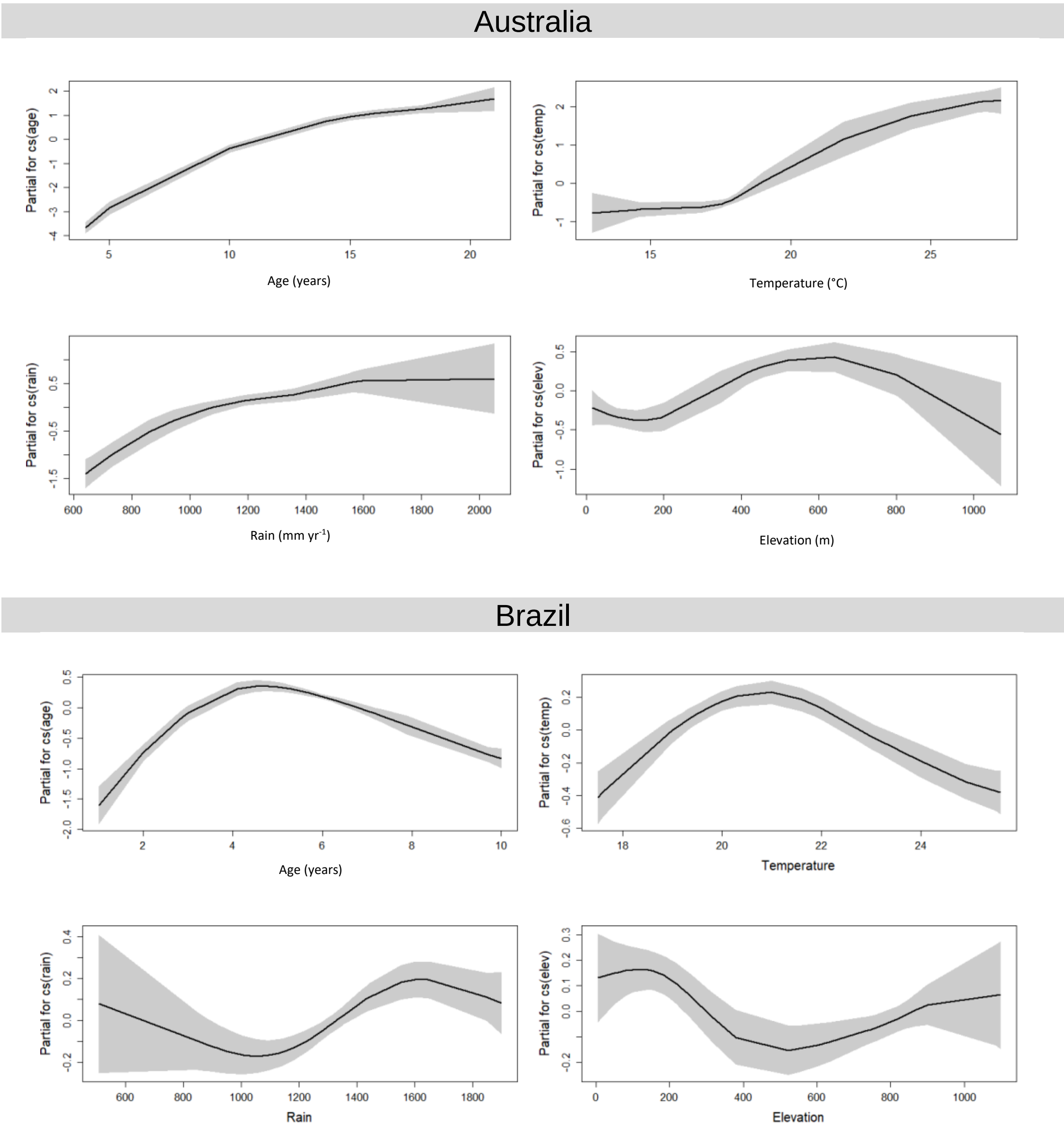


Fig. 5 Splines for means of carbon stock including: age (years), temperature (°C), rain (mm yr-1) and elevation (m). The gray areas represent the 95% confidence interval, the x-axis presents the values of the variables considered in the regression model, and on the y-axis are the partial effects considering the cubic splines of the model for Australia and Brazil.

In Brazil, the main species are fast-growing, accumulating high amounts of carbon within the first five years before their growth rate slows down. These species, being exotic, also face fewer natural enemies such as pests and diseases (Silva et al., 2019). Conversely, Australian species typically exhibit slow growth in the initial years, accelerating their growth after 5 to 10 years.

Maximum tree growth in Brazil was achieved with temperatures ranging between 20°C and 22°C, as reported by Queiroz et al. (2020), while temperatures above 25°C were more suitable for Eucalyptus plantations in Australia. Optimal growth was observed at elevations of around 600 m in Australia and 200 m in Brazil. Both countries showed higher carbon stock values with rainfall exceeding 1600 mm yr^{-1}.

Figure 6 demonstrates that the correlation in Brazil is 0.81, indicating that the model captures the variation in the data well. For Australia, the correlation was 0.70, which is less accurate. This lower accuracy can be attributed to the data variability, as the planting plots encompassed a broader range of species, leading to an unbalanced number of observations.

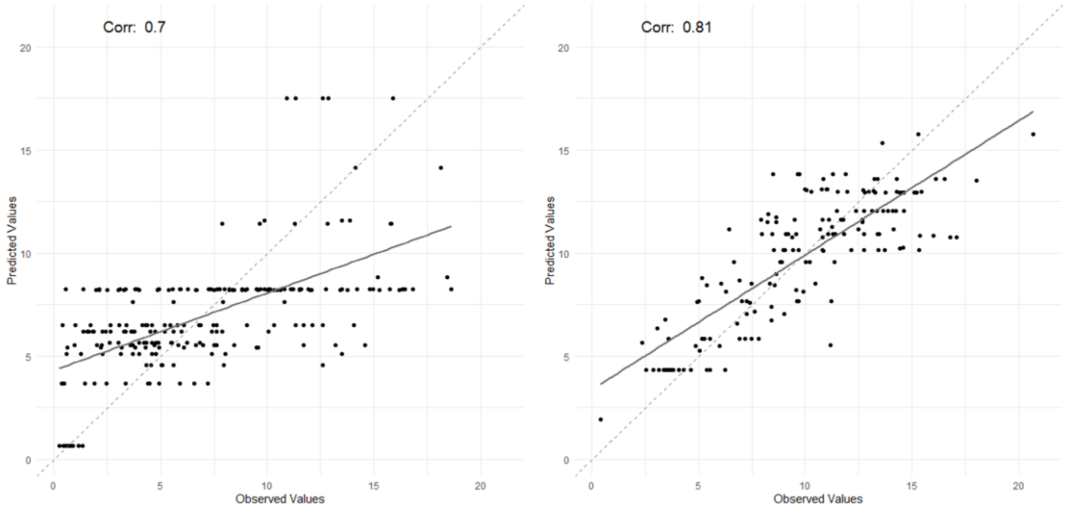


Fig. 6. Scatter plot of predicted versus observed values (dashed lines - slope lines; solid lines - linear regression trend) with the corresponding correlation values, on the left for the planting plots in Australia and on the right for the planting plots in Brazil.

1.4. Discussion

We conducted a PCA analysis to comprehensively explore the determinants of carbon stock in Australia and Brazil. Differences were observed, particularly in the correlations between carbon stock, temperature, and precipitation in each country, which were further elucidated by the adjusted GAM models. Notably, elevation was the variable most strongly correlated with carbon stockin both countries—positively in Australia and negatively in Brazil.

In Australia, the species/hybrids are dominated by those that grow slowly in the initial years (e.g., *Eucalyptus pilularis*, *Eucalyptus citriodora subsp. variegata*, and *Eucalyptus argophloia*) and accelerate their growth as indicated by the mean annual increment (MAI) after 5 to 10 years. For instance, *Eucalyptus argophloia* showed an increasing MAI at age 18 in three trials in Queensland (Lee et al., 2011b). Other studies also found that fast-growing species tend to have higher carbon stocks (Weber et al., 2018). The fast carbon stock continues to increase until it reaches a maximum rate and then starts to decline (Olmedo et al., 2020). Interestingly, the highest measured carbon stock of 23.5 MgC ha^{-1} yr^{-1} occurred in Australia, while the highest stock recorded in Brazil was 20.7 MgC ha^{-1} yr^{-1}.

Elevation resulted in different effects on the carbon concentration of eucalypt plantations, being more favorable for carbon stock in Australia. In Brazil, some studies indicate that higher altitudes are associated with lower temperatures and reduced evaporative demand, leading to lower annual increments and consequently, lower carbon stock (Souza et al., 2006). This may explain the inverse correlation found between elevation and carbon stock. In contrast, for Australia, better data on carbon concentration for *Eucalyptus nitens*, *Eucalyptus globulus*, and *Eucalyptus dunnii* might influence the correlation between carbon stock and elevation, as these species are well-suited to higher altitudes and colder climates (Grant et al., 2010; Brawner et al., 2013; Mosisa et al., 2024).

In general, carbon stock tended to increase from 1,100 mm yr^{-1} of rainfall in the Australian and Brazilian planting plots, although a complex interaction among eucalypt species and climatic conditions was observed. Brazilian plantations often utilize more tropical species such as *Eucalyptus urophylla*, either in pure form or hybrid combinations, while Australia uses more subtropical species.

We found that stemwood carbon stock increased by an average of 0.744 MgC ha^{-1} $year^{-1}$ for each 100 mm yr^{-1} increase in precipitation, which corroborates findings reported by other authors (Binkley et al., 2017). This relationship varies among species, as demonstrated by Brawner et al. (2013). In Brazil, *Eucalyptus urophylla* × *Eucalyptus grandis* showed the most robust positive relationship between carbon stock and temperature and rainfall. In Australia, stemwood carbon stock increased by an average of 0.356 MgC ha^{-1} year^{-1} for each 100 mm yr^{-1} increase in precipitation.

Still regarding the species in Brazil, Eucalyptus saligna showed a positive relationship with water availability, with its carbon stock concentration significantly influenced by precipitation. Similarly, Bastos (2022) observed that Eucalyptus saligna had the highest transpiration rates among the analyzed species, with its ecophysiological dynamics closely linked to climatic factors such as precipitation and radiation. These findings underscore the species' sensitivity to environmental water inputs, illustrating its pivotal role in hydrological processes and carbon storage within forest ecosystems.

A more in-depth analysis comparing species, as done by Brawner et al. (2013), found that *Eucalyptus cypellocarpa* showed better carbon stock with increasing rainfall, while *Eucalyptus oreades*, *Eucalyptus muelleriana*, and *Eucalyptus sieberi* exhibited the opposite trend. Other studies have also found positive correlations between rainfall and carbon stock in Chile and Australia (Olmedo et al., 2020; Paul et al., 2008).

The annual average precipitation in the Australian and Brazilian plantations of this study were 1,200 mm yr^{-1} and 1,341 mm yr^{-1}, respectively, with the highest average carbon stock across all trials occurring in Brazilian Eucalyptus plantations—9.89 MgC ha^{-1} yr^{-1}. The higher rainfall values suggest greater soil water availability, which facilitates continuous CO_2 uptake during tree growth, regulated by the opening of leaf stomata (Fernández et al., 2021; Nedukha et al., 2023). In drier areas, CO_2 diffuses through the stomatal pores without substantial counterflow of water, leading to stomatal closure and restricted CO_2 absorption (Bhatla and Lal, 2023; Zhu et al., 2024).

Regarding temperature, *Eucalyptus agglomerata* showed significant carbon stock at lower temperatures, while *Eucalyptus citriodora subsp. variegata*, *Eucalyptus citriodora subsp. citriodora*, and *Eucalyptus grandis* exhibited better carbon stock at higher temperatures. Brazilian planting plots were conducted at higher average air temperatures (21°C, ranging from 15.5°C to 26°C) compared to Australia (18°C, ranging from 13°C to 27°C), which increased the complexity of observing the contribution of temperature to carbon uptake. It is important to note that the planting plots evaluated were performed during different periods and in different locations.

Overall, the relationship between temperature and MAI is complex, influenced by water availability, species adaptability, and environmental interactions. MAI tends to decrease with increasing temperatures in regions where water stress and excessive heat hinder ecophysiological performance. High temperatures increase evaporative demand, leading to stomatal closure, reduced CO_2 uptake, and lower biomass production. Additionally, elevated temperatures accelerate respiration, reducing carbon use efficiency. In moderate climates, where temperature and water availability align with the species' physiological needs, negative impacts can be minimized. Well-adapted species, such as Eucalyptus benthamii, may even benefit from slightly higher temperatures, provided sufficient water supply (Klippel, V. H.,2015).

1.5. Conclusion

In Australia, Eucalyptus species grow slowly in the initial years, accelerating after 5-10 years, while in Brazil, carbon stock increases progressively, peaking between 4-6 years before declining. Rainfall showed a stronger correlation with carbon stock than temperature in both regions, and elevation was the most influential factor in the multivariate analysis. These findings suggest that forest engineers should tailor management practices to local conditions. In Brazil, thinning and harvesting should be prioritized during the peak carbon uptake period, while in Australia, interventions should focus on optimizing early growth conditions and leveraging later accelerated growth. Additionally, rainfall variability must be integrated into water management strategies, and elevation should be a key consideration in site selection. Monitoring systems are essential to track growth and adapt management practices over time to ensure plantations maximize their carbon sequestration potential and contribute effectively to climate change mitigation.

Since that this analysis is based on PCA, it is essential to interpret the results with caution, as it reflects interrelationships among variables rather than direct relationships. In the case of Australia, carbon stock was higher in plantations located at higher elevations, with higher temperatures and lower precipitation levels. In Brazil, carbon stock was greater in plantations situated in areas with higher precipitation, higher temperatures, and lower elevations. These contrasting patterns highlight the importance of considering regional climatic and topographical conditions in the management of Eucalyptus plantations to optimize carbon sequestration.

Given that climate change is a global issue and forest vegetation plays a significant role in the global carbon cycle, the findings presented in this manuscript are expected to enhance the understanding of the best strategies to promote greater carbon stock through eucalypt forest plantations. Forestry is increasingly recognized as an effective climate-policy option for many countries due to its relatively low cost and competitiveness with other methods of carbon mitigation, assisting foresters in adopting optimal management practices. While these studies provide valuable insights into carbon stock dynamics, further research encompassing a broader range of species and climatic conditions is imperative to develop robust strategies for sustainable forestry management. Promising results with more efficient prediction models, such as those based on Bayesian analysis, could be achieved by including a wider range of species in the modeling.

Authors contribution

Juliana Campos Amorim: conceptualization, methodology, investigation, and writing—original draft. João Marcos Rebessi de Sousa: data curation and formal analysis. Paulo Henrique Müller da Silva: writing—review and editing. Fábio Prataviera: formal analysis, visualization, and validation. Sérgio Augusto Rodrigues: data curation and formal analysis. Sam Van Holsbeeck: writing—original draft and writing—review. Saulo Philipe Sebastião Guerra: conceptualization, writing—review and editing. David J. Lee: conceptualization, methodology, writing—review. Humberto de Jesus Eufrade-Junior: conceptualization, methodology, writing—review and editing, project administration, and supervision.

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Statements and Declarations

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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CHAPTER 2: Enhancing the Recycling Process of Beverage Carton Packages: Characterization of Residues Generated

ABSTRACT

Beverage cartons, introduced in 1952, are constructed with a multilayer composition—75% paper, 20% polyethylene, and 5% aluminum—that enhances food preservation. With a recycling rate of 39.1% and high renewable content, these packages provide valuable sustainable attributes. The global beverage carton market, valued at USD 17.2 billion in 2022, is projected to grow to USD 25.6 billion by 2032, driven by rising demand for eco-friendly and convenient packaging. In Brazil, the packaging sector grew by 17.21% in 2023, with increased adoption of beverage cartons as consumers show greater environmental awareness. In the final stage of beverage carton recycling process, a residual, non-marketable byproduct is generated, representing around 6% of the packaging's weight and ending up in landfills. To improve the environmental performance of beverage cartons, this exploratory study conducted a complete physical and chemical characterization of this residue, analyzing elemental composition and thermal properties. The residue analysis indicates strong potential for energy recovery, with a Useful Heating Value (UHV) of 15.76 MJ/kg after 60 days of drying and a high carbon and volatile content that supports thermal processing. Coupled with its classification as a non-hazardous Class II A waste, this suggests its potential use as Refuse-Derived Fuel (RDF). Field Emission Gun Scanning Electron Microscope (FEG-SEM) and Thermal Analysis (TGA) results further indicate that its mixed plastic and fibre composition may also be suitable for bio-oil and gas production, with optimal degradation occurring between 400°C and 550°C. Elemental analysis reveals favourable combustion properties and minimal environmental risks due to low levels of toxic elements.

Keywords: Beverage cartons, Recycling, Residue, Refuse-Derived Fuel

2.1 INTRODUCTION

The beverage carton package was created by Ruben Rausing and Erik Wallenberg, patented by Ruben Rausing, and introduced into the market in 1952 (TETRA PAK, 2023a; RAUSING, 1969). The invention pertains to a technique for packaging sterile filling material in aseptic conditions. The process involves placing the sterile filling material into containers that are also sterile. These containers are then heat-sealed to make them impermeable to both bacteria and the intended filling material (RAUSING, 1969), making the filled product have a shelf life of at least 3-6 months without refrigeration (REJEESH, 2023).

Besides the filling method, the composition of the packaging is also crucial to fulfill its function. This type of packaging comprises 6 layers of material, on average, 75% of paperboard, 20% of polyethylene, and 5% of aluminum (SIDDIQUI, 2020). Each layer performs a specific role, and from out to inner, the materials of the layers and the respective functions are (TETRA PAK, 2023b):

- Polymer: Protects the package from moisture.
- Paperboard: Provides strength and rigidity. The printing of the packaging occurs on this layer.
- Polymer: Glue the paper to the aluminum foil.
- Aluminum: Acts as a barrier against light and oxygen and enables induction sealing.
- Polymer: Glues the aluminum foil to the polymer.
- Polymer: Protects the package from the product inside.

In addition to protecting food, this packaging features key sustainability attributes, such as high renewable content and a market validated recycling process (TETRA PAK, 2021).

The global consumption of beverage cartons has been steadily increasing over the years, mainly fuelled by the demand for convenient packaging solutions for fast-moving consumer goods like milk, juices, and other beverages. Furthermore, the heightened demand for environmentally friendly products, particularly among health-conscious younger consumers, has opened significant growth opportunities for manufacturers. In 2022, the beverage cartons market was valued at USD 17.2 billion, with projections to reach USD 25.6 billion by 2032 (Market Research Future, 2023).

The Brazilian packaging market, including beverage cartons, showed a growth of 17.21% compared to 2022, reaching a gross production value of R$ 144.4 billion in 2023, according to the Brazilian Packaging Association (ABRE) (ABRE, 2023a). In the specific segment of beverage cartons, the demand for more sustainable and recyclable options has driven adoption, reflecting consumers' growing environmental awareness (ABRE, 2023b). The protein and plant-based beverage market has shown strong potential for the adoption of carton packaging. According to Mordor Intelligence, the global market for ready-to-drink protein beverages was valued at USD 1.34 billion in 2020 and is projected to grow at an annual rate of 7.72% from 2022 to 2027 (Mordor Intelligence, 2022). This global trend is also evident in Brazil, where increasing demand for healthy and sustainable products is driving the adoption of carton packaging in this segment (Tetra Pak, 2023c).

Brazil's Solid Waste Policy, established by Law 12.305/2010, provides a comprehensive framework for waste management, emphasizing the importance of selective collection and recycling. The law highlights the need for integrated and sustainable practices to reduce waste generation and increase the recovery of recyclable materials. Selective collection plays a pivotal role by ensuring that materials are separated at the source, enhancing their recycling potential and reducing the environmental impact. Additionally, the law promotes the inclusion of waste pickers in the recycling chain, recognizing their contribution to material recovery and fostering social inclusion (BRASIL, 2010). By aligning selective collection practices with the principles of Law 12.305/2010, Brazil can advance toward a circular economy while addressing environmental and social challenges.

After consumption, the initial stage in the packaging's journey towards the recycling process is the proper disposal by the consumer. This can be done through door-to-door selective collection, by delivering it to voluntary drop-off points or by engaging with an autonomous collector. After disposal, the material will be directed to a waste picker cooperative or broker and forwarded to the final recycler (CEMPRE, 2019). In 2023, Brazil's recycling rate of carton packages was 39.1% (TETRA PAK, 2024).

The most well-established technology for used beverage cartons (UBC) is hydropulping, resembling conventional paper recycling with minor adjustments required during pulp separation from the polymer-aluminum (polyAl) components. In the presence of water and subjected to a high-speed mixer, cellulose fibers adsorb water and transform into pulp. The mixture, comprising pulp and polyAl laminate, is subsequently separated by sieving off the non-fibered materials (ZAWADIAK *et al.*, 2017).

The paper undergoes the recycling process, being converted into cardboard boxes, tubes, or other products that aim to maintain the paper's characteristics as close as possible to cellulose (NEVES, 2004). The polyAl, separated in hydrapulper, usually contain 5% to 7% of paper fibers (NEVES, 2004; GEORGIOPOULOU *et al.*, 2021) and can be recycled into: (1) pelleted composite, obtained through the extrusion process, which is suitable for application in plastics transformation industries, through injection molding and blow molding processes; (2) Roof tiles and boards (NEVES, 2004; ZAWADIAK *et al.*, 2017).

The manufacturing process for boards and roof tiles involves melting the material under pressure and then cooling it subsequently (ZAWADIAK *et al.*, 2017). The initial phase of the process involves centrifugation, aiming to pre-select the material and eliminate contaminants that pass through the hydrapulper (NEVES, 2004).

The cleaned polyAl is crushed into small fragments using knife mills. After crushing, the material is placed into molds for shaping the boards. These molds, filled with polyAl, are introduced into presses for producing plywood sheets at approximately 180°C. The material undergoes a cooling process for curing and hardening to produce the boards. For roof tiles production, the still-hot boards are pressed into corrugated molds during a cold pressing process, allowing the material to take on the shape of tiles as it cools (ARAÚJO; MORAIS; ALTIDES, 2008).

Considering the entire process (paper and polyAl recycling), remaining waste is generated from the polyAl centrifugation step, and this residue is sent to the landfill by the PolyAl Recyclers. Since the PolyAl represents 25% of the carton package, this residue's percentage of the total weight is 6%.

Considering that more than 100,000 tons of those packages were recycled in Brazil in 2023 (TETRA PAK, 2024), we would have 6,000 tons of this residue sent to the landfill. One significant issue associated with landfill disposal pertains to the emission of landfill gas (LFG), primarily composed of methane (CH4) (constituting 55–60% v/v) and carbon dioxide (CO2) (making up 40–45% v/v) (Mønster *et al.*, 2019).

Methane represents a significant greenhouse gas, with a global warming potential (GWP) of 27.9 over 100 years (IPCC, 2021). On a global scale, methane (CH4) generated by the municipal solid waste sector contributes 11% of the total annual anthropogenic emissions worldwide (GLOBAL METHANE INITIATIVE, 2020).

Therefore, the main objective of this study is to analyze the composition and properties of the residue generated in the centrifugation step of the polyAl recycling process and explore its potential applications to bioenergy as refuse-derived fuel (RDF).

2.2 MATERIAL AND METHODS

2.2.1 Sampling

The residue samples were collected from a PolyAl Recycler located in São Paulo state, Brazil. The carton package recycling process focusing on the PolyAl recycling step was shown in Figure 1.

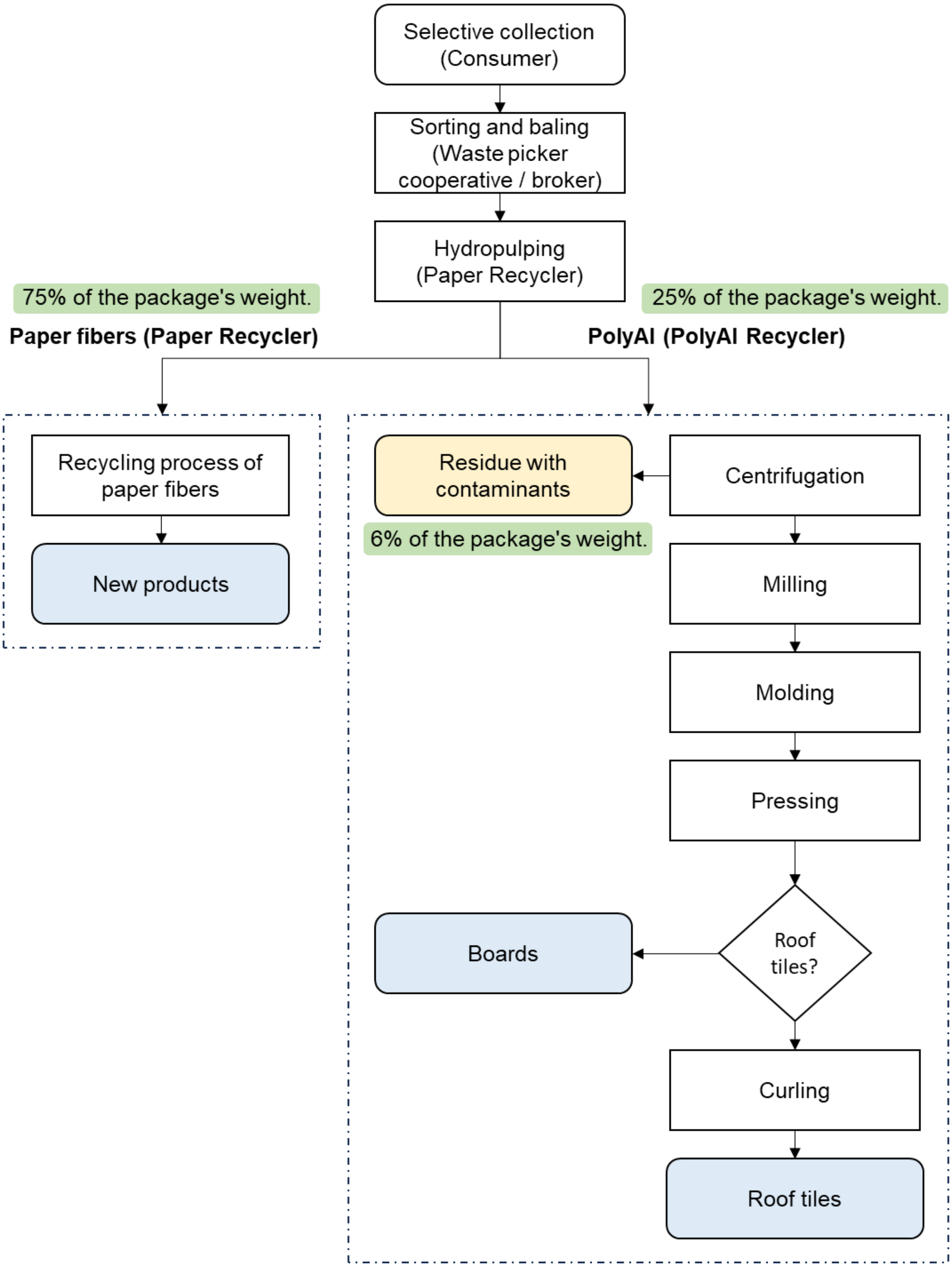

Figure 1. Carton package recycling process, focusing on the PolyAl recycling step.

To ensure representativeness, a composite sample was prepared by combining residues from different collection times (in the years 2023 and 2024) for laboratory analyses, following the procedures outlined in NBR 10007 for sampling. The samples, weighing a total of 35 kg, were taken from the pile of residue located at the recycler's facility, with material collected from the base, center, and top of the pile to ensure comprehensive coverage. This composite sampling approach provided a comprehensive overview of the residue characteristics. The samples were stored in buckets and transported to the laboratory for analysis. In Figure 2, in the process flowchart, it is shown that the residue was extracted from the centrifugation process, the initial step in the recycling process. In the figure, the label 'Residue with contaminants' refers to the residue under study.

Figure 2. Residue collected at the PolyAl Recycler's site – the image shows (from left to right) the residue exiting the centrifugation process, the stored residue pile, a close-up of the residue, and the residue being stored in a bucket for laboratory analysis

The PolyAl Recycler provided the weighing note of the residue stored for one week that was sent to the landfill, with a net weight of 21.3t. Given that this recycler processes, on average, 350 tons of PolyAl per month (data provided by the recycler), this waste represents 24% of the volume processed by the PolyAl recycler.

For some analyses, the residue needed to be classified and ground, as shown in the photos in Figure 3.

Figure 3. Classified and Ground Residue – The image shows (from left to right) the classified residue, followed by the ground residue

2.2.2 Residue Composition Analysis

After performing quartering and homogenization of the waste, a manual separation of its components was carried out using approximately 100g of the material. The process involved visual identification and careful separation of the constituent elements, such as paper, plastic, and aluminium, ensuring the representativeness of the sample for the composition analysis.

2.2.3 Physical and chemical characterization

The residues were classified according NBR 10004 (ABNT, 2004). After, the physical and chemical analyses were carried out to understand the organic and inorganic composition of the residue and its behavior during burning for direct combustion.

2.2.3.1 Proximate Analysis

The proximate analysis consists of determining the following components: moisture content, based on ASTM E871-82 (2019); volatile material (burned in the gaseous state), following ASTM E872-82 (2019); fixed carbon (burned in the solid state), according to ASTM E870-82 (2019); and ash (residual component after combustion), based on ASTM D1102-84 (2013).

The moisture based on dry basis (MCdb) relates the weight of the water contained in the sample to the weight of the dry sample, and the moisture based on wet basis (MCwb) relates the weight of the water contained in the sample to the weight of the wet sample, according to equations 1 and 2. The samples were dried in an oven at 105 ˚C ± 2 ˚C to obtain the dry material.

$$MCwb = \frac{WW - DW}{WW} \times 100 \ (Equation\ 1)$$

$$MCdb = \frac{WW - DW}{DW} \times 100 \ (Equation\ 2)$$

Where:
MCwb = Moisture based on wet basis (%);
MCdb = Moisture based on dry basis (%);
WW = Wet sample weight (g);
DW = Dry sample weight (g).

Moisture content on wet basis was determined at three stages: immediately after collection at the PolyAl Recycler's site, after 30 days of air-drying indoors without ventilation, and after 60 days, following an additional 30 days of air-drying outdoors in an open area with ventilation. As will be seen in the results, the initial days of drying without ventilation were not sufficient to adequately dry the residue. Therefore, the process continued with a ventilation stage in an outdoor area protected from rain.

Volatile matters refer to the part of the sample that is released when heated under a specified methodology. During this heating process, the biomass decomposes into gases and solid matter. This test method determines the percentage of gaseous products, excluding moisture vapor (LEONELLO *et al.*, 2019). The volatile matter content was obtained after the sample remained in the muffle at 950°C±10°C for seven minutes. In turn, the ash is the solid residue produced by the process of thermochemical decomposition of the sample during combustion (LEONELLO *et al.*, 2019). It was obtained after keeping the sample in the muffle at 600°C±20°C for three hours.

The fixed carbon concentration is represented by the remaining material after the release of volatile matter, excluding ash and moisture content. This differs from the maximum carbon content of the sample since a part of the carbon is released in the form of hydrocarbons with the volatile matter (EUFRADE-JUNIOR, 2015). Therefore, the fixed carbon was obtained indirectly using Equation 3.

$$FC = 100 - (VM + A) \; (Equation\ 3)$$

Where:
FC = Fixed carbon content (%);
VM = Volatile material content at the same reference moisture (%);
A = Ashes content at the same reference moisture (%).

2.2.3.2 Heating Value

The higher heating value of a material is defined as the total amount of energy released as heat when a unit mass of the material undergoes complete combustion, typically in the presence of excess oxygen (CORTEZ; LORA; GOMES, 2008). The Lower Heating Value (LHV) at dry basis is the amount of energy available (heat effectively possible to be used in fuels), considering the energy lost due to the vaporization of water. This value is determined using a sample of the material with a specified water content (SHENG; AZEVEDO, 2005).

To obtain the higher heating value (HHV), according to ASTM E711-84 (2023), an IKA® WERKE C2000 calorimeter, linked with a KV 400 model thermostat and a C5010 model calorimetric bomb (or decomposition flask), was used. The samples were dried in an oven at 105°C ± 2°C prior to analysis.

To obtain the LHV, the following equation was used:

$$LHV = HHV - 600\ \times (9 \times \frac{H}{100})\ (Equation\ 4)$$

Where:

LHV = Lower heating value (Kcal Kg^{-1});

HHV = Higher heating value (Kcal Kg^{-1});

H = Hydrogen content (%).

The Useful Heating Value (UHV), or Lower Heating Value (LHV) at wet basis (or as received), represents the effective heat quantity that a particular material is expected to produce, considering the residual moisture of the sample. It is referred to as "useful" because not all the available heat in the material will be fully utilized by the system. This happens due to the consumption of sensible and latent heat for the evaporation of residual moisture (DE PAIVA; DOS SANTOS FALCÃO FILHO, 2023). Equation 5 was used to obtain the UHV.

$$UHV = LHV\ \times \left(100 - \frac{MCwb}{100}\right) - 6 \times MCwb\ (Equation\ 5)$$

Where:
UHV = Useful heating value (Kcal Kg^{-1});
LHV = Lower heating value (Kcal Kg^{-1});
MCwb = Moisture based on wet basis (%).

The useful calorific value was also measured three times: for the residue collected directly from the recycler's site, for the residue that was air-dried for 30 days without coverage, and for the residue that was air-dried for 60 days, including 30 days with coverage.

2.2.3.3 Bulk Density

The bulk density was determined using the stoichiometric method, which involves obtaining the volume through measurements using a caliper, and the mass on a balance with a precision of 0.001 grams, according to ASTM D2395-17 (2022). The bulk density was calculated using Equation 6:

$$BD = \frac{m}{v} \ (Equation\ 6)$$

Where:
BD = Bulk Density (g cm^{-3});
m = Initial mass (g);
v = Volume (cm).

2.2.3.4 Statistical analysis

For the proximate analysis, heating value, and bulk density, a two-sample t-test assuming equal variances was conducted to assess the significance of differences between the residue before and after drying. This analysis aimed to identify statistically significant differences between treatments, considering a confidence level of 95%. The calculations were conducted using the statistical analysis tool in Excel (Data Analysis

ToolPak), which provided the *t*-statistic, *p*-values, and critical *t*-values. The hypotheses tested were H_0 (no difference between the means) and H_1 (a difference exists between the means). Differences were considered significant when $p < 0.05$ or $t > t$-critical, and the results were analyzed to determine the statistical significance among the treatments.

2.2.3.5 Elemental composition

The first elemental analysis involves the determination of the following chemical constituents: carbon (C), hydrogen (H), nitrogen (N), sulfur (S), and oxygen (O). The analysis was carried out using a Perkin Elmer model 2400 Elemental Analyzer (CHNS), which determines the elemental composition based on the modified Pregl-Dumas classical method. A known sample mass is combusted at high temperatures in the presence of oxygen, resulting in complete combustion and the emission of CO_2, H_2O, N_2, and SO_2. These gases are separated using the frontal chromatography technique, and the thermal conductivity detector is employed to determine the content of the chemical elements (THOMPSON, 2008). The oxygen content was determined indirectly from Equation 7, as adopted by ASTM E870 − 82 (2006):

$$O = 100 - (C + H + N + S + A)\ (Equation\ 7)$$

Where:

O = Oxygen content (%);

C = Carbon content (%);

H = Hydrogen content (%);

N = Nitrogen content (%);

S = Sulfur content (%);

A = Ashes content obtained from immediate analysis (%).

2.2.3.6 X-ray fluorescence (XRF)

To identify and quantify the chemical elements present in the residue, an X-ray fluorescence (XRF) analysis was conducted. A 379 mg ground sample was placed in a cuvette, pressed, and covered with a 6μm polypropylene LGC film. The equipment used for this analysis was the portable BRUKER C3 X-ray device, performing 3 analyses of 200 seconds each and one blank analysis using cellulose. The analysis was carried out at the Center for Nuclear Energy in Agriculture of the University of São Paulo (CENA/USP) in Piracicaba/SP.

Figure 4. Ground sample pressed into the sample holder and BRUKER C3 portable X-ray device

2.2.3.7 X-ray Diffraction (XRD)

To characterize the crystalline structure of the residue, X-ray diffraction (XRD) analysis was performed. X-ray diffractograms were recorded from samples with a particle size of 60 mesh using a Rigaku MiniFlex600-C diffractometer, with a diffraction angle (2θ) ranging from 5º to 85º in in 0.02º steps and a scanning rate of 0.5 ºC min^{-1}. The analysis was performed at the Laboratory of Chemical Analysis and Materials Characterization (LACMAT/CCAE/UFES).

2.2.3.8 Field Emission Gun Scanning Electron Microscope (FEG-SEM)

The structural analysis of the material was conducted to assess its morphology and crystalline structure. This includes detailed observation of the surface characteristics and internal arrangement of the sample components. To assess the microstructure of the residue, the samples were initially dried and affixed to a metal support with carbon tape. They were subsequently coated with gold for microscopic examination using the Balzers Union SCD 030 system, which ensures precise scanning of secondary electrons during microscopy with a scanning electron microscope (Jeol, model JSM-IT200, Peabody, MA, USA) operating at 10 kV. SEM images were obtained using JEOL's proprietary software. The images were captured using objective lenses with magnifications of 50x, 100x, 200x, and 500x. The analysis was carried out at the Scanning Electron Microscopy Laboratory (LMEV/UFES/ALEGRE) in collaboration with the Biomass Energy Laboratory (LEB) at the Federal University of Espírito Santo (UFES), Monteiro, ES.

2.2.3.9 Fourier Transform Infrared (FTIR) spectroscopy analysis

To characterize the aromatic structures, including functional groups and chemical bonds, a Fourier Transform Infrared (FTIR) spectroscopy analysis was conducted at the Central Analytical Laboratory II in collaboration with the LEB/UFES. Composite FTIR spectra were acquired using attenuated total reflectance (ATR) within the 4000–600 cm^{-1} range, with a resolution of 4 cm^{-1}, employing a Bruker Tensor 27 spectrometer.

2.2.3.10 Thermal Analysis

Thermogravimetric analysis (TGA) was carried out at the Laboratory of Chemical Analysis and Materials Characterization (LACMAT/CCAE/UFES) using a Labsysevo Setaram instrument. The samples were heated at a rate of 10 ºC per minute. Thermograms were recorded starting from room temperature (50 ºC) under a nitrogen atmosphere with a flow rate of 1.8 bar, up to a maximum temperature of 950 ºC. The total duration of the analysis was 95 minutes.

2.3 RESULTS AND DISCUSSION

According to NBR 10004, waste can be classified into Class I, which comprises hazardous waste, and Class II, which includes non-hazardous waste. Hazardous wastes have one of the following characteristics: flammability, corrosivity, reactivity, toxicity, or pathogenicity. Non-hazardous waste is subdivided into Class II A and Class II B. Class II A is the so-called non-inert waste and may have properties such as: biodegradability, combustibility, or solubility in water. Finally, Class II B waste, known as inert, when subjected to dynamic and static contact with water, has no constituents solubilized at concentrations higher than the water potability standards (NBR 10004).

Paper, plastic (low-density polyethylene), and aluminium are classified as Class II A – non-inert, as they may exhibit water solubility, combustibility, and biodegradability. Since the residue is primarily composed of these components, its classification falls under Class II A according to NBR 10004.

Regarding its composition, it was identified that 91.42% of the waste is composed of paper (pulp from the first stage of the recycling process that was carried along with the PolyAl bales), while 8.57% consists of plastic and aluminium. As expected, it was not possible to separate these two materials, so they were accounted for together. This result makes sense since the residue is generated during the PolyAl cleaning stage, which aims to remove the remaining pulp.

Figure 5. From left to right: Residue before separation and residue after separation with its components: Paper and Plastic + Aluminium.

The average results and standard deviations of the immediate analysis and heating value of the residue can be seen in Table 1.

Table 1. Proximate analysis and heating value of the residue.

Properties	Fresh residue	Residue after 60 drying
MCwb (%)	69.02 ± 0.65 a	5.27 ± 0.16 b
A (%)	16.73 ± 0.6 a	14.23 ± 0.21 b
VM (%)	74.33 ± 1.07 b	77.51 ± 1.03 a
FC (%)	8.95 ± 1.3 a	8.26 ± 0.83 a
BD (kg m-3)	443.96 ± 23.57 a	139.42 ± 2.69 b
HHV (MJ Kg-1)	17.22 ± 0.41 a	17.89 ± 0.18 a
LHV (MJ Kg-1)	15.86 ± 0.41 a	16.99 ± 0.18 a
UHV (MJ Kg-1)	3.37 ± 0.17 b	15.76 ± 0.17 a

Note: The letters 'a' and 'b' represent the means ranked from highest to lowest within the same rows. The means that do not differ significantly at a 95% confidence level are marked with the same letters.

The analyzed residue exhibits characteristics that indicate both opportunities and challenges for its use in thermal applications. Its high moisture content (69.02%) highlights the need for pre-drying to enhance energy performance, as excessive moisture significantly reduces the useful calorific value (3.37 MJ/kg). The MC of 69% on a wet basis indicates that the material would need to undergo pre-drying to optimize its use in thermal processes, a common practice for biomass with high moisture levels (DUKU; GU; HAGAN; 2011). Besides that, the material's density significantly decreased after the residue was dried. This implies that, if transported in its original form, a substantial portion of its volume would consist of water, highlighting the importance of the drying process.

The volatile matter content suggests a strong potential for gas production, comparable to materials like Pinus (76.50%) and Soybean Residue (68.95%). However, the fixed carbon content is lower than that of Eucalyptus leaves (20.19%) and Soybean Residue (15.62%), indicating limited char production. The ash content is relatively high, resembling Rice Straw (15.25%) and Peanut Shells (12.15%), which may complicate its direct use in energy systems due to handling and equipment wear. Despite these challenges, the higher heating value is competitive, falling close to Soybean Residue (16.96 MJ/kg) and Peanut Shells (18.62 MJ/kg) (EUFRADE-JUNIOR, 2015; VASSILEV et al., 2010). These values demonstrate that, with proper treatment—such as drying and ash control—the residue could be effectively utilized in thermal conversion processes, particularly pyrolysis or combustion.

The drying methods adopted in this study proved to be effective: the material dried for 30 days without coverage reached a moisture content of 46.02%, while the material subjected to an additional 30 days of drying with coverage achieved a moisture content of 5.27%. With the reduction in moisture content after drying, the UHV was recalculated to assess the improvement in energy performance. For the residue dried for 30 days without ventilation, the UHV more than doubled, reaching 8.44 MJ/kg, indicating a substantial enhancement in its energy potential. This value is comparable to the useful calorific value of sugarcane bagasse, which, with a moisture content of 50%, achieves approximately 8.11 MJ/kg (Souza, 2015). For the residue that underwent an additional 30 days of air-drying outdoors in an open area with ventilation, totalling 60 days, the Useful Heating Value (UHV) reached 15.76 MJ/kg, with a moisture content of 5.27%. This value is comparable to the useful heating value of stumps and roots from planted forests, which reach approximately 13 MJ kg^{-1} at a moisture content of 17%, aligning with similar values when the moisture content is reduced, as observed with the residue in question (GUERRA et al., 2019). This similarity reinforces that prolonged covered drying can enhance the residue's energy potential to levels comparable to traditional biomass fuels.

Table 2 shown the ultimate composition of residue, which was analyzed only in its fresh state, without drying. The C/N ratio is an important measure of the material's decomposition rate and can affect its energy yield. It has a high C/N ratio, which indicates a good opportunity for storage and drying in the field

Table 2. Carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and sulfur (S) content of the fresh residue

	Arithmetic mean ± standard deviation
C (%)	40.27 ± 3.69
H (%)	4.02 ± 0.01
O (%)	38.75 ± 3.51
N (%)	0.24 ± 0.04
S(%)	0.61 ± 0.01

The presence of 40% carbon, 4% hydrogen, and 0.6% sulfur indicates a relatively rich organic composition with low sulfur content, which is beneficial for thermal processes such as combustion, minimizing the emission of polluting gases (BASU, 2013). Compared to other waste types, such as pure biomass or plastics without additives, the material studied can still be a viable energy source if appropriately treated, as noted by DEMIRBAS (2004) when studying the pyrolysis of plastic waste.

The analysis of the physical and chemical properties of the residue showed a reasonable potential for energy recovery, with the heating value of 17 MJ/kg. According to BRIDGWATER (2012), solid wastes with reasonable volatile and carbon content are suitable for pyrolysis, especially when there is a significant proportion of lignocellulosic materials. Additionally, MENIKPURA; SANG-ARUN; BENGTSSON (2014) demonstrated that pyrolysis yields better energy efficiency outcomes compared to incineration for mixed compositions, including plastics and biomass. A study by RAGAERT; DELVA; VAN GEEM (2017) highlights the feasibility of pyrolysis for multi-material packaging waste, emphasizing that despite the material's heterogeneity, the thermal separation of organic and inorganic components can produce valuable byproducts, such as bio-oil and combustible gases.

In Figure 6, which refers to the X-ray fluorescence (XRF) analysis, the x-axis is labeled “Channel,” representing the energy channels, ranging from approximately 25 to 825, and the y-axis is labeled “Count,” indicating the count of detected photons at each energy level, ranging from about 300 to 30,000. The three series are represented in the graph (Series1, Series2, Series3), indicating the similarity of the results. The X-ray fluorescence analysis of the sample confirms the presence of elements that can be attributed to the components of paper, plastic, and aluminum. The presence of calcium (Ca), silicon (Si), potassium (K), and sulfur (S) suggests the presence of paper (LIBRETEXTS). Titanium (Ti) and zinc (Zn) may be associated with additives in plastics (BAUTISTA-PÉREZ et al., 2024). Aluminum (Al) is clearly identified by the corresponding peak. The presence of iron (Fe) suggests that it may be present as an additive in the plastic or as a component of aluminum alloys in the sample, or it may be the result of contamination during the recycling process (EBHOTA; JEN, 2018).

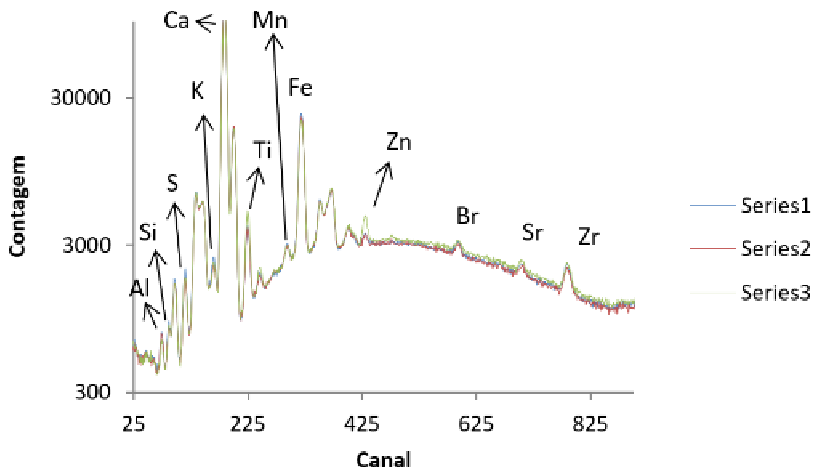

Figure 6: X-ray Fluorescence Analysis Graph

In Figure 7, it is possible to observe that the most intense peaks of X-ray Diffraction (XRD) are located around 20° and 30° in 2θ. The peak at 20° may be related to the presence of cellulose, which is the main component of paper. The diffraction pattern of cellulose can exhibit a characteristic peak in this region, indicating a significant amount of paper in the sample. Moreover, a strong peak at 20° suggests good crystallization of cellulose, which is common in high-quality papers (AHVENAINEN; KONTRO; SVEDSTRÖM, 2016). The peak at 30° may be associated with an amorphous phase or some other material present in the residue, possibly related to plastic. Many non-crystalline plastics exhibit a diffuse background, and a peak at 30° may be due to a small amount of semicrystalline material or additives present in the plastic (VONK; PIJPERS, 1985). Aluminium peaks generally occur around 38°, 44°, and 65° in 2θ. In Figure 7, no peaks were observed in these areas, indicating that the amount of aluminium present is low (AL-FADHALAH; ALMAZROUEE; ALORAIIER, 2014).

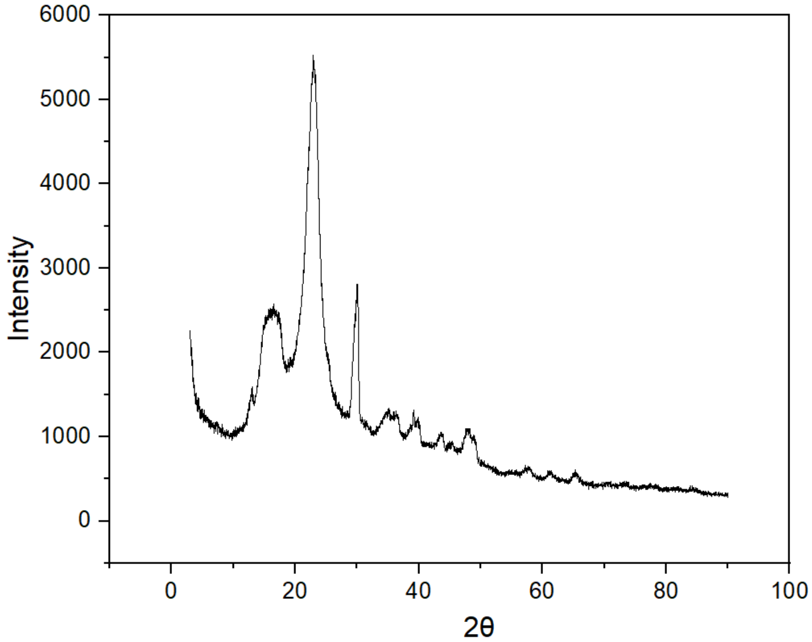

Figure 7: X-ray Diffraction Analysis Graph

In the images obtained from the Field Emission Gun Scanning Electron Microscope (FEG-SEM), the differentiation between the regions corresponding to paper (fibrous structures), plastic (smooth surfaces), and aluminum (reflective metallic surfaces) can be visualized. In Figure 8 (A), with a magnification of 50x, a heterogeneity in the distribution of the materials is noted, with variations in the size and shape of the particles. Figure 8 (B), with a magnification of 100x, reveals more precise details of the material structures. The long and intertwined fibers of the paper are clearly visible, as well as the continuous surfaces of the plastic and the reflective areas of the aluminium. The microstructural analysis indicates a good interface between the different materials, suggesting a homogeneous mixture. Figure 8 (C), with a magnification of 200x, confirms the previous observations, and the presence of particles of different sizes and shapes indicates a heterogeneous distribution of the materials in the sample. In Figure 8 (D), with a magnification of 500x, the layered structure with fibers or filaments intersecting at various angles suggests the complexity of the mixture of these materials in the sample. Figure 8 (E), with a magnification of 1000x, reveals a highly detailed surface with various crevices and protrusions. The long and intertwined fibers of the paper, the smooth surfaces of the plastic, and the reflective areas of the aluminium are clearly visible, indicating a complexity in the microstructure of the materials.

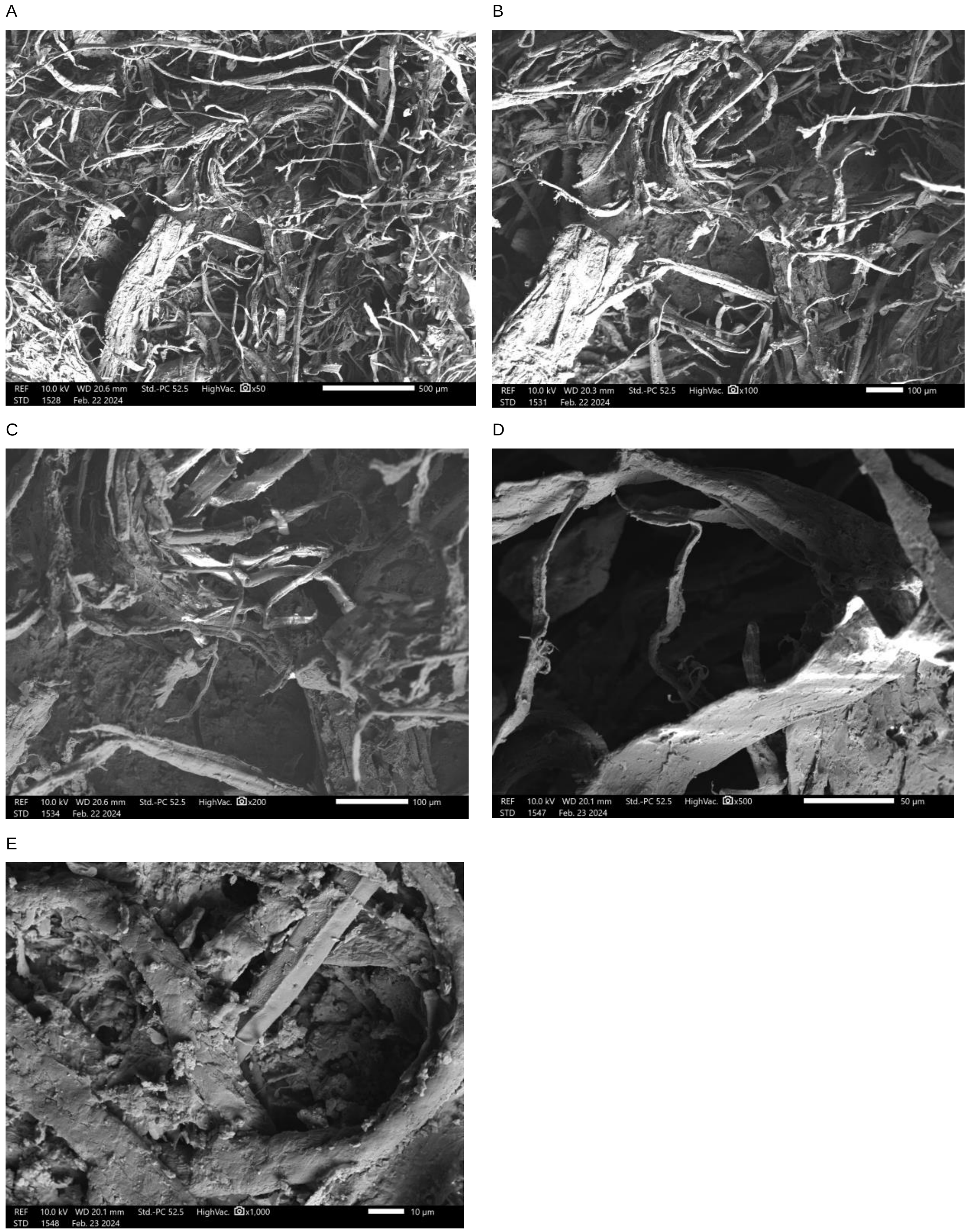

Figure 8. Morphology of the materials observed by scanning electron microscopy at (A) 50x magnification (B) 100x magnification (C) 200x magnification (D) 500x magnification (E) 1000x magnification

The SEM characterization of the waste material's interface confirms that material heterogeneity can influence thermal degradation behaviour. BRIDGWATER (2012) highlights how different surfaces, such as smooth plastics and intertwined fibers, can create distinct zones of thermal degradation, affecting reaction rates during pyrolysis. Similarly, LOPEZ, et al. (2011) demonstrated through SEM analysis that the combination of smooth plastic surfaces and fibrous materials results in heterogeneous degradation. Both studies suggest that pyrolysis remains an effective solution for processing multimaterial waste, optimizing the production of bio-oil and combustible gases despite varied degradation rates.

FTIR spectroscopy analysis was shown in Figure 9. It is important to observe that the infrared spectrum of polyethylene (PE) shows strong bands between 2848 cm^{-1} and 2919 cm^{-1}, corresponding to C-H stretching (JORDI, 2014; SMITH, 2021), as observed in Figure 9. The presence of paper can be identified through O-H stretching, with a peak around 3300 cm^{-1}, with a significant bandwidth due to hydrogen bonding (SMITH, 2024); and the C-O stretching peaks generally appear between 1300 and 1000 cm^{-1}, being intense and characteristic of functional groups containing the C-O bond (SMITH, 2017). Metallic aluminium does not show peaks in the IR spectrum (LUDWIG; BURKE, 2022). The Table 3 presents the main spectral bands observed in the FTIR analysis of the materials, along with their corresponding chemical attributions and references. These attributions highlight the functional groups or compounds responsible for the absorption at specific wavelengths, providing insights into the composition of the analyzed residue.

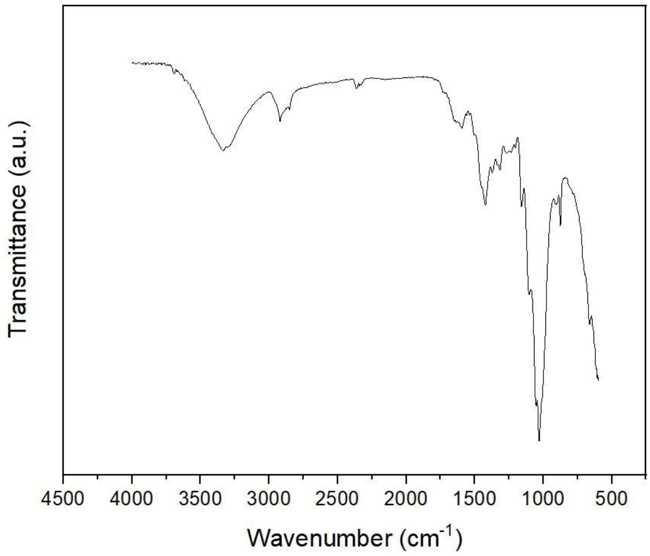

Figure 9: FTIR spectroscopy profile.

Table 3. FTIR Spectroscopy Bands and Attributions for Chemical Compounds

Spectral Bands (cm^{-1})	Attributions	References
2850, 2919	C-H stretching (Polyethylene)	SMITH (2021)
2848, 2916	C-H stretching (Polyethylene)	JORDI (2014)
3300	O-H stretching (Paper, hydrogen bonding)	SMITH (2024)
1300-1000	C-O stretching (Paper, functional groups with C-O bond)	SMITH (2017)

In Figure 10, the thermogravimetric analysis (TGA) shows a slight mass loss can in the temperature range up to 100°C, which is typically associated with the evaporation of water or other low-temperature volatiles (POLETTO et al., 2011). In the range of 200°C to 400°C, there is a significant decline in the mass loss curve, indicating an important degradation of the sample components. Cellulose, the major component of paper, begins to decompose at relatively low temperatures, between 200°C and 300°C, with the majority of mass loss occurring between 350°C and 400°C (LÓPEZ-BECEIRO et al., 2016). Polyethylene (PE) decomposes between 300°C and 500°C. High-Density Polyethylene (HDPE), the primary type of plastic present in the waste, exhibits stable thermal degradation behavior up to approximately 450°C, with most degradation occurring between 450°C and 500°C (FARD et al., 2020). After 600°C, the mass loss becomes more gradual, suggesting that a large portion of the combustible (organic) components has already decomposed. The remaining waste may contain inorganic aluminum components, which do not decompose at this temperature due to the metal's high resistance to oxidation and elevated melting point (660°C), thus remaining solid (CHEN; WANG; GAO, 2007). The red curve (first derivative) highlights the mass loss rates, with peaks corresponding to the moments of the most rapid decomposition. The sharper peaks around 300-400°C confirm the main decomposition of both paper and plastic.

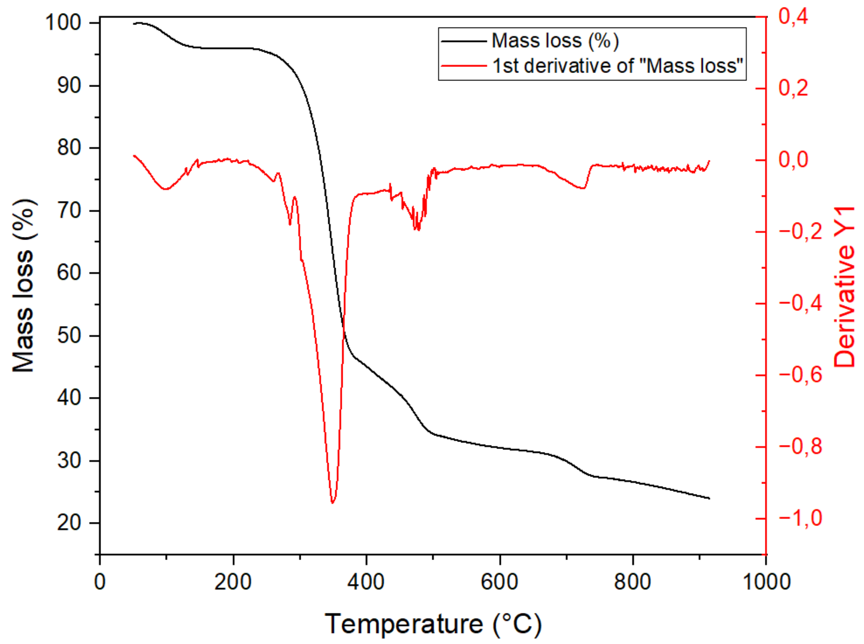

Figure 10: Thermal Analysis (TGA) Graph

The thermal analysis of the waste under TGA showed that a temperature range between 400°C and 550°C would be ideal for conducting pyrolysis. According to DIAZ-SILVARREY et al. (2018), pyrolysis of HDPE at around 500°C results in significant polymer degradation, with catalytic processes enhancing the production of valuable gases and oils. Similarly, cellulose, a major component of paper, starts decomposing between 200°C and 400°C, with the most mass loss occurring between 350°C and 400°C (LÓPEZ-BECEIRO et al., 2015).

2.4 CONCLUSION

The fresh residue, in its collected state, is not recommended for combustion due to its low Useful Heating Value (UHV). With a high moisture content, the energy potential remains insufficient for practical applications. However, the drying methods adopted in this study proved effective in significantly enhancing its energy performance. After 60 days of drying, including a covered period, the residue achieved a UHV comparable to stumps and roots from planted forests. This demonstrates that simple drying techniques can transform the residue into a viable energy source, with performance levels similar to traditional biomass fuels.

Based on the general technical requirements established by CETESB (Environmental Company of the State of São Paulo) and the criteria defined in Article 16 of Resolution SIMA 47/2020, the residue under study demonstrates potential for use as Refuse-Derived Fuel (RDF). Its classification as Class II A – non-hazardous, according to the ABNT NBR 10004 standard, confirms its suitability for the proposed application, given that RDF cannot be prepared from hazardous waste (Class I). Furthermore, the residue achieves a calorific value compatible with the minimum requirements for RDF, meeting the necessary environmental and energy criteria. Thus, the residue proves to be a viable and sustainable alternative for energy recovery.

Its high volatile matter content makes it favourable for initial burning, and its low carbon content indicates a faster combustion process. SEM and TGA analyses confirmed that the heterogeneous composition—both plastic and fibrous materials—affects thermal degradation, suggesting the residues can be also used to bio-oil production and combustible gases. A temperature range of 400°C to 550°C was identified, where HDPE and cellulose components degrade effectively.

Nonetheless, an optimal solution to prevent the generation of this residue would be the separation of its three constituent materials—paper, plastic, and aluminum—during the recycling process. Recycling each material individually would eliminate the production of this composite waste and align more closely with sustainable waste management practices.

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CHAPTER 3: VALORISATION OF NON-RECYCLABLE RESIDUES THROUGH PYROLYSIS

ABSTRACT

The primary recycling method for used beverage cartons (UBC) involves hydropulping, separating cellulose fibers from polyAl (polymer-aluminum) components. While cellulose fibers are recycled into paper products, the polyAl fraction generates a non-recyclable residue that is sent to landfills. Pyrolysis offers a sustainable alternative by converting this waste into valuable products like biochar, bio-oil, and gas while preventing microplastic formation. Co-pyrolysis, combining materials such as waste and wood, further enhances biochar properties, improving its suitability for soil health and carbon sequestration. This study evaluates the feasibility of pyrolysis to valorize UBC residues, focusing on sustainable biochar applications and contributing to waste valorization and decarbonization. Pyrolysis was conducted at three temperatures: 450°C, 550°C, and 750°C, using the residue as raw material. Additionally, co-pyrolysis with 75% *Eucalyptus urophylla x Eucalyptus grandis* wood chips was performed. The resulting biochar was analyzed for its physical and chemical properties to assess potential applications, including energy generation and soil amendment. The findings demonstrated that co-pyrolysis at 750°C significantly improved biochar properties, increasing fixed carbon content and energy retention (HHV > 30 MJ/kg). The biochar also provided essential nutrients such as calcium, magnesium, and potassium, enhancing its suitability for soil applications. Although high aluminum content may limit use in acidic soils, the biochar's low levels of toxic elements and proper management support its agricultural viability. These results highlight co-pyrolysis as a sustainable strategy for waste valorization and advancing decarbonization efforts.

3.1 INTRODUCTION

The main recycling method for used beverage cartons (UBC) is hydropulping, which separates cellulose fibers from polyAl (polymer-aluminum) components. The fibers are recycled into paper products, while polyAl is used to produce items like roof tiles and boards (ROBERTSON, 2021; NEVES, 2004). However, approximately 6% of

UBC weight becomes a non-recyclable byproduct during polyAl recycling, being sent to landfills. In Brazil, this reached 6,000 tons in 2023, considering that 100,000 tons were recycled (TETRA PAK, 2024), raising environmental concerns due to methane emissions and the presence of microplastics in the residue (GLOBAL METHANE INITIATIVE, 2020; SHEN *et al*., 2022).

The accumulation and degradation of plastics in landfills pose an environmental risk due to microplastic formation—plastic particles under 5 mm that fragment from larger waste over time (GEYER; JAMBECK; LAW, 2017). These particles are highly mobile in soil and groundwater, spreading across ecosystems where they can impact environmental and human health (ROCHMAN *et al*., 2015). In Brazil, which generated 13.7 million tons of plastic waste in 2022 (ABRELPE, 2023), addressing this issue is crucial. Measures to limit microplastic formation, like waste valorization technologies, are essential to reduce plastic disposal in landfills.

Pyrolysis emerges as a viable alternative for addressing the environmental risks posed by microplastic formation, particularly for residues that can be utilized as refuse-derived fuel (RDF). Unlike the degradation processes in landfills, which fragment plastics into persistent particles, pyrolysis decomposes materials into valuable products, effectively preventing microplastic generation (BAEYENS; BREMS; DEWIL, 2010). This process is especially advantageous for residues like RDF, which are unsuitable for direct combustion due to high moisture content or complex composition, as it transforms them into energy-rich byproducts while minimizing toxic emissions (AL-SALEM; LETTIERI; BAEYENS, 2017).

Pyrolysis is a thermochemical process in which organic materials, including biomass and certain types of waste, are decomposed at high temperatures (typically ranging from 400°C to 800°C) in the absence of oxygen. This process results in three primary products: biochar, a carbon-rich solid with applications as fuel, a soil amendment, or an adsorbent in industrial processes; bio-oil, a liquid with significant energy potential that can be refined into chemicals, fuels, or even precursors for new materials; and gas, a combustible mixture of gases such as carbon monoxide, hydrogen, and methane, suitable for heat or power generation (BASU, 2010; MOLDOVEANU, 2010).

Recent advancements in pyrolysis research have highlighted its remarkable versatility in converting diverse waste streams, such as municipal solid waste, single-use plastics, and wood residues, into high-value products with multiple applications. For example, pyrolysis of municipal solid waste, when optimized for temperature (300°C–900°C) and residence time, produces a range of products including energy-rich gases, bio-oil, and char, while minimizing environmental emissions (CHEN *et al*., 2014). Additionally, co-pyrolysis of materials like single-use plastics and Eucalyptus wood has proven effective in generating soil-enhancing composites with improved cation exchange capacity and electrical conductivity, promoting plant growth and increasing soil fertility (JAYANTHI *et al*., 2021). Similarly, pilot-scale pyrolysers have successfully transformed complex solid wastes, such as furniture wood and sewage sludge, into activated carbon with high microporosity, suitable for industrial adsorption processes (SAINZ-DÍAZ; GRIFFITHS, 2000).

Building on this versatility, pyrolysis also significantly contributes to decarbonization by addressing key environmental challenges. In landfills, the anaerobic decomposition of organic materials generates methane, a potent greenhouse gas with a global warming potential much higher than carbon dioxide. Pyrolysis, on the other hand, processes carbon-rich waste, converting it into valuable energy products. These products can replace fossil fuels, reducing dependency on these resources and the CO_2 emissions associated with their use (TÔRRES FILHO, 2014; CAIBRE et al., 2016).

This study aims to evaluate the feasibility of pyrolysis for treating the non-recyclable byproduct from used beverage carton recycling. By optimizing process conditions, it seeks to identify sustainable applications for the resulting biochar and other energy products, providing an alternative to landfilling while contributing to waste valorisation, decarbonization of the value chain, and environmental sustainability.

3.2 MATERIAL AND METHODS

3.2.1 Raw material

The material used in this research is a residue derived from the recycling process of used beverage cartons (UBC), classified as Class IIA, and composed of paper, plastic, and aluminium. Previously characterized, the residue analysis reveals strong potential for energy recovery, with a Useful Heating Value (UHV) of 15.76 MJ/kg after 60 days of drying, as well as high carbon and volatile content (see Chapter 2).

3.2.2 Experimental Method for Pyrolysis and Charcoal Yield

To obtain the charcoal and the pyroligneous liquor (IPL), pyrolysis processes were conducted in a laboratory muffle furnace (Figure 1 A), model Q318S from the manufacturer QUIMIS, in the absence of oxygen, using D. asper particles. The pyrolysis was carried out at three different temperatures: 450°C, 550°C, and 750°C. In the range of 400°C to 550°C, HDPE and cellulose components degrade effectively (López-Beceiro et al., 2015), while 660.32°C is the melting point of aluminum. The muffle furnace, equipped with electric resistance and temperature control, housed a metallic container (Figure 1 B) with a nominal volume of 500 cm^3. This container held approximately 100 g of the material to be pyrolyzed. The furnace was connected to a glass collection system designed to separate condensable gases. For the collection of pyroligneous liquors, a system of two glass condensers, coupled to a volumetric flask previously weighed on a semi-analytical balance, was connected to the metallic container already placed inside the laboratory muffle furnace. A flow of cold water circulated through the condensers throughout the entire process.

Figure 1. From left to right: A) Laboratory muffle coupled to the system of glass condensers and volumetric flask, used during the pyrolysis and collection of pyrolytic liquors; B) Metallic container.

For the pyrolysis process, the muffle furnace was calibrated with a heating ramp of 4°C per minute until the desired temperatures were reached. At the beginning of the procedure, a heating ramp to 110°C will be applied for 20 minutes to dry the material, followed by the ramp of 4°C per minute. Once the target temperature was achieved, the material in the metallic container was maintained at this temperature for 1 hour. Thus:

- **For the treatment at 450°C:** The muffle furnace was programmed to heat the material to 110°C for 20 minutes. Then, a ramp was applied to 200°C in 23 minutes, to 350°C in 38 minutes, and to 450°C in 25 minutes. The material was held at 450°C for 60 minutes.
- **For the treatment at 550°C:** The muffle furnace was programmed to heat the material to 110°C for 20 minutes. Then, a ramp was applied to 200°C in 23 minutes, to 350°C in 38 minutes, and to 550°C in 50 minutes. The material was held at 550°C for 60 minutes.

- **For the treatment at 750°C:** The muffle furnace was programmed to heat the material to 110°C for 20 minutes. Then, a ramp was applied to 200°C in 23 minutes, to 350°C in 38 minutes, to 550°C in 50 minutes, and to 750°C in 50 minutes. The material was held at 750°C for 60 minutes.

Before being placed in the metallic container and starting the pyrolysis procedure, the material was dried and weighed. After the procedure, the remaining solid material (charcoal) was weighed to determine its yield. Additionally, the mass of the condensable gases, which compose the pyroligneous liquor, was measured to calculate the overall conversion efficiency. Non-condensable gases were estimated by subtracting the initial mass of the residue from the combined masses of the charcoal and pyroligneous liquor. The yield of the charcoal was calculated using the Equation 1:

$$Charcoal\ Yield\ (\%) = \left(\frac{Mass\ of\ Charcoal\ (g)}{Initial\ mass\ of\ the\ material\ (g)}\right) \times 100 \qquad (1)$$

3.2.3 Charcoal characterization

3.2.3.1 Proximate Analysis

The proximate analysis consists of determined moisture content; volatile material (burned in the gaseous state); fixed carbon (burned in the solid state by difference) and ash (residual component after combustion), based on ASTM D1762-84 (2007).

To determine the moisture content of the sample, an indirect calculation based on the dry matter was used, obtained after complete drying in an oven at 105°C ± 3°C until a constant weight was achieved. The dry matter was expressed as the remaining solid fraction, and the moisture content was calculated by subtracting the percentage of dry matter from 100%, following the Equation 2:

$$Moisture\ (\%) = 100 - Dry\ matter\ (\%) \qquad (2)$$

Volatile matters refer to the part of the sample that is released when heated under a specified methodology. During this heating process, the biomass decomposes into gases and solid matter. This test method determines the percentage of gaseous products, excluding moisture vapor. The volatile matter content was obtained after the sample remained in the muffle at 950°C±10°C for six minutes. In turn, the ash is the solid residue produced by the process of thermochemical decomposition of the sample during combustion. It was obtained after keeping the sample in the muffle at 750°C±20°C for six hours (LEONELLO *et al.*, 2019).

The fixed carbon concentration is represented by the remaining material after the release of volatile matter, excluding ash and moisture content. This differs from the maximum carbon content of the sample since a part of the carbon is released in the form of hydrocarbons with the volatile matter (EUFRADE-JUNIOR, 2015). Therefore, the fixed carbon was obtained indirectly using Equation 3.

$$FC = 100 - (VM + A) \tag{3}$$

Where:
FC = Fixed carbon content (%);
VM = Volatile material content at the same reference moisture (%);
A = Ashes content at the same reference moisture (%).

3.2.3.2 Heating Value

The higher heating value of a material is defined as the total amount of energy released as heat when a unit mass of the material undergoes complete combustion, typically in the presence of excess oxygen (CORTEZ; LORA; GOMES, 2008). The Lower Heating Value (LHV) at dry basis is the amount of energy available (heat effectively possible to be used in fuels), considering the energy lost due to the vaporization of water. This value is determined using a sample of the material with a specified water content (SHENG; AZEVEDO, 2005).

To obtain the higher heating value (HHV), according to ASTM E711-84 (2023), an IKA® WERKE C200 calorimeter, linked with a KV 400 model thermostat and a C5010 model calorimetric bomb (or decomposition flask), was used. The samples were dried in an oven at 105°C ± 2°C prior to analysis.

To obtain the LHV, the Equation 4 was used:

$$LHV = HHV - 600 \times (9 \times \frac{H}{100}) \quad (4)$$

Where:
LHV = Lower heating value (Kcal Kg^{-1});
HHV = Higher heating value (Kcal Kg^{-1});
H = Hydrogen content (%).
The hydrogen content used for calculations was 4.02%, as determined in previous analyses of the non-carbonized residue

The Useful Heating Value (UHV), or Lower Heating Value (LHV) at wet basis (or as received), represents the effective heat quantity that a particular material is expected to produce, considering the residual moisture of the sample. It is referred to as "useful" because not all the available heat in the material will be fully utilized by the system. This happens due to the consumption of sensible and latent heat for the evaporation of residual moisture (DE PAIVA; DOS SANTOS FALCÃO FILHO, 2023). Equation 5 was used to obtain the UHV.

$$UHV = LHV \times \left(100 - \frac{MCwb}{100}\right) - 6 \times MCwb \quad (5)$$

Where:
UHV = Useful heating value (Kcal Kg^{-1});
LHV = Lower heating value (Kcal Kg^{-1});
MCwb = Moisture based on wet basis (%).

3.2.3.3 ICP-OES

For the ICP-OES (Inductively Coupled Plasma Optical Emission Spectroscopy) analysis, the charcoal obtained through pyrolysis at 450°C was used. Since the objective of this analysis was to understand the concentration of chemical elements, it was not necessary to perform it for all charcoal samples. The sample, which was previously dried in an oven to remove moisture, was finely ground before analysis. A blank sample was included to ensure there was no contamination, and an internal reference sample was used for quality control. Approximately 0.250 g of the sample was weighed with a precision of 0.01 g and transferred to a microwave vessel using parchment paper to prevent the sample from adhering to the vessel walls. In a fume hood and wearing gloves, 2 mL of hydrogen peroxide was added and left for 2 hours, followed by 5 mL of nitric acid, left until the next day, and finally 5 mL of ultrapure water. The caps were placed to allow for pressure relief. The extraction was microwave-assisted, with the tubes placed in the microwave carousel according to specific distribution rules. The heating program included controlled heating and cooling steps. After the program ended, the tubes were cooled in a fume hood, and the contents were filtered and transferred to Falcon tubes, adjusting the volume to 50 mL. The extract was then prepared for the analysis of the elements of interest. Samples with high levels of certain elements were diluted as necessary, and concentration calculations were performed considering these dilutions. The analysis was conducted at the Environmental Analysis Laboratory - Department of Soil Science, Esalq/USP, Piracicaba – SP.

Figure 2. From left to right: Finely ground charcoal ready for analysis; Tube containing the sample and digestive reagents; Tubes in the microwave.

3.2.4 Statistical analysis

To evaluate the significance of differences among the results obtained under different conditions, a two-sample t-test assuming equal variances was performed. This analysis aimed to identify statistically significant differences between treatments, considering a confidence level of 95%. The calculations were conducted using the statistical analysis tool in Excel (Data Analysis ToolPak), which provided the *t*-statistic, *p*-values, and critical *t*-values. The hypotheses tested were H_0 (no difference between the means) and H_1 (a difference exists between the means). Differences were considered significant when $p < 0.05$ or $t > t$-critical, and the results were analyzed to determine the statistical significance among the treatments.

3.3 RESULTS AND DISCUSSION

During the pyrolysis process, as shown in Figure 3, the charcoal yield decreased with the increase in temperature, while the yields of condensable vapors and non-condensable gases, despite being slightly different in the graph, did not present statistically significant differences according to the statistical analysis performed. Table 1 presents the linear regression coefficients for these relationships, with the slope (m) and y-intercept (b) for each product, as well as the coefficient of determination (R^2) for the regression models.

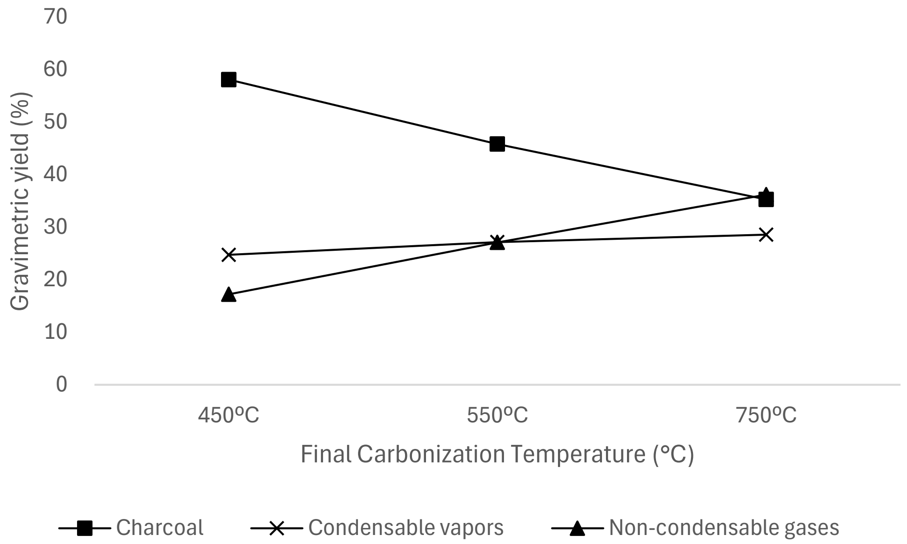

Figure 3. Gravimetric yields of the products from the carbonization of the residue generated in the recycling process of used beverage cartons at different final Carbonization temperatures

Table 1. Linear Regression Parameters Relating Temperature and Yield for Pyrolysis Products

Parameter	Charcoal	Condensable vapors	Non-condensable gases
Slope (m)	-11.398	1.9175	9.4809
Y-intercept (b)	69.163	22.975	7.8617
R^2	0.9979	0.9782	0.9994

For a better understanding of the behaviour of the charcoal yield, Figure 4 presents the average yield for each studied temperature. The statistical analysis revealed the following: 450 vs 550 – significant difference, with higher yield at 450°C; 450 vs 750 – highly significant difference, with higher yield at 450°C; 550 vs 750 – marginally significant difference in the one-tailed test (higher yield at 550°C).

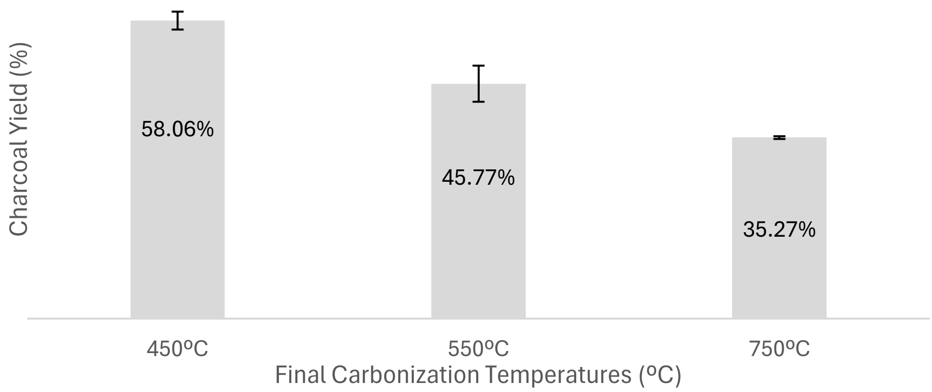

Figure 4. Charcoal yields from the carbonization of the residue generated in the recycling process of used beverage cartons at different final Carbonization temperatures

Figure 5 shows the charcoal produced during the pyrolysis process, along with the resulting pyroligneous liquor. These products demonstrate the transformation of the residue during thermal treatment, highlighting the different phases obtained after the controlled degradation of materials at high temperatures.

Figure 5. From left to right: charcoal and pyroligneous liquor obtained from the carbonization process of the residue from used beverage carton recycling

Table 2 presents the Moisture Content (MCwb), Volatile Matter (VM), Ash Content (A), and Fixed Carbon Content (FC) of the residue before carbonization and after carbonization at final temperatures of 450°C, 550°C, and 750°C. The results illustrate how the carbonization process alters these properties, with a significant reduction in moisture and volatile matter and an increase in ash and fixed carbon content as the temperature increases. These changes reflect the transformation of the residue into a more carbon-rich material with reduced volatile components at higher temperatures.

Table 2. Moisture Content, Volatile Matter, Ash Content, and Fixed Carbon Content of the Residue Before Carbonization and After Carbonization at Final Temperatures of 450°C, 550°C, and 750°C

Properties	Pure Residue	Charcoal at 450°C	Charcoal at 550°C	Charcoal at 750°C
MCwb (%)	5.27 ± 0.16 a	1.68 ± 0.07 c	1.59 ± 0.02 c	2.43 ± 0.12 b
VM (%)	77.51 ± 1.03 a	50.82 ± 1.38 b	30.57 ± 4.43 c	14.03 ± 0.99 d
A (%)	14.23 ± 0.21 c	26.66 ± 0.91 b	35.53 ± 1.52 a	46.39 ± 5.79 a
FC (%)	8.26 ± 0.83 c	22.52 ± 1.92 b	33.89 ± 5.90 a	39.58 ± 6.26 a

Note: The letters from 'a' to 'c' represent the means ranked from highest to lowest within the same rows. The means that do not differ significantly at a 95% confidence level are marked with the same letters.

Table 3 presents the Higher Heating Value (HHV), Lower Heating Value (LHV), and Useful Heating Value (UHV) of the residue both before and after carbonization at final temperatures of 450°C, 550°C, and 750°C. The results highlight that the carbonization process significantly influences the heating values, with the highest values observed at 450°C. Specifically, the UHV of the residue increased from 15.76 MJ/kg to 22.75 MJ/kg at 450°C, reflecting an enhancement in energy content. A similar trend is seen for HHV and LHV, which also peaked at 450°C and gradually decreased at higher temperatures.

Table 3. Higher Heating Value, Lower Heating Value and Useful Heating Value of the Residue Before Carbonization and After Carbonization at Final Temperatures of 450°C, 550°C, and 750°C

Heating Value	Pure Residue	Charcoal at 450°C	Charcoal at 550°C	Charcoal at 750°C
HHV (MJ/kg)	17.89 ± 0.18 c	25.35 ± 0.07 a	23.69 ± 0.13 b	18.28 ± 0.29 c
LHV (MJ/kg)	16.99 ± 0.18 c	24.44 ± 0.07 a	22.78 ± 0.13 b	17.37 ± 0.29 c
UHV (MJ/kg)	15.76 ± 0.17 c	22.75 ± 0.07 a	21.20 ± 0.12 b	16.12 ± 0.27 c

Note: The letters from 'a' to 'c' represent the means ranked from highest to lowest within the same rows. The means that do not differ significantly at a 95% confidence level are marked with the same letters.

The results obtained after carbonization are directly related to the initial composition of the residue, which is characterized by fibers with low lignin content. This profile results from the delignification process applied during kraft paper production, where lignin is removed to enhance the quality of cellulose fibers (FARIAS, 2017). This lower lignin content directly impacts the properties and charcoal yields observed during and after the carbonization process. The gradual decrease in charcoal yield was attributed to the decomposition of lignocellulose and the volatilization of organic matter. This explains the higher biochar yield observed at 450°C (MOHAMMAD *et al.*, 2015). Lignin, recognized for its higher thermal stability and broad decomposition range (200–800°C), contributes to fixed carbon formation and the release of volatiles at different stages of the process (EL-SAYED; MOSTAFA, 2014; DÍEZ *et al.*, 2020). The absence or low concentration of this component in the evaluated residue explains the lower fixed carbon content and the accelerated reduction in volatile matter, as compounds like hemicellulose and cellulose decompose at lower temperatures, whereas lignin exhibits greater thermal stability, releasing volatiles at higher temperature ranges (CARVALHO, 2022).

The increase in ash content with rising temperature, observed from 14.23% in the pure residue to 46.39% at 750°C, indicates the accumulation of inorganic compounds after the decomposition of organic matter. This behavior aligns with studies linking high ash contents to materials rich in mineral components, such as aluminum in the evaluated residue (FREITAS et al., 2012). Moisture content (MCwb) values decreased significantly after pyrolysis, with the lowest value observed at 550°C (1.59%). However, there was an unexpected increase at 750°C (2.43%), possibly due to moisture reabsorption during cooling or the formation of hydrophilic groups after high-temperature reactions.

The higher heating value (HHV) of biochar is significantly influenced by the pyrolysis temperature. Studies have shown that as the pyrolysis temperature increases, the HHV of biochar initially rises, reaching an optimal point, and then declines at higher temperatures. This trend is attributed to the retention of energy-dense compounds at moderate temperatures and the degradation of organic components at elevated temperatures. For instance, research indicates that biochar produced at 500°C exhibits a higher HHV compared to biochar produced at 350°C or 600°C, suggesting that moderate pyrolysis temperatures are favorable for producing biochar with high energy density (DHAR; SAKIB; HILARY, 2022).

The VM/FC ratio, as shown in Table 4, serves as an index of charcoal stability. The VM/FC ratios decreased significantly from 2.28 to 0.37 as the pyrolysis temperature increased from 450°C to 750°C. According to Nartey and Zhao (2014), biochar produced through pyrolysis achieves thermal and biological stability when the VM/FC ratio falls within the range of 0.21 to 0.28. This indicates that the charcoal produced at 750°C is nearly stable.

Table 4. VM/FC ratio After Carbonization at Final Temperatures of 450°C, 550°C, and 750°C

Properties	Charcoal at 450°C	Charcoal at 550°C	Charcoal at 750°C
VM/FC	2.28 ± 0.25	0.96 ± 0.33	0.37 ± 0.08

To address the limitations of the evaluated residue, co-pyrolysis with lignin-rich materials, such as wood chips and forestry residues, could be an effective strategy. This approach aims to enhance the fixed carbon content and improve the overall quality of the produced charcoal. The VM/FC ratio at 750°C indicates that charcoal at this temperature is nearing optimal stability. However, adding lignin-rich biomass could further enhance its properties by compensating for the low lignin content of the residue. This adjustment could lead to charcoal with a higher carbon density, reduced ash content, and better suitability for applications like carbon sequestration and soil improvement. To test this hypothesis, a co-pyrolysis experiment at 750°C was conducted using a mixture of 75% *Eucalyptus urophylla x Eucalyptus grandis* wood chips and 25% of the residue.

Table 5. Properties of Charcoal from the Co-Pyrolysis Experiment at 750°C Using a Mixture of 75% *Eucalyptus urophylla x Eucalyptus grandis*

Properties	Charcoal at 750°C (co-pyrolisis)
Charcoal Yield (%)	29.39 ± 0.27
VM (%)	7.61 ± 0.57
A (%)	10.98 ± 0.9
FC (%)	81.41 ± 1.46
HHV (MJ/kg)	30.21 ± 0.28
LHV (MJ/kg)	29.3 ± 0.28
UHV (MJ/kg)	27.30 ± 0.26

The co-pyrolysis yielded significant enhancements in the charcoal properties. Despite the charcoal yield being 29.39 ± 0.27%, the volatile matter (VM) content significantly decreased to 7.61 ± 0.57%, while the ash content (A) reduced to 10.98 ± 0.9%. Notably, the fixed carbon (FC) content increased substantially, reaching 81.41 ± 1.46%. The energy properties of the charcoal also demonstrated considerable improvements. The higher heating value (HHV) was measured at 30.21 ± 0.28 MJ/kg, while the lower heating value (LHV) and useful heating value (UHV) were recorded as 29.3 ± 0.28 MJ/kg and 27.30 ± 0.26 MJ/kg, respectively. These results indicate the biochar's enhanced energy retention, with values exceeding those of the charcoal produced at 450°C; and suggest the potential for dual-purpose applications: as an energy source and as biochar for soil improvement and carbon sequestration.

Biochar applications in soil serve as an effective strategy for carbon stock management and addressing climate change. Biochar significantly enhances soil organic carbon (SOC) levels, with studies demonstrating that its application can result in an average SOC stock increase of 11.5 to 14.6 Mg ha^{-1}, equivalent to a 26–33% relative increase (GROSS; BROMM; GLASER, 2021). To ensure the effective use of biochar in soil applications, it is essential to thoroughly understand its chemical composition, particularly the concentration of chemical elements. By understanding the chemical profile of biochar through ICP analysis, it is possible to tailor its application to specific soil and crop requirements.

As can be seen in the Table 6, the ICP-OES analysis of the solid residue revealed a high concentration of aluminum (51,014 ppm), likely due to the aluminum component of the analyzed material. Calcium also showed a high concentration (54,930 ppm), suggesting the presence of calcium-rich materials, such as paper or plastic. Other elements detected in moderate concentrations include iron (4,199 ppm), which may be associated with paints or contaminants; sulfur (3,976 ppm), possibly from additives or contaminants; potassium (982 ppm), associated with organic components of paper; magnesium (1,927 ppm); and silicon (2,294 ppm), which may come from plastic components. Toxic elements such as cadmium (1 ppm) was found in low concentrations, which is positive. Arsenic, mercury, molybdenum, and lead were not detected, which is favourable due to the toxicity of these elements.

Table 6. Concentration of the chemical elements (ppm) - ICP-OES analysis

Chemical Element	Concentration (ppm)
Al	51014
As	-
B	171
Ba	29
Ca	54930
Cd	1
Co	2
Cr	6
Cu	45
Fe	4199
Hg	-
K	982
Mg	1927
Mn	363
Mo	0
Ni	5
P	351
Pb	-
S	3976
Se	4
Si	2294
Ti	263
Zn	157

The results of the ICP-OES analysis indicate that the biochar produced contains key nutrients beneficial for soil applications, such as calcium (54,930 ppm), magnesium (1,927 ppm), and potassium (982 ppm), which are essential for improving soil fertility and plant growth. Calcium, in particular, plays a crucial role in ameliorating soil acidity and enhancing soil structure, making the biochar a potential liming agent (LEHMANN; JOSEPH, 2015). The low concentrations of toxic elements like cadmium (1 ppm), alongside the absence of arsenic, mercury, and lead, further support the suitability of this biochar for soil use, minimizing environmental risks (JEFFERY *et al*., 2011). However, the high aluminium content (51,014 ppm) raises concerns, especially in acidic soils where aluminium becomes more bioavailable and can impede root growth (NARTEY; ZHAO, 2014). In particular, NOVAIS et al. (1990) demonstrated that the genus *Eucalyptus* is highly tolerant to exchangeable aluminum in dystrophic soils and efficiently absorbs nitrogen in its ammoniacal form. To mitigate this, the biochar could be blended with amendments or applied to neutral or alkaline soils. These findings align with studies such as Cho et al. (2017), which demonstrated improvements in soil quality and tree growth with biochar from wood chips and rice husks, and Rockwood et al. (2020), which highlighted the potential of biochar for long-term carbon sequestration in *Eucalyptus spp.* plantations. Additionally, Chandra et al. (2022) emphasized that biochar from *Eucalyptus* wood increased soil fertility and reduced metal toxicity in contaminated soils, demonstrating its capacity to enhance nutrient availability and mitigate environmental stress.

3.4 CONCLUSION

The study demonstrated that the pyrolysis of the evaluated residue, particularly when combined with lignin-rich materials like *Eucalyptus* wood chips, significantly enhances biochar properties. While the residue's low lignin content initially limited fixed carbon formation and thermal stability, the co-pyrolysis approach at 750°C successfully increased the biochar's fixed carbon content, energy retention, and overall quality. The resulting biochar exhibits favorable characteristics for dual-purpose applications: as an energy source, with higher heating values exceeding 30 MJ/kg, and as a soil amendment, providing essential nutrients such as calcium, magnesium, and potassium, which are vital for improving soil fertility and plant growth.

Despite the high aluminum content, which could pose challenges in acidic soils, the biochar's low concentrations of toxic elements like cadmium and its high nutrient content make it a viable option for agricultural applications when properly managed. In particular, aluminum still needs to be studied in order to assess its form and whether it would be available to the plant. This aligns with previous studies demonstrating biochar's ability to improve soil quality, support carbon sequestration, and mitigate environmental stress. These findings highlight the potential of co-pyrolysis as a sustainable approach to waste valorization, offering opportunities to advance energy production and agricultural sustainability while addressing climate change challenges.

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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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APPENDIX A

reference	country	city	state	lat	long	elev	temp	rain	soil	specie	age	stand_density	carbon_ha	carbon_ha_year
Stape et al., 2010	Brazil	Aracruz	ES	-19.82	-40.08	12	23.6	1360	acrisols	eucalyptus spp.	6	1100	49.46	8.24
Stape et al., 2010	Brazil	Aracruz	ES	-19.82	-40.08	12	23.6	1360	acrisols	eucalyptus spp.	6	1100	51.80	8.63
Stape et al., 2010	Brazil	Aracruz	ES	-19.82	-40.08	12	23.6	1360	acrisols	eucalyptus spp.	6	1111	76.10	12.68
Stape et al., 2010	Brazil	Guanhaes	MG	-19.82	-40.08	870	23.6	1360	acrisols	eucalyptus spp.	6	1069	65.03	10.84
Stape et al., 2010	Brazil	Guanhaes	MG	-18.58	-42.98	870	19.4	1108	ferralsols	eucalyptus spp.	5	1111	50.36	9.50
Stape et al., 2010	Brazil	Guanhaes	MG	-18.58	-42.98	870	19.4	1108	ferralsols	eucalyptus spp.	5	1095	57.29	10.81
Stape et al., 2010	Brazil	Guanhaes	MG	-18.58	-42.98	870	19.4	1108	ferralsols	eucalyptus spp.	5	1111	58.95	11.12
Stape et al., 2010	Brazil	Guanhaes	MG	-18.58	-42.98	870	19.4	1108	ferralsols	eucalyptus spp.	5	1095	62.51	11.79
Stape et al., 2010	Brazil	Guanhaes	MG	-18.58	-42.98	870	19.4	1108	ferralsols	eucalyptus spp.	5	1041	61.92	11.68
Stape et al., 2010	Brazil	Mogi Guacu	SP	-22.35	-46.97	312	21.6	1317	ferralsols	eucalyptus spp.	6	1153	69.21	11.54
Stape et al., 2010	Brazil	Mogi Guacu	SP	-22.35	-46.97	312	21.6	1317	ferralsols	eucalyptus spp.	6	1161	71.73	11.96
Stape et al., 2010	Brazil	Mogi Guacu	SP	-22.35	-46.97	312	21.6	1317	ferralsols	eucalyptus spp.	6	1186	92.61	15.44
Stape et al., 2010	Brazil	Mogi Guacu	SP	-22.35	-46.97	312	21.6	1317	ferralsols	eucalyptus spp.	6	1161	85.77	14.30
Stape et al., 2010	Brazil	Mogi Guacu	SP	-22.35	-46.97	312	21.6	1317	ferralsols	eucalyptus spp.	6	1085	61.74	10.29
Stape et al., 2010	Brazil	Mogi Guacu	SP	-22.35	-46.97	312	21.6	1317	ferralsols	eucalyptus spp.	6	1136	77.85	12.98
Stape et al., 2010	Brazil	Teixeira de Freitas	BA	-18.03	-39.87	84	23.1	1351	acrisols	eucalyptus spp.	6	1111	53.01	9.64
Stape et al., 2010	Brazil	Teixeira de Freitas	BA	-18.03	-39.87	84	23.1	1351	acrisols	eucalyptus spp.	6	1087	53.42	9.71
Stape et al., 2010	Brazil	Teixeira de Freitas	BA	-18.03	-39.87	84	23.1	1351	acrisols	eucalyptus spp.	6	1041	65.39	11.89
Stape et al., 2010	Brazil	Teixeira de Freitas	BA	-18.03	-39.87	84	23.1	1351	acrisols	eucalyptus spp.	6	1087	46.76	8.50
Stape et al., 2010	Brazil	Teixeira de Freitas	BA	-18.03	-39.87	84	23.1	1351	acrisols	eucalyptus spp.	6	1018	62.19	11.31
Stape et al., 2010	Brazil	Luis Antonio	SP	-21.53	-48.37	680	22.0	1307	gleysols	eucalyptus spp.	3	966	14.04	5.01
Stape et al., 2010	Brazil	Luis Antonio	SP	-21.53	-48.37	680	22.0	1307	gleysols	eucalyptus spp.	3	1041	19.67	7.02
Stape et al., 2010	Brazil	Luis Antonio	SP	-21.53	-48.37	680	22.0	1307	gleysols	eucalyptus spp.	3	1056	20.34	7.26
Stape et al., 2010	Brazil	Luis Antonio	SP	-21.53	-48.37	680	22.0	1307	gleysols	eucalyptus spp.	3	948	26.87	9.59
Stape et al., 2010	Brazil	Luis Antonio	SP	-21.53	-48.37	680	22.0	1307	gleysols	eucalyptus spp.	3	1080	31.41	11.22
Stape et al., 2010	Brazil	Luis Antonio	SP	-21.53	-48.37	680	22.0	1307	gleysols	eucalyptus spp.	3	894	27.14	9.69
Stape et al., 2010	Brazil	Eunapolis	BA	-16.35	-39.57	187	23.0	1433	acrisols	eucalyptus spp.	6	1087	80.42	13.40
Stape et al., 2010	Brazil	Eunapolis	BA	-16.35	-39.57	187	23.0	1433	acrisols	eucalyptus spp.	6	1064	85.73	14.29
Stape et al., 2010	Brazil	Eunapolis	BA	-16.35	-39.57	187	23.0	1433	acrisols	eucalyptus spp.	6	1072	99.09	16.52
Stape et al., 2010	Brazil	Eunapolis	BA	-16.35	-39.57	187	23.0	1433	acrisols	eucalyptus spp.	6	1080	96.66	16.11
Stape et al., 2010	Brazil	Eunapolis	BA	-16.35	-39.57	187	23.0	1433	acrisols	eucalyptus spp.	6	1103	64.98	10.83

Stape et al., 2010	Brazil	Eunapolis	BA	-16.35	-39.57	187	23.0	1433	acrisols	eucalyptus spp.	6	918	79.47	13.25
Stape et al., 2010	Brazil	Luis Antonio	SP	-21.53	-48.37	680	22.7	1247	gleysols	eucalyptus spp.	5	1318	30.92	6.44
Stape et al., 2010	Brazil	Luis Antonio	SP	-21.53	-48.37	680	22.7	1247	gleysols	eucalyptus spp.	5	1210	51.35	10.70
Stape et al., 2010	Brazil	Luis Antonio	SP	-21.53	-48.37	680	22.7	1247	gleysols	eucalyptus spp.	5	1266	51.35	10.70
Stape et al., 2010	Brazil	Luis Antonio	SP	-21.53	-48.37	680	22.7	1247	gleysols	eucalyptus spp.	5	1310	67.82	14.13
Stape et al., 2010	Brazil	Luis Antonio	SP	-21.53	-48.37	680	22.7	1247	ferralsols	eucalyptus spp.	5	1088	59.99	12.50
Stape et al., 2010	Brazil	Bocaiuva	MG	-17.33	-43.83	900	23.6	848	ferralsols	eucalyptus spp.	5	1018	42.17	9.37
Stape et al., 2010	Brazil	Bocaiuva	MG	-17.33	-43.83	900	23.6	848	ferralsols	eucalyptus spp.	5	1080	48.65	10.81
Stape et al., 2010	Brazil	Bocaiuva	MG	-17.33	-43.83	900	23.6	848	ferralsols	eucalyptus spp.	5	1056	75.65	16.81
Stape et al., 2010	Brazil	Bocaiuva	MG	-17.33	-43.83	900	23.6	848	ferralsols	eucalyptus spp.	5	1056	76.95	17.10
Stape et al., 2004	Brazil	Entre-Rios	MG	-11.92	-38.53	230	25.5	882	arenosols	eucalyptus grandis x eucalyptus urophylla	5	1098.901099	35.24	6.91
Stape et al., 2004	Brazil	Entre-Rios	MG	-11.95	-38.48	270	25.5	916	arenosols	eucalyptus grandis x eucalyptus urophylla	7	1098.901099	36.45	5.06
Stape et al., 2004	Brazil	Entre-Rios	MG	-11.78	-38.55	210	25.5	853	ferralsols	eucalyptus grandis x eucalyptus urophylla	6	1098.901099	30.11	4.94
Stape et al., 2004	Brazil	Entre-Rios	MG	-11.85	-38.47	250	25.5	935	ferralsols	eucalyptus grandis x eucalyptus urophylla	7	1098.901099	42.57	6.00
Stape et al., 2004	Brazil	Entre-Rios	MG	-11.82	-38.37	220	25.5	902	acrisols	eucalyptus grandis x eucalyptus urophylla	7	1098.901099	35.42	4.85
Stape et al., 2004	Brazil	Entre-Rios	MG	-11.97	-38.55	300	25.5	955	arenosols	eucalyptus grandis x eucalyptus urophylla	6	1098.901099	40.77	6.80
Stape et al., 2004	Brazil	Entre-Rios	MG	-11.78	-37.90	150	25.5	1143	acrisols	eucalyptus grandis x eucalyptus urophylla	5	1098.901099	43.97	8.62
Stape et al., 2004	Brazil	Entre-Rios	MG	-12.03	-38.47	310	25.5	958	acrisols	eucalyptus grandis x eucalyptus urophylla	5	1098.901099	36.99	7.40
Stape et al., 2004	Brazil	Entre-Rios	MG	-12.08	-38.25	180	25.5	1008	arenosols	eucalyptus grandis x eucalyptus urophylla	6	1098.901099	45.59	7.24
Stape et al., 2004	Brazil	Entre-Rios	MG	-11.97	-38.12	180	25.5	1131	acrisols	eucalyptus grandis x eucalyptus urophylla	6	1098.901099	51.35	8.42
Stape et al., 2004	Brazil	Entre-Rios	MG	-12.00	-38.23	200	25.5	1054	acrisols	eucalyptus grandis x eucalyptus urophylla	6	1098.901099	55.80	9.00
Stape et al., 2004	Brazil	Entre-Rios	MG	-12.27	-38.85	50	25.5	1605	arenosols	eucalyptus grandis x eucalyptus urophylla	8	1098.901099	66.38	8.40
Stape et al., 2004	Brazil	Entre-Rios	MG	-12.30	-38.02	80	25.5	1611	acrisols	eucalyptus grandis x eucalyptus urophylla	6	1098.901099	90.86	14.42
Stape et al., 2004	Brazil	Entre-Rios	MG	-12.25	-38.95	100	25.5	1654	acrisols	eucalyptus grandis x eucalyptus urophylla	6	1098.901099	91.80	14.57
Ribeiro et al., 2014	Brazil	Curvelo	MG	-18.80	-44.40	600	23.5	1150	ferralsols	eucalyptus urophylla x eucalyptus grandis	6	1111	52.56	9.56
Valadao et al., 2020	Brazil	Distrito Federal	DF	-15.97	-47.90	1087	21.9	1443	ferralsols	eucalyptus urophylla x eucalyptus grandis	6	1666	81.63	13.61
Jose et al. 2020	Brazil	Barra do Ribeiro	RS	-30.39	-51.13	5	19.5	1400	planosols	eucalyptus saligna	7	1666	57.91	8.27
Binkley et al., 2017	Brazil	Telemaco Borba	PR	-24.32	-50.53	888	19.8	1554	nitisols	eucalyptus urophylla	6	1111	91.80	15.30
Binkley et al., 2017	Brazil	Mogi Guaçu	SP	-22.35	-46.97	633	23.1	1224	lixisols	eucalyptus urophylla	6	1111	51.30	8.55
Binkley et al., 2017	Brazil	Bocaiúva	MG	-17.32	-43.77	848	25.6	507	ferralsols	eucalyptus urophylla	6	1111	59.40	9.90
Binkley et al., 2017	Brazil	Telemaco Borba	PR	-24.32	-50.53	888	19.8	1554	nitisols	eucalyptus grandis x eucalyptus camaldulensis	6	1111	124.20	20.70
Binkley et al., 2017	Brazil	Mogi Guaçu	SP	-22.35	-46.97	633	23.1	1224	lixisols	eucalyptus grandis x eucalyptus camaldulensis	6	1111	32.40	5.40
Binkley et al., 2017	Brazil	Bocaiúva	MG	-17.32	-43.77	848	25.6	507	ferralsols	eucalyptus grandis x eucalyptus camaldulensis	6	1111	37.80	6.30
Eufrade et. al. 2020	Brazil	Ribas do Rio Pardo	MS	-20.32	-53.29	380	24.9	1252	ferralsols	eucalyptus urophylla	7	987	15.98	2.35

Eufrade et. al. 2020	Brazil	Ribas do Rio Pardo	MS	-20.32	-53.29	380	24.9	1252	ferralsols	eucalyptus urophylla x eucalyptus camaldulensis	6	1037	19.22	3.05
Eufrade et. al. 2020	Brazil	Ribas do Rio Pardo	MS	-20.32	-53.29	380	24.9	1252	ferralsols	eucalyptus urophylla	6	1703	20.57	3.43
Eufrade et. al. 2020	Brazil	Ribas do Rio Pardo	MS	-20.32	-53.29	380	24.9	1252	ferralsols	eucalyptus urophylla x eucalyptus camaldulensis	6	1635	43.47	7.63
Ribeiro et al., 2017	Brazil	Lençóis Paulista	SP	-22.81	-48.80	550	21.0	1330	ferralsols	eucalyptus grandis x eucalyptus urophylla	6	2469	87.75	14.63
Ribeiro et al., 2017	Brazil	Lençóis Paulista	SP	-22.81	-48.80	550	21.0	1330	ferralsols	eucalyptus grandis x eucalyptus urophylla	6	2020	85.50	14.25
Ribeiro et al., 2017	Brazil	Lençóis Paulista	SP	-22.81	-48.80	550	21.0	1330	ferralsols	eucalyptus grandis x eucalyptus urophylla	6	1709	84.60	14.10
Ribeiro et al., 2017	Brazil	Lençóis Paulista	SP	-22.81	-48.80	550	21.0	1330	ferralsols	eucalyptus grandis x eucalyptus urophylla	6	1481	83.25	13.88
Ribeiro et al., 2017	Brazil	Lençóis Paulista	SP	-22.81	-48.80	550	21.0	1330	ferralsols	eucalyptus grandis x eucalyptus urophylla	6	1282	81.90	13.65
Ribeiro et al., 2017	Brazil	Lençóis Paulista	SP	-22.81	-48.80	550	21.0	1330	ferralsols	eucalyptus grandis x eucalyptus urophylla	6	1111	80.10	13.35
Ribeiro et al., 2017	Brazil	Lençóis Paulista	SP	-22.81	-48.80	550	21.0	1330	ferralsols	eucalyptus grandis x eucalyptus urophylla	6	980	78.75	13.13
Ribeiro et al., 2017	Brazil	Lençóis Paulista	SP	-22.81	-48.80	550	21.0	1330	ferralsols	eucalyptus grandis x eucalyptus urophylla	6	877	76.50	12.75
Ribeiro et al., 2017	Brazil	Lençóis Paulista	SP	-22.81	-48.80	550	21.0	1330	ferralsols	eucalyptus grandis x eucalyptus urophylla	6	784	74.25	12.38
Ribeiro et al., 2017	Brazil	Lençóis Paulista	SP	-22.81	-48.80	550	21.0	1330	ferralsols	eucalyptus grandis x eucalyptus urophylla	6	635	68.85	11.48
Campoe et al., 2013	Brazil	Itatinga	SP	-22.97	-48.72	738	19.2	1277	ferralsols	eucalyptus grandis	6	1666	92.03	15.34
Campoe et al., 2013	Brazil	Itatinga	SP	-22.97	-48.72	738	19.2	1277	ferralsols	eucalyptus grandis	6	1666	64.75	10.79
Campoe et al., 2013	Brazil	Itatinga	SP	-22.97	-48.72	738	19.2	1277	ferralsols	eucalyptus grandis	6	1666	76.52	12.75
Campoe et al., 2013	Brazil	Itatinga	SP	-22.97	-48.72	738	19.2	1277	ferralsols	eucalyptus grandis	6	1666	80.53	13.42
Campoe et al., 2013	Brazil	Itatinga	SP	-22.97	-48.72	738	19.2	1277	ferralsols	eucalyptus grandis	6	1666	82.32	13.72
Campoe et al., 2013	Brazil	Itatinga	SP	-22.97	-48.72	738	19.2	1277	ferralsols	eucalyptus grandis	6	1666	73.00	12.17
Campoe et al., 2013	Brazil	Itatinga	SP	-22.97	-48.72	738	19.2	1277	ferralsols	eucalyptus grandis	6	1666	51.25	8.54
Campoe et al., 2013	Brazil	Itatinga	SP	-22.97	-48.72	738	19.2	1277	ferralsols	eucalyptus grandis	6	1666	54.37	9.06
Campoe et al., 2013	Brazil	Itatinga	SP	-22.97	-48.72	738	19.2	1277	ferralsols	eucalyptus grandis	6	1666	56.50	9.42
Campoe et al., 2013	Brazil	Itatinga	SP	-22.97	-48.72	738	19.2	1277	ferralsols	eucalyptus grandis	6	1666	54.24	9.04
Campoe et al., 2013	Brazil	Itatinga	SP	-22.97	-48.72	738	19.2	1277	ferralsols	eucalyptus grandis	6	1666	58.07	9.68
Campoe et al., 2013	Brazil	Itatinga	SP	-22.97	-48.72	738	19.2	1277	ferralsols	eucalyptus grandis	6	1666	53.76	8.96
Hubbard et al., 2010	Brazil	Aracruz	ES	-19.82	-40.08	60	24.0	1250	acrisols	eucalyptus grandis x eucalyptus urophylla	5	1111	39.60	7.92
Hubbard et al., 2010	Brazil	Aracruz	ES	-19.82	-40.08	60	24.0	1250	acrisols	eucalyptus grandis x eucalyptus urophylla	5	1111	63.45	12.69
Hubbard et al., 2010	Brazil	Eunapolis	BA	-16.35	-39.57	189	24.0	1180	acrisols	eucalyptus grandis x eucalyptus urophylla	5	1111	76.95	15.39
Hubbard et al., 2010	Brazil	Eunapolis	BA	-16.35	-39.57	189	24.0	1180	acrisols	eucalyptus grandis x eucalyptus urophylla	5	1111	80.10	16.02
le Maire et al., 2013	Brazil	Itatinga	SP	-23.03	-48.63	845	19.0	1360	ferralsols	eucalyptus grandis	6	1111	67.50	11.25
Eufrade et. al. 2021	Brazil	Botucatu	SP	-22.89	-48.45	872	20.0	1428	ferralsols	eucalyptus urophylla x eucalyptus grandis	2	2380	7.15	3.57
Eufrade et. al. 2021	Brazil	Botucatu	SP	-22.89	-48.45	872	20.0	1428	ferralsols	eucalyptus urophylla x eucalyptus grandis	2	2380	10.51	5.25
Eufrade et. al. 2021	Brazil	Botucatu	SP	-22.89	-48.45	872	20.0	1428	ferralsols	eucalyptus urophylla x eucalyptus grandis	2	2380	10.33	5.16
Eufrade et. al. 2021	Brazil	Botucatu	SP	-22.89	-48.45	872	20.0	1428	ferralsols	eucalyptus urophylla x eucalyptus grandis	2	1786	11.08	5.54

Eufrade et. al. 2021	Brazil	Botucatu	SP	-22.89	-48.45	872	20.0	1428	ferralsols	eucalyptus urophylla x eucalyptus grandis	2	1786	13.81	6.91
Eufrade et. al. 2021	Brazil	Botucatu	SP	-22.89	-48.45	872	20.0	1428	ferralsols	eucalyptus urophylla x eucalyptus grandis	2	1786	14.94	7.47
Eufrade et. al. 2021	Brazil	Botucatu	SP	-22.89	-48.45	872	20.0	1428	ferralsols	eucalyptus urophylla x eucalyptus grandis	2	1429	14.38	7.19
Eufrade et. al. 2021	Brazil	Botucatu	SP	-22.89	-48.45	872	20.0	1428	ferralsols	eucalyptus urophylla x eucalyptus grandis	2	1429	13.87	6.94
Eufrade et. al. 2021	Brazil	Botucatu	SP	-22.89	-48.45	872	20.0	1428	ferralsols	eucalyptus urophylla x eucalyptus grandis	2	1429	15.65	7.83
Araujo et al. 2021	Brazil	Chapadão do Sul	MS	-18.80	-52.60	820	22.0	1850	ferralsols	eucalyptus grandis x eucalyptus urophylla	7	1058	94.24	13.46
Araujo et al. 2021	Brazil	Chapadão do Sul	MS	-18.80	-52.60	820	22.0	1850	ferralsols	eucalyptus grandis x eucalyptus urophylla	7	546	93.66	13.38
Araujo et al. 2021	Brazil	Chapadão do Sul	MS	-18.80	-52.60	820	22.0	1850	ferralsols	eucalyptus grandis x eucalyptus urophylla	7	404	79.13	11.30
Araujo et al. 2021	Brazil	Chapadão do Sul	MS	-18.80	-52.60	820	22.0	1850	ferralsols	eucalyptus grandis x eucalyptus urophylla	7	1058	82.75	11.82
Araujo et al. 2021	Brazil	Chapadão do Sul	MS	-18.80	-52.60	820	22.0	1850	ferralsols	eucalyptus grandis x eucalyptus urophylla	7	546	77.45	11.06
Araujo et al. 2021	Brazil	Chapadão do Sul	MS	-18.80	-52.60	820	22.0	1850	ferralsols	eucalyptus grandis x eucalyptus urophylla	7	404	63.64	9.09
Araujo et al. 2021	Brazil	Chapadão do Sul	MS	-18.80	-52.60	820	22.0	1850	ferralsols	eucalyptus grandis x eucalyptus urophylla	7	1058	89.18	12.74
Araujo et al. 2021	Brazil	Chapadão do Sul	MS	-18.80	-52.60	820	22.0	1850	ferralsols	eucalyptus grandis x eucalyptus urophylla	7	546	64.48	9.21
Araujo et al. 2021	Brazil	Chapadão do Sul	MS	-18.80	-52.60	820	22.0	1850	ferralsols	eucalyptus grandis x eucalyptus urophylla	7	404	67.07	9.58
Araujo et al. 2021	Brazil	Chapadão do Sul	MS	-18.80	-52.60	820	22.0	1850	ferralsols	eucalyptus grandis x eucalyptus urophylla	7	1058	79.79	11.40
Araujo et al. 2021	Brazil	Chapadão do Sul	MS	-18.80	-52.60	820	22.0	1850	ferralsols	eucalyptus grandis x eucalyptus urophylla	7	546	55.82	7.97
Araujo et al. 2021	Brazil	Chapadão do Sul	MS	-18.80	-52.60	820	22.0	1850	ferralsols	eucalyptus grandis x eucalyptus urophylla	7	404	59.20	8.46
Watzlawick. et al., 2020	Brazil	Guarapuava	PR	-25.40	-51.50	1098	17.5	1900	ferralsols	eucalyptus benthamii	6	1666.666667	62.85	10.48
Watzlawick. et al., 2020	Brazil	Guarapuava	PR	-25.40	-51.50	1098	17.5	1900	ferralsols	eucalyptus benthamii	6	1111.111111	50.01	8.33
Watzlawick. et al., 2020	Brazil	Guarapuava	PR	-25.40	-51.50	1098	17.5	1900	ferralsols	eucalyptus benthamii	6	833.3333333	44.87	7.48
Watzlawick. et al., 2020	Brazil	Guarapuava	PR	-25.40	-51.50	1098	17.5	1900	ferralsols	eucalyptus benthamii	6	625	36.23	6.04
Viera & Rodríguez-Soalleiro, 2019	Brazil	Eldorado do Sul	RS	-30.20	-51.60	175	18.9	1600	planosols	eucalyptus urophylla × eucalyptus globulus	10	1043	111.97	11.20
Campoe et al., 2012	Brazil	Itatinga	SP	-23.00	-48.70	726	19.2	1646	ferralsols	eucalyptus grandis	6	1666	91.40	15.23
Campoe et al., 2012	Brazil	Itatinga	SP	-23.00	-48.70	727	19.2	1646	ferralsols	eucalyptus grandis	6	1666	76.80	12.80
Campoe et al., 2012	Brazil	Itatinga	SP	-23.00	-48.70	730	19.2	1646	ferralsols	eucalyptus grandis	6	1666	86.70	14.45
Campoe et al., 2012	Brazil	Itatinga	SP	-23.00	-48.70	731	19.2	1646	ferralsols	eucalyptus grandis	6	1666	79.60	13.27
Campoe et al., 2012	Brazil	Itatinga	SP	-23.00	-48.70	740	19.2	1646	ferralsols	eucalyptus grandis	6	1666	79.30	13.22
Campoe et al., 2012	Brazil	Itatinga	SP	-23.00	-48.70	746	19.2	1646	ferralsols	eucalyptus grandis	6	1666	76.40	12.73
Campoe et al., 2012	Brazil	Itatinga	SP	-23.00	-48.70	747	19.2	1646	ferralsols	eucalyptus grandis	6	1666	60.40	10.07
Campoe et al., 2012	Brazil	Itatinga	SP	-23.00	-48.70	755	19.2	1646	ferralsols	eucalyptus grandis	6	1666	64.60	10.77
Campoe et al., 2012	Brazil	Itatinga	SP	-23.00	-48.70	755	19.2	1646	ferralsols	eucalyptus grandis	6	1666	65.90	10.98
Campoe et al., 2012	Brazil	Itatinga	SP	-23.00	-48.70	756	19.2	1646	ferralsols	eucalyptus grandis	6	1666	66.20	11.03
Campoe et al., 2012	Brazil	Itatinga	SP	-23.00	-48.70	756	19.2	1646	ferralsols	eucalyptus grandis	6	1666	64.70	10.78
Campoe et al., 2012	Brazil	Itatinga	SP	-23.00	-48.70	756	19.2	1646	ferralsols	eucalyptus grandis	6	1666	59.80	9.97

Simetti et al., 2018	Brazil	São Francisco de Assis	RS	-29.60	-55.10	141	20.0	1375	planosols	eucalyptus benthamii	7	1666	101.96	14.57
Simetti et al., 2018	Brazil	São Francisco de Assis	RS	-29.60	-55.10	141	20.0	1375	planosols	eucalyptus dunnii	7	1666	105.66	15.09
Simetti et al., 2018	Brazil	São Francisco de Assis	RS	-29.60	-55.10	141	20.0	1375	planosols	eucalyptus grandis	7	1666	102.26	14.61
Simetti et al., 2018	Brazil	São Francisco de Assis	RS	-29.60	-55.10	141	20.0	1375	planosols	eucalyptus saligna	7	1666	106.08	15.15
Simetti et al., 2018	Brazil	São Francisco de Assis	RS	-29.60	-55.10	141	20.0	1375	planosols	eucalyptus grandis x eucalyptus urophylla	7	1666	96.22	13.75
Santos et al., 2019	Brazil	Eldorado do Sul	RS	-30.10	-51.62	158	17.6	1283.6	planosols	eucalyptus benthamii	4	986	36.54	8.91
Santos et al., 2019	Brazil	Eldorado do Sul	RS	-30.10	-51.62	158	17.6	1283.6	planosols	eucalyptus benthamii	4	1000	41.87	10.21
Santos et al., 2019	Brazil	Eldorado do Sul	RS	-30.10	-51.62	158	17.6	1283.6	planosols	eucalyptus saligna	4	972	36.19	8.83
Santos et al., 2019	Brazil	Eldorado do Sul	RS	-30.10	-51.62	158	17.6	1283.6	planosols	eucalyptus dunnii	4	875	27.32	6.66
Santos et al., 2019	Brazil	Eldorado do Sul	RS	-30.10	-51.62	158	17.6	1283.6	planosols	eucalyptus uroglobulus	4	903	46.59	11.36
Santos et al., 2019	Brazil	Eldorado do Sul	RS	-30.10	-51.6	158	17.6	1283.6	planosols	eucalyptus urograndis	4	1111	41.10	10.03
Eloy et al., 2016	Brazil	Frederico Westphalen	RS	-27.37	-53.42	522	19.0	1606	ferralsols	eucalyptus grandis	1	2222	0.40	0.40
Eloy et al., 2016	Brazil	Frederico Westphalen	RS	-27.37	-53.42	522	19.0	1606	ferralsols	eucalyptus grandis	3	2222	15.51	5.17
Eloy et al., 2016	Brazil	Frederico Westphalen	RS	-27.37	-53.42	522	19.0	1606	ferralsols	eucalyptus grandis	5	2222	90.11	18.02
Campoe et al., 2016	Brazil	Itatinga	SP	-22.97	-48.73	760	19.3	1350	ferralsols	eucalyptus grandis	6	1667	50.15	8.65
Fernandez et al., 2000	Brazil	Lassance	MG	-17.45	-44.50	820	20.3	1094	ferralsols	eucalyptus camaldulensis	10	2222	28.09	2.90
Fernandez et al., 2000	Brazil	Lassance	MG	-17.45	-44.50	820	20.3	1094	ferralsols	eucalyptus camaldulensis	10	2222	35.85	3.70
Fernandez et al., 2000	Brazil	Lassance	MG	-17.45	-44.50	820	20.3	1094	ferralsols	eucalyptus camaldulensis	10	2222	53.55	5.52
Fernandez et al., 2000	Brazil	Lassance	MG	-17.45	-44.50	820	20.3	1094	ferralsols	eucalyptus camaldulensis	10	2222	35.27	3.64
Fernandez et al., 2000	Brazil	Lassance	MG	-17.45	-44.50	820	20.3	1094	ferralsols	eucalyptus camaldulensis	10	2222	41.62	4.29
Fernandez et al., 2000	Brazil	Lassance	MG	-17.45	-44.50	820	20.3	1094	ferralsols	eucalyptus camaldulensis	10	2222	52.29	5.39
Fernandez et al., 2000	Brazil	Lassance	MG	-17.45	-44.50	820	20.3	1094	ferralsols	eucalyptus camaldulensis	10	2222	36.73	3.79
Fernandez et al., 2000	Brazil	Lassance	MG	-17.45	-44.50	820	20.3	1094	ferralsols	eucalyptus camaldulensis	10	2222	33.36	3.44
Fernandez et al., 2000	Brazil	Lassance	MG	-17.45	-44.50	820	20.3	1094	ferralsols	eucalyptus camaldulensis	10	2222	32.58	3.36
Fernandez et al., 2000	Brazil	Lassance	MG	-17.45	-44.50	820	20.3	1094	ferralsols	eucalyptus camaldulensis	10	2222	30.27	3.12
Fernandez et al., 2000	Brazil	Lassance	MG	-17.45	-44.50	820	20.3	1094	ferralsols	eucalyptus camaldulensis	10	2222	37.13	3.83
Fernandez et al., 2000	Brazil	Lassance	MG	-17.45	-44.50	820	20.3	1094	ferralsols	eucalyptus camaldulensis	10	2222	44.94	4.63
Fernandez et al., 2000	Brazil	Lassance	MG	-17.45	-44.50	820	20.3	1094	ferralsols	eucalyptus camaldulensis	10	2222	39.51	4.07
Fernandez et al., 2000	Brazil	Lassance	MG	-17.45	-44.50	820	20.3	1094	ferralsols	eucalyptus camaldulensis	10	2222	60.44	6.23
Fernandez et al., 2000	Brazil	Lassance	MG	-17.45	-44.50	820	20.3	1094	ferralsols	eucalyptus camaldulensis	10	2222	34.21	3.53
Fernandez et al., 2000	Brazil	Lassance	MG	-17.45	-44.50	820	20.3	1094	ferralsols	eucalyptus camaldulensis	10	2222	24.64	2.54
Johnson et al., 1993	Australia	Awaba	Nova Gales do Sul	-33.00	151.50	200	17.7	1190	podzols	eucalyptus agglomerata	4	1111	0.33	0.08
Johnson et al., 1993	Australia	Awaba	Nova Gales do Sul	-33.00	151.50	200	17.7	1190	podzols	eucalyptus agglomerata	4	1111	0.01	0.00
Johnson et al., 1993	Australia	Awaba	Nova Gales do Sul	-33.00	151.50	200	17.7	1190	podzols	eucalyptus agglomerata	4	1111	0.15	0.04

Johnson et al., 1993	Australia	Awaba	Nova Gales do Sul	-33.00	151.50	200	17.7	1190	podzols	corymbia citriodora	4	1111	0.05	0.01
Johnson et al., 1993	Australia	Awaba	Nova Gales do Sul	-33.00	151.50	200	17.7	1190	podzols	corymbia citriodora	4	1111	0.02	0.00
Johnson et al., 1993	Australia	Awaba	Nova Gales do Sul	-33.00	151.50	200	17.7	1190	podzols	corymbia citriodora	4	1111	0.20	0.05
Johnson et al., 1993	Australia	Awaba	Nova Gales do Sul	-33.00	151.50	200	17.7	1190	-	eucalyptus globulus	4	1111	0.01	0.00
Johnson et al., 1993	Australia	Awaba	Nova Gales do Sul	-33.00	151.50	200	17.7	1190	podzols	corymbia maculata	4	1111	0.05	0.01
Johnson et al., 1993	Australia	Awaba	Nova Gales do Sul	-33.00	151.50	200	17.7	1190	podzols	corymbia maculata	4	1111	0.04	0.01
Johnson et al., 1993	Australia	Awaba	Nova Gales do Sul	-33.00	151.50	200	17.7	1190	podzols	eucalyptus pilularis	4	1111	0.27	0.07
Johnson et al., 1993	Australia	Awaba	Nova Gales do Sul	-33.00	151.50	200	17.7	1190	podzols	eucalyptus piperita	4	1111	0.11	0.03
Johnson et al., 1993	Australia	Awaba	Nova Gales do Sul	-33.00	151.50	200	17.7	1190	-	eucalyptus globulus	4	1111	0.00	0.00
Johnson et al., 1993	Australia	Awaba	Nova Gales do Sul	-33.00	151.50	200	17.7	1190	podzols	corymbia maculata	4	1111	0.07	0.02
Johnson et al., 1993	Australia	Awaba	Nova Gales do Sul	-33.00	151.50	200	17.7	1190	podzols	corymbia maculata	4	1111	0.02	0.00
Johnson et al., 1993	Australia	Awaba	Nova Gales do Sul	-33.00	151.50	200	17.7	1190	podzols	eucalyptus pilularis	4	1111	0.07	0.02
Johnson et al., 1993	Australia	Awaba	Nova Gales do Sul	-33.00	151.50	200	17.7	1190	podzols	eucalyptus piperita	4	1111	0.02	0.01
Johnson et al., 1993	Australia	Awaba	Nova Gales do Sul	-33.00	151.50	200	17.7	1190	podzols	eucalyptus sieberi	4	1111	0.01	0.00
Johnson et al., 1993	Australia	Awaba	Nova Gales do Sul	-33.00	151.50	200	17.7	1190	-	eucalyptus globulus	4	1111	0.13	0.03
Johnson et al., 1993	Australia	Awaba	Nova Gales do Sul	-33.00	151.50	200	17.7	1190	podzols	corymbia maculata	4	1111	0.14	0.03
Johnson et al., 1993	Australia	Awaba	Nova Gales do Sul	-33.00	151.50	200	17.7	1190	podzols	corymbia maculata	4	1111	0.28	0.07
Johnson et al., 1993	Australia	Awaba	Nova Gales do Sul	-33.00	151.50	200	17.7	1190	podzols	eucalyptus pilularis	4	1111	0.75	0.19
Johnson et al., 1993	Australia	Awaba	Nova Gales do Sul	-33.00	151.50	200	17.7	1190	podzols	eucalyptus piperita	4	1111	0.05	0.01
Johnson et al., 1993	Australia	Awaba	Nova Gales do Sul	-33.00	151.50	200	17.7	1190	podzols	eucalyptus sieberi	4	1111	0.35	0.09
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	eucalyptus agglomerata	4	1111	0.41	0.10
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	eucalyptus agglomerata	18	1111	107.58	5.98
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	eucalyptus agglomerata	18	1111	180.96	10.05
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	eucalyptus agglomerata	16	1111	128.59	8.04
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	corymbia citriodora	4	1111	0.05	0.01
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	corymbia citriodora	18	1111	24.66	1.37
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	corymbia citriodora	18	1111	47.81	2.66
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	corymbia citriodora	16	1111	36.43	2.28
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	eucalyptus cypellocarpa	16	1111	20.43	1.28
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	eucalyptus globoidea	4	1111	0.22	0.05
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	eucalyptus grandis	4	1111	0.02	0.00
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	eucalyptus grandis	4	1111	0.13	0.03
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	corymbia maculata	4	1111	0.02	0.01
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	corymbia maculata (var. grayii)	4	1111	0.06	0.01

Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	eucalyptus muelleriana	4	1111	0.25	0.06
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	eucalyptus oreades	4	1111	0.03	0.01
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	solonetz	eucalyptus pilularis	4	1111	0.29	0.07
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	eucalyptus saligna	4	1111	0.02	0.00
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	eucalyptus saligna	4	1111	0.02	0.01
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	eucalyptus sieberi	4	1111	0.14	0.03
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	eucalyptus globoidea	18	1111	141.95	7.89
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	eucalyptus grandis	18	1111	33.84	1.88
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	eucalyptus grandis	18	1111	32.82	1.82
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	corymbia maculata	18	1111	40.99	2.28
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	corymbia maculata (var. grayii)	18	1111	29.61	1.64
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	eucalyptus muelleriana	18	1111	93.79	5.21
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	eucalyptus pilularis	18	1111	137.44	7.64
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	eucalyptus saligna	18	1111	60.46	3.36
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	eucalyptus globoidea	18	1111	101.02	5.61
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	eucalyptus grandis	18	1111	68.17	3.79
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	eucalyptus grandis	18	1111	40.74	2.26
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	corymbia maculata	18	1111	81.53	4.53
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	corymbia maculata (var. grayii)	18	1111	65.84	3.66
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	eucalyptus muelleriana	18	1111	85.25	4.74
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	eucalyptus oreades	18	1111	65.44	3.64
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	solonetz	eucalyptus pilularis	18	1111	132.98	7.39
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	eucalyptus piperita	18	1111	43.87	2.44
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	eucalyptus saligna	18	1111	28.31	1.57
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	eucalyptus saligna	18	1111	58.92	3.27
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	lixisols	eucalyptus dalrympleana	16	1111	50.51	3.16
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	eucalyptus grandis	16	1111	63.72	3.98
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	corymbia maculata (var. grayii)	16	1111	118.50	7.41
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	eucalyptus muelleriana	16	1111	59.35	3.71
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	eucalyptus oreades	16	1111	36.27	2.27
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	solonetz	eucalyptus pilularis	16	1111	215.99	13.50
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	eucalyptus saligna	16	1111	73.43	4.59
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	eucalyptus saligna	16	1111	76.48	4.78
Johnson et al., 1993	Australia	Bulahdelah	Nova Gales do Sul	-32.40	152.30	80	17.9	1360	podzols	eucalyptus sieberi	16	1111	9.31	0.58

Johnson et al., 1993	Australia	Cairncross	Nova Gales do Sul	-31.40	152.70	50	18.1	1280	podzols	eucalyptus agglomerata	16	1111	135.06	8.44
Johnson et al., 1993	Australia	Cairncross	Nova Gales do Sul	-31.40	152.70	50	18.1	1280	podzols	eucalyptus agglomerata	16	1111	122.02	7.63
Johnson et al., 1993	Australia	Cairncross	Nova Gales do Sul	-31.40	152.70	50	18.1	1280	podzols	corymbia citriodora	16	1111	35.77	2.24
Johnson et al., 1993	Australia	Cairncross	Nova Gales do Sul	-31.40	152.70	50	18.1	1280	podzols	corymbia citriodora	16	1111	32.14	2.01
Johnson et al., 1993	Australia	Cairncross	Nova Gales do Sul	-31.40	152.70	50	18.1	1280	podzols	corymbia maculata	16	1111	93.56	5.85
Johnson et al., 1993	Australia	Cairncross	Nova Gales do Sul	-31.40	152.70	50	18.1	1280	podzols	corymbia maculata (var. grayii)	16	1111	106.22	6.64
Johnson et al., 1993	Australia	Cairncross	Nova Gales do Sul	-31.40	152.70	50	18.1	1280	podzols	eucalyptus muelleriana	16	1111	120.33	7.52
Johnson et al., 1993	Australia	Cairncross	Nova Gales do Sul	-31.40	152.70	50	18.1	1280	podzols	eucalyptus pilularis	16	1111	187.53	11.72
Johnson et al., 1993	Australia	Cairncross	Nova Gales do Sul	-31.40	152.70	50	18.1	1280	podzols	eucalyptus saligna	16	1111	121.53	7.60
Johnson et al., 1993	Australia	Cairncross	Nova Gales do Sul	-31.40	152.70	50	18.1	1280	podzols	eucalyptus sieberi	16	1111	57.30	3.58
Johnson et al., 1993	Australia	Cairncross	Nova Gales do Sul	-31.40	152.70	50	18.1	1280	podzols	corymbia maculata	16	1111	59.00	3.69
Johnson et al., 1993	Australia	Cairncross	Nova Gales do Sul	-31.40	152.70	50	18.1	1280	podzols	corymbia maculata (var. grayii)	16	1111	211.26	13.20
Johnson et al., 1993	Australia	Cairncross	Nova Gales do Sul	-31.40	152.70	50	18.1	1280	podzols	eucalyptus muelleriana	16	1111	75.26	4.70
Johnson et al., 1993	Australia	Cairncross	Nova Gales do Sul	-31.40	152.70	50	18.1	1280	podzols	eucalyptus pilularis	16	1111	233.58	14.60
Johnson et al., 1993	Australia	Cairncross	Nova Gales do Sul	-31.40	152.70	50	18.1	1280	podzols	eucalyptus saligna	16	1111	111.97	7.00
Johnson et al., 1993	Australia	Cairncross	Nova Gales do Sul	-31.40	152.70	50	18.1	1280	podzols	eucalyptus sieberi	16	1111	15.42	0.96
Johnson et al., 1993	Australia	Cascade	Wild Cattle Creek	-30.20	152.70	640	14.5	1560	podzols	eucalyptus agglomerata	14	1111	142.14	10.15
Johnson et al., 1993	Australia	Cascade	Wild Cattle Creek	-30.20	152.70	640	14.5	1560	podzols	eucalyptus agglomerata	14	1111	161.14	11.51
Johnson et al., 1993	Australia	Cascade	Wild Cattle Creek	-30.20	152.70	640	14.5	1560	podzols	eucalyptus agglomerata	14	1111	125.88	8.99
Johnson et al., 1993	Australia	Cascade	Wild Cattle Creek	-30.20	152.70	640	14.5	1560	podzols	eucalyptus agglomerata	14	1111	187.72	13.41
Johnson et al., 1993	Australia	Cascade	Wild Cattle Creek	-30.20	152.70	640	14.5	1560	podzols	eucalyptus cypellocarpa	14	1111	55.74	3.98
Johnson et al., 1993	Australia	Cascade	Wild Cattle Creek	-30.20	152.70	640	14.5	1560	podzols	eucalyptus cypellocarpa	14	1111	146.85	10.49
Johnson et al., 1993	Australia	Cascade	Wild Cattle Creek	-30.20	152.70	640	14.5	1560	podzols	eucalyptus cypellocarpa	14	1111	75.31	5.38
Johnson et al., 1993	Australia	Cascade	Wild Cattle Creek	-30.20	152.70	640	14.5	1560	podzols	eucalyptus cypellocarpa	14	1111	93.48	6.68
Johnson et al., 1993	Australia	Cascade	Wild Cattle Creek	-30.20	152.70	640	14.5	1560	lixisols	eucalyptus dalrympleana	14	1111	68.02	4.86
Johnson et al., 1993	Australia	Cascade	Wild Cattle Creek	-30.20	152.70	640	14.5	1560	podzols	eucalyptus grandis	14	1111	167.81	11.99
Johnson et al., 1993	Australia	Cascade	Wild Cattle Creek	-30.20	152.70	640	14.5	1560	solonetz	eucalyptus oreades	14	1111	133.85	9.56
Johnson et al., 1993	Australia	Cascade	Wild Cattle Creek	-30.20	152.70	640	14.5	1560	solonetz	eucalyptus oreades	14	1111	146.35	10.45
Johnson et al., 1993	Australia	Cascade	Wild Cattle Creek	-30.20	152.70	640	14.5	1560	podzols	eucalyptus pilularis	14	1111	192.88	13.78
Johnson et al., 1993	Australia	Cascade	Wild Cattle Creek	-30.20	152.70	640	14.5	1560	podzols	eucalyptus saligna	14	1111	93.39	6.67
Johnson et al., 1993	Australia	Cascade	Wild Cattle Creek	-30.20	152.70	640	14.5	1560	podzols	eucalyptus saligna	14	1111	29.83	2.13
Johnson et al., 1993	Australia	Cascade	Wild Cattle Creek	-30.20	152.70	640	14.5	1560	lixisols	eucalyptus dalrympleana	14	1111	118.54	8.47
Johnson et al., 1993	Australia	Cascade	Wild Cattle Creek	-30.20	152.70	640	14.5	1560	podzols	eucalyptus grandis	14	1111	140.24	10.02
Johnson et al., 1993	Australia	Cascade	Wild Cattle Creek	-30.20	152.70	640	14.5	1560	solonetz	eucalyptus oreades	14	1111	266.31	19.02

Johnson et al., 1993	Australia	Cascade	Wild Cattle Creek	-30.20	152.70	640	14.5	1560	solonetz	eucalyptus oreades	14	1111	297.23	21.23
Johnson et al., 1993	Australia	Cascade	Wild Cattle Creek	-30.20	152.70	640	14.5	1560	podzols	eucalyptus pilularis	14	1111	169.04	12.07
Johnson et al., 1993	Australia	Cascade	Wild Cattle Creek	-30.20	152.70	640	14.5	1560	podzols	eucalyptus saligna	14	1111	114.97	8.21
Johnson et al., 1993	Australia	Cascade	Wild Cattle Creek	-30.20	152.70	640	14.5	1560	podzols	eucalyptus saligna	14	1111	27.84	1.99
Johnson et al., 1993	Australia	Cascade	Wild Cattle Creek	-30.20	152.70	640	14.5	1560	-	eucalyptus globulus	14	1111	35.27	2.52
Johnson et al., 1993	Australia	Cascade	Wild Cattle Creek	-30.20	152.70	640	14.5	1560	podzols	eucalyptus grandis	14	1111	144.33	10.31
Johnson et al., 1993	Australia	Cascade	Wild Cattle Creek	-30.20	152.70	640	14.5	1560	podzols	eucalyptus oreades	14	1111	123.31	8.81
Johnson et al., 1993	Australia	Cascade	Wild Cattle Creek	-30.20	152.70	640	14.5	1560	podzols	eucalyptus oreades	14	1111	213.59	15.26
Johnson et al., 1993	Australia	Cascade	Wild Cattle Creek	-30.20	152.70	640	14.5	1560	podzols	eucalyptus pilularis	14	1111	226.47	16.18
Johnson et al., 1993	Australia	Cascade	Wild Cattle Creek	-30.20	152.70	640	14.5	1560	podzols	eucalyptus saligna	14	1111	148.78	10.63
Johnson et al., 1993	Australia	Cascade	Wild Cattle Creek	-30.20	152.70	640	14.5	1560	podzols	eucalyptus saligna	14	1111	42.27	3.02
Johnson et al., 1993	Australia	Cascade	Wild Cattle Creek	-30.20	152.70	640	14.5	1560	podzols	eucalyptus grandis	14	1111	117.41	8.39
Johnson et al., 1993	Australia	Cascade	Wild Cattle Creek	-30.20	152.70	640	14.5	1560	podzols	eucalyptus oreades	14	1111	148.76	10.63
Johnson et al., 1993	Australia	Cascade	Wild Cattle Creek	-30.20	152.70	640	14.5	1560	podzols	eucalyptus saligna	14	1111	105.03	7.50
Johnson et al., 1993	Australia	Cascade	Wild Cattle Creek	-30.20	152.70	640	14.5	1560	podzols	eucalyptus saligna	14	1111	46.18	3.30
Johnson et al., 1993	Australia	Chichester	Chichester	-32.20	151.70	800	16.8	1550	podzols	eucalyptus agglomerata	18	1111	173.72	9.65
Johnson et al., 1993	Australia	Chichester	Chichester	-32.20	151.70	800	16.8	1550	podzols	eucalyptus grandis	18	1111	203.21	11.29
Johnson et al., 1993	Australia	Chichester	Chichester	-32.20	151.70	800	16.8	1550	podzols	corymbia maculata	18	1111	231.12	12.84
Johnson et al., 1993	Australia	Chichester	Chichester	-32.20	151.70	800	16.8	1550	podzols	eucalyptus muelleriana	18	1111	285.09	15.84
Johnson et al., 1993	Australia	Chichester	Chichester	-32.20	151.70	800	16.8	1550	podzols	eucalyptus pilularis	18	1111	284.04	15.78
Johnson et al., 1993	Australia	Chichester	Chichester	-32.20	151.70	800	16.8	1550	podzols	eucalyptus saligna	18	1111	141.83	7.88
Johnson et al., 1993	Australia	Mount Boss	Mount Boss	-31.20	152.40	1070	12.9	2050	-	eucalyptus fastigata	21	1111	226.96	10.81
Johnson et al., 1993	Australia	Mount Boss	Mount Boss	-31.20	152.40	1070	12.9	2050	-	eucalyptus obliqua	21	1111	166.40	7.92
Johnson et al., 1993	Australia	Mount Boss	Mount Boss	-31.20	152.40	1070	12.9	2050	-	eucalyptus oreades	21	1111	117.65	5.60
Johnson et al., 1993	Australia	Mount Boss	Mount Boss	-31.20	152.40	1070	12.9	2050	-	eucalyptus saligna	21	1111	78.06	3.72
Johnson et al., 1993	Australia	Nadgee	Nadgee	-37.40	149.80	130	14.6	1050	-	eucalyptus globulus	10	1111	2.50	0.25
Johnson et al., 1993	Australia	Nadgee	Nadgee	-37.40	149.80	130	14.6	1050	-	eucalyptus botryoides	10	1111	9.07	0.91
Johnson et al., 1993	Australia	Nadgee	Nadgee	-37.40	149.80	130	14.6	1050	-	eucalyptus cypellocarpa	10	1111	4.42	0.44
Johnson et al., 1993	Australia	Nadgee	Nadgee	-37.40	149.80	130	14.6	1050	-	eucalyptus fastigata	10	1111	0.84	0.08
Johnson et al., 1993	Australia	Nadgee	Nadgee	-37.40	149.80	130	14.6	1050	-	eucalyptus globulus	10	1111	8.36	0.84
Johnson et al., 1993	Australia	Nadgee	Nadgee	-37.40	149.80	130	14.6	1050	-	eucalyptus grandis	10	1111	4.67	0.47
Johnson et al., 1993	Australia	Nadgee	Nadgee	-37.40	149.80	130	14.6	1050	-	corymbia maculata	10	1111	1.01	0.10
Johnson et al., 1993	Australia	Nadgee	Nadgee	-37.40	149.80	130	14.6	1050	-	eucalyptus globulus	10	1111	5.15	0.52
Johnson et al., 1993	Australia	Nadgee	Nadgee	-37.40	149.80	130	14.6	1050	-	eucalyptus muelleriana	10	1111	6.97	0.70

Johnson et al., 1993	Australia	Nadgee	Nadgee	-37.40	149.80	130	14.6	1050	-	eucalyptus nitens	10	1111	2.06	0.21
Johnson et al., 1993	Australia	Nadgee	Nadgee	-37.40	149.80	130	14.6	1050	-	eucalyptus obliqua	10	1111	11.55	1.16
Johnson et al., 1993	Australia	Nadgee	Nadgee	-37.40	149.80	130	14.6	1050	-	eucalyptus saligna	10	1111	7.08	0.71
Johnson et al., 1993	Australia	Nadgee	Nadgee	-37.40	149.80	130	14.6	1050	-	eucalyptus sieberi	10	1111	13.39	1.34
Johnson et al., 1993	Australia	Nadgee	Nadgee	-37.40	149.80	130	14.6	1050	-	eucalyptus viminalis	10	1111	6.50	0.65
Johnson et al., 1993	Australia	Olney	Nova Gales do Sul	-33.00	151.30	410	17.8	1190	-	eucalyptus agglomerata	21	1736	381.11	18.15
Johnson et al., 1993	Australia	Olney	Nova Gales do Sul	-33.00	151.30	410	17.8	1190	-	eucalyptus muelleriana	21	1736	296.64	14.13
Johnson et al., 1993	Australia	Olney	Nova Gales do Sul	-33.00	151.30	410	17.8	1190	-	eucalyptus pilularis	21	1736	447.57	21.31
Johnson et al., 1993	Australia	Barcoongere	Barcoongere	-29.90	153.20	30	19.0	1420	-	eucalyptus amplifolia	5	2500	0.28	0.06
Johnson et al., 1993	Australia	Barcoongere	Barcoongere	-29.90	153.20	30	19.0	1420	-	eucalyptus grandis	5	2500	3.47	0.69
Johnson et al., 1993	Australia	Barcoongere	Barcoongere	-29.90	153.20	30	19.0	1420	-	corymbia maculata	5	2500	1.13	0.23
Johnson et al., 1993	Australia	Barcoongere	Barcoongere	-29.90	153.20	30	19.0	1420	-	eucalyptus moluccana	5	2500	0.23	0.05
Johnson et al., 1993	Australia	Barcoongere	Barcoongere	-29.90	153.20	30	19.0	1420	-	eucalyptus pilularis	5	2500	5.74	1.15
Johnson et al., 1993	Australia	Barcoongere	Barcoongere	-29.90	153.20	30	19.0	1420	-	eucalyptus resinifera	5	2500	2.42	0.48
Johnson et al., 1993	Australia	Barcoongere	Barcoongere	-29.90	153.20	30	19.0	1420	-	eucalyptus tereticornis	5	2500	0.78	0.16
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	podzols	eucalyptus agglomerata	18	1111	171.72	9.54
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	podzols	eucalyptus agglomerata	18	1111	201.91	11.22
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	podzols	eucalyptus agglomerata	18	1111	295.90	16.44
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	podzols	eucalyptus agglomerata	18	1111	170.75	9.49
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	podzols	corymbia citriodora	18	1111	10.02	0.56
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	podzols	corymbia citriodora	18	1111	55.64	3.09
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	podzols	corymbia citriodora	18	1111	1.84	0.10
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	solonetz	eucalyptus fastigata	18	1111	214.45	11.91
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	-	eucalyptus globulus	18	1111	60.38	3.35
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	podzols	corymbia maculata	18	1111	174.63	9.70
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	podzols	eucalyptus muelleriana	18	1111	255.93	14.22
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	podzols	eucalyptus oreades	18	1111	294.14	16.34
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	solonetz	eucalyptus pilularis	18	1111	283.73	15.76
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	podzols	eucalyptus saligna	18	1111	132.31	7.35
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	podzols	eucalyptus sieberi	18	1111	269.51	14.97
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	solonetz	eucalyptus fastigata	18	1111	159.07	8.84
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	-	eucalyptus globulus	18	1111	70.42	3.91
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	podzols	corymbia maculata	18	1111	106.65	5.92
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	podzols	eucalyptus muelleriana	18	1111	200.19	11.12

Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	podzols	eucalyptus oreades	18	1111	182.37	10.13
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	solonetz	eucalyptus pilularis	18	1111	243.11	13.51
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	podzols	eucalyptus sieberi	18	1111	208.72	11.60
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	solonetz	eucalyptus fastigata	18	1111	229.89	12.77
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	-	eucalyptus globulus	18	1111	177.66	9.87
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	podzols	corymbia maculata	18	1111	139.82	7.77
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	podzols	eucalyptus muelleriana	18	1111	162.90	9.05
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	podzols	eucalyptus oreades	18	1111	266.73	14.82
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	solonetz	eucalyptus pilularis	18	1111	335.01	18.61
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	podzols	eucalyptus saligna	18	1111	132.84	7.38
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	podzols	eucalyptus sieberi	18	1111	302.75	16.82
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	solonetz	eucalyptus fastigata	18	1111	137.82	7.66
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	-	eucalyptus globulus	18	1111	70.63	3.92
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	podzols	corymbia maculata	18	1111	24.83	1.38
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	podzols	eucalyptus muelleriana	18	1111	144.26	8.01
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	podzols	eucalyptus oreades	18	1111	68.59	3.81
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	solonetz	eucalyptus pilularis	18	1111	130.26	7.24
Johnson et al., 1993	Australia	Watagan	Watagan	-33.05	151.30	430	16.1	1190	podzols	eucalyptus sieberi	18	1111	148.06	8.23
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	eucalyptus agglomerata	15	1111	135.89	9.06
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	eucalyptus agglomerata	15	1111	103.44	6.90
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	eucalyptus agglomerata	15	1111	169.88	11.33
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	corymbia citriodora	15	1111	2.83	0.19
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	corymbia citriodora	15	1111	6.00	0.40
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	corymbia citriodora	15	1111	15.38	1.03
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	corymbia citriodora	14	1111	8.96	0.64
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	eucalyptus agglomerata	14	1111	60.04	4.29
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	eucalyptus cypellocarpa	15	1111	81.62	5.44
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	eucalyptus cypellocarpa	15	1111	62.25	4.15
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	eucalyptus cypellocarpa	15	1111	26.00	1.73
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	eucalyptus cypellocarpa	14	1111	44.58	3.18
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	eucalyptus grandis	15	1111	155.08	10.34
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	corymbia maculata	15	1111	78.01	5.20
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	eucalyptus pilularis	15	1111	211.17	14.08
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	eucalyptus saligna	15	1111	112.39	7.49

Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	eucalyptus saligna	15	1111	64.22	4.28
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	eucalyptus grandis	15	1111	102.29	6.82
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	corymbia maculata	15	1111	65.45	4.36
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	eucalyptus oreades	15	1111	91.29	6.09
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	eucalyptus pilularis	15	1111	181.82	12.12
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	eucalyptus saligna	15	1111	86.85	5.79
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	eucalyptus saligna	15	1111	46.03	3.07
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	eucalyptus grandis	15	1111	114.49	7.63
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	corymbia maculata	15	1111	69.00	4.60
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	eucalyptus oreades	15	1111	188.78	12.59
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	eucalyptus pilularis	15	1111	175.41	11.69
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	eucalyptus saligna	15	1111	51.05	3.40
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	eucalyptus saligna	15	1111	39.77	2.65
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	eucalyptus grandis	14	1111	132.91	9.49
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	corymbia maculata	14	1111	53.15	3.80
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	eucalyptus oreades	14	1111	85.24	6.09
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	eucalyptus pilularis	14	1111	134.18	9.58
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	eucalyptus saligna	14	1111	69.31	4.95
Johnson et al., 1993	Australia	Yabbra	Yabbra	-28.53	152.56	520	17.6	1080	podzols	eucalyptus saligna	14	1111	30.77	2.20
Lee et al, 1990	Australia	Wide Bay and Burnett - coastal	Queensland	-26.50	152.80	150	26.9	946.625	-	corymbia citriodora subsp. citriodora	10	727.41	152.00	15.20
Lee et al, 1991	Australia	Wide Bay and Burnett - inland	Queensland	-26.80	152.00	458	26.8	640.33	nitisols	corymbia citriodora subsp. citriodora	10	395.99	42.30	4.23
Lee et al, 1992	Australia	Darling Downs and Granite Belt	Queensland	-28.50	152.10	820	24.3	660.83	-	corymbia citriodora subsp. citriodora	10	350	18.90	1.89
Lee et al, 1993	Australia	Central Coast - Whitsunday	Queensland	-21.60	149.10	193	27.5	1425.33	-	corymbia citriodora subsp. citriodora	10	753.7	128.60	12.86
Lee et al, 1994	Australia	Capricornia	Queensland	-23.50	150.70	15	27.2	863	-	corymbia citriodora subsp. citriodora	10	420	55.80	5.58
Lee et al, 1995	Australia	Southeast Coast	Queensland	-27.80	152.70	58	26.7	734	-	corymbia citriodora subsp. citriodora	10	421.73	51.00	5.10
Lee et al, 1996	Australia	Wide Bay and Burnett - coastal	Queensland	-26.50	152.80	150	26.9	946.625	-	corymbia citriodora subsp.variegata	10	631.06	184.50	18.45
Lee et al, 1997	Australia	Wide Bay and Burnett - inland	Queensland	-26.80	152.00	458	26.8	640.33	nitisols	corymbia citriodora subsp.variegata	10	403.93	48.00	4.80
Lee et al, 1998	Australia	Darling Downs and Granite Belt	Queensland	-28.50	152.10	820	24.3	660.83	-	corymbia citriodora subsp.variegata	10	292.97	24.50	2.45
Lee et al, 1999	Australia	Northern Rivers	Queensland	-28.60	153.10	345	21.9	1594	-	corymbia citriodora subsp.variegata	10	482.14	135.10	13.51
Lee et al, 2000	Australia	Southeast Coast	Queensland	-27.80	152.70	58	26.7	734	-	corymbia citriodora subsp.variegata	10	597.37	56.20	5.62
Lee et al, 2001	Australia	Central Coast - Whitsunday	Queensland	-21.60	149.10	193	27.5	1425.33	-	corymbia citriodora subsp.variegata	10	750	159.10	15.91
Lee et al, 2002	Australia	Capricornia	Queensland	-23.50	150.70	15	27.2	863	-	corymbia citriodora subsp.variegata	10	790.31	115.30	11.53
Lee et al, 2003	Australia	Wide Bay and Burnett - inland	Queensland	-26.80	152.00	458	26.8	640.33	nitisols	corymbia henryi	10	397.02	48.60	4.86
Lee et al, 2004	Australia	Wide Bay and Burnett - inland	Queensland	-26.80	152.00	458	26.8	640.33	nitisols	corymbia torelliana x C. citriodora subsp. Variegata	10	266.67	62.60	6.26

Lee et al, 2005	Australia	Wide Bay and Burnett - inland	Queensland	-26.80	152.00	458	26.8	640.33	nitisols	eucalyptus grandis x E. resinifera	10	344.38	68.40	6.84
Lee et al, 2011	Australia	Southeast Coast	Queensland	-27.80	152.70	58	26.7	734	-	eucalyptus argophloia	10	521	43.30	4.33
Lee et al, 2011	Australia	Wide Bay and Burnett - inland	Queensland	-26.80	152.00	458	26.8	640.33	nitisols	eucalyptus argophloia	10	421.95	55.00	5.50
Lee et al, 2011	Australia	Capricornia	Queensland	-23.50	150.70	15	27.2	863	-	eucalyptus argophloia	10	596.25	100.60	10.06
Lee et al, 2011	Australia	Darling Downs and Granite Belt	Queensland	-28.50	152.10	820	24.3	660.83	-	eucalyptus argophloia	10	575.63	59.10	5.91
Lee et al, 2011	Australia	Wide Bay and Burnett - inland	Queensland	-26.80	152.00	458	26.8	640.33	nitisols	eucalyptus camaldulensis	10	470	39.90	3.99
Lee et al, 2011	Australia	Capricornia	Queensland	-23.50	150.70	15	27.2	863	-	eucalyptus camaldulensis	10	700	49.50	4.95
Lee et al, 2011	Australia	Wide Bay and Burnett - inland	Queensland	-26.80	152.00	458	26.8	640.33	nitisols	eucalyptus cambageana	10	516.6667	46.00	4.60
Lee et al, 2011	Australia	Darling Downs and Granite Belt	Queensland	-28.50	152.10	820	24.3	660.83	-	eucalyptus cambageana	10	535.7143	44.20	4.42
Lee et al, 2011	Australia	Wide Bay and Burnett - inland	Queensland	-26.80	152.00	458	26.8	640.33	nitisols	eucalyptus cloeziana	10	352.46	40.00	4.00
Lee et al, 2011	Australia	Wide Bay and Burnett - inland	Queensland	-26.80	152.00	458	26.8	640.33	nitisols	eucalyptus crebra	10	420	26.20	2.62
Lee et al, 2011	Australia	Capricornia	Queensland	-23.50	150.70	15	27.2	863	-	eucalyptus crebra	10	420	21.40	2.14
Lee et al, 2011	Australia	Darling Downs and Granite Belt	Queensland	-28.50	152.10	820	24.3	660.83	-	eucalyptus crebra	10	410	3.60	0.36
Lee et al, 2011	Australia	Central Coast - Whitsunday	Queensland	-21.60	149.10	193	27.5	1425.33	-	eucalyptus dunnii	10	755.56	109.20	10.92
Lee et al, 2011	Australia	Capricornia	Queensland	-23.50	150.70	15	27.2	863	-	eucalyptus dunnii	10	536.25	38.80	3.88
Lee et al, 2011	Australia	Wide Bay and Burnett - inland	Queensland	-26.80	152.00	458	26.8	640.33	nitisols	eucalyptus dunnii	10	215.84	62.40	6.24
Lee et al, 2011	Australia	Darling Downs and Granite Belt	Queensland	-28.50	152.10	820	24.3	1594	-	eucalyptus dunnii	10	529.23	65.10	6.51
Lee et al, 2011	Australia	Northern Rivers	Queensland	-28.60	153.10	345	21.9	1594	-	eucalyptus dunnii	10	500	273.60	27.36
Lee et al, 2011	Australia	Southeast Coast	Queensland	-27.80	152.70	58	26.7	734	-	eucalyptus dunnii	10	667.68	126.00	12.60
Lee et al, 2011	Australia	Wide Bay and Burnett - inland	Queensland	-26.80	152.00	458	26.8	640.33	nitisols	eucalyptus globulus subsp. maidenii	10	268.45	46.10	4.61
Lee et al, 2011	Australia	Northern Rivers	Queensland	-28.60	153.10	345	21.9	1594	-	eucalyptus globulus subsp. maidenii	10	458.33	138.90	13.89
Lee et al, 2011	Australia	Darling Downs and Granite Belt	Queensland	-28.50	152.10	820	24.3	660.83	-	eucalyptus globulus subsp. maidenii	10	559.52	72.00	7.20
Lee et al, 2011	Australia	Central Coast - Whitsunday	Queensland	-21.60	149.10	193	27.5	1425.33	-	eucalyptus grandis	10	558.33	159.00	15.90
Lee et al, 2011	Australia	Northern Rivers	Queensland	-28.60	153.10	345	21.9	1594	-	eucalyptus grandis	10	442.85	98.60	9.86
Lee et al, 2011	Australia	Darling Downs and Granite Belt	Queensland	-28.50	152.10	820	24.3	660.83	-	eucalyptus grandis	10	625	65.80	6.58
Lee et al, 2011	Australia	Wide Bay and Burnett - inland	Queensland	-26.80	152.00	458	26.8	640.33	nitisols	eucalyptus longirostrata	10	407.45	43.30	4.33
Lee et al, 2011	Australia	Darling Downs and Granite Belt	Queensland	-28.50	152.10	820	24.3	660.83	-	eucalyptus longirostrata	10	511.9	49.40	4.94
Lee et al, 2011	Australia	Wide Bay and Burnett - coastal	Queensland	-26.50	152.80	150	26.9	946.625	-	eucalyptus longirostrata	10	716.33	235.20	23.52
Lee et al, 2011	Australia	Southeast Coast	Queensland	-27.80	152.70	58	26.7	734	-	eucalyptus longirostrata	10	488.78	79.60	7.96
Lee et al, 2011	Australia	Capricornia	Queensland	-23.50	150.70	15	27.2	863	-	eucalyptus longirostrata	10	958.33	108.20	10.82
Lee et al, 2011	Australia	Wide Bay and Burnett - inland	Queensland	-26.80	152.00	458	26.8	640.33	nitisols	eucalyptus melliodora	10	400	30.30	3.03
Lee et al, 2011	Australia	Capricornia	Queensland	-23.50	150.70	15	27.2	863	-	eucalyptus melliodora	10	400	48.80	4.88
Lee et al, 2011	Australia	Darling Downs and Granite Belt	Queensland	-28.50	152.10	820	24.3	660.83	-	eucalyptus melliodora	10	350	33.50	3.35
Lee et al, 2011	Australia	Southeast Coast	Queensland	-27.80	152.70	58	26.7	734	-	eucalyptus moluccana	10	515.47	45.50	4.55

Lee et al, 2011	Australia	Darling Downs and Granite Belt	Queensland	-28.50	152.10	820	24.3	660.83	-	eucalyptus moluccana	10	517.14	14.40	1.44
Lee et al, 2011	Australia	Wide Bay and Burnett - inland	Queensland	-26.80	152.00	458	26.8	640.33	nitisols	eucalyptus moluccana	10	436.56	55.20	5.52
Lee et al, 2011	Australia	Capricornia	Queensland	-23.50	150.70	15	27.2	863	-	eucalyptus moluccana	10	400	90.40	9.04
Lee et al, 2011	Australia	Central Coast - Whitsunday	Queensland	-21.60	149.10	193	27.5	1425.33	-	eucalyptus pellita	10	675	113.20	11.32
Lee et al, 2011	Australia	Capricornia	Queensland	-23.50	150.70	15	27.2	863	-	eucalyptus pellita	10	660.69	63.00	6.30
Lee et al, 2011	Australia	Southeast Coast	Queensland	-27.80	152.70	58	26.7	734	-	eucalyptus sideroxylon	10	539.68	50.50	5.05
Lee et al, 2011	Australia	Darling Downs and Granite Belt	Queensland	-28.50	152.10	820	24.3	660.83	-	eucalyptus sideroxylon	10	500	44.70	4.47
Lee et al, 2011	Australia	Darling Downs and Granite Belt	Queensland	-28.50	152.10	820	24.3	660.83	-	eucalyptus tereticornis	10	540.85	4.80	0.48
Lee et al, 2011	Australia	Wide Bay and Burnett - inland	Queensland	-26.80	152.00	458	26.8	640.33	nitisols	eucalyptus tereticornis	10	456.38	48.90	4.89