Thermogravimetric and calorimetric evaluation of pellets obtained from the biomass of *Coffea arabica* L.

Evaluación termogravimétrica y calorimétrica de pellets obtenidos a partir de la biomasa de Coffea arabica L.

Avaliação termogravimétrica e calorimétrica de pellets obtidos da biomassa de Coffea arabica L.

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Received: October 1st, 2024
Accepted: December 16th, 2024
Available: April 21th, 2025

How to cite this article:
G.F. Escobar Fiesco, C.P. Ortiz, R.E. Cárdenas-Torres, and D.R. Delgado, "Thermogravimetric and Calorimetric Evaluation of Pellets Obtained from the Biomass of *Coffea arabica* L.," *Revista Ingeniería Solidaria*, vol. 21, no. 1, 2025.
doi: https://doi.org/10.16925/2357-6014.2025.01.04

Research article. https://doi.org/10.16925/2357-6014.2025.01.04

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Abstract

Introduction: This article presents the results of the research titled Dendroenergetic Analysis of Agricultural and Forest Biomass, conducted in 2024 by Universidad América in collaboration with Fundación Universitaria Minuto de Dios (UNIMINUTO) and Politécnico Grancolombiano.

*Problem***:** Colombia is one of the world's largest coffee producers, yet the biomass generated beyond the coffee fruit is underutilized. This biomass represents a promising source of energy.

Objective: To conduct a dendroenergetic analysis of Coffea arabica L. biomass pellets by evaluating five key factors: moisture content (%), ash content (%), volatile matter, thermogravimetric properties, and calorific value.

Methodology: The calorific value was evaluated using a CAL3K calorimeter, TGA 8000 thermogravimetric analyzer, the percentage of moisture was determined using a RADWAG moisture balance (±0.0001 g), and the percentage of ash and volatiles was determined using a RADWAG analytical balance (±0.0001 g).

Results: The study found promising energetic properties across samples. Coal derived from the biomass showed particularly high calorific value, low volatile matter, and good resistance to moisture. These findings indicate that Coffea arabica L. biomass is a strong candidate for producing densified biofuels with high energy output.

Conclusion: Given the abundant availability of Coffea arabica L. biomass in Colombia and the favorable calorific characteristics of both wood and pyrolysis charcoal, this biomass is an ideal raw material for developing sustainable, high-energy biofuels.

Originality: This research provides novel dendroenergetic data on Coffea arabica L. biomass under specific conditions.

Limitations: The analysis was limited to a single coffee variety.

Key words: Forest biomass, biochar, heating power, renewable energy.

Resumen

Introducción: El artículo es producto de la investigación titulada Análisis dendroenergético de biomasa agrícola y forestal desarrollada por la universidad América, en conjunto con la Fundación Universitaria Minuto de Dios y Politécnico Grancolombiano en el año 2024.

Problema: Colombia es uno de los mayores productores de café, sin embargo, su biomasa además del fruto es poco utilizada, por lo que es una excelente fuente de biomasa.

Objetivo: En este contexto se realizó un análisis dendroenergético de pellet de biomasa de *Coffea arabica L.* evaluando cinco factores: % humedad, % de cenizas, volátiles, termogravimetría y poder calorífico.

Metodología: El poder calorífico se evaluó mediante un Calorímetro CAL3K, Analizador termogravimétrico TGA 8000, el porcentaje de humedad se determinó mediate una Balanza de humedad RADWAG (±0.0001 g), y el porcentaje de ceniza y volátiles mediante una balanza analítica RADWAG (±0.0001 g).

Resultados: En todos los casos, se obtuvieron resultados energéticos interesantes, pero el carbón es una de las mejores opciones por su gran poder calorífico, su bajo contenido de volátiles y buen comportamiento frente a la humedad. Así, la biomasa de *Coffea arabica L* es una potencial materia prima para el desarrollo de biocombustibles densificados de alto poder calorífico.

Conclusión: La gran disponibilidad de este tipo de biomasa en Colombia, junto con el alto poder calorífico tanto de la madera como del carbón de pirolisis hacen de esta biomasa un material idóneo para tal fin.

Originalidad: Se reportan datos de dendroenergéticos de biomasa de *Coffea arabica L.* en condiciones específicas.

Limitaciones: Se realiza el análisis dendroenergético de una sola variedad de café.

Palabras clave: Biomasa forestal, biocarbón, energía calorífica, energías renovables.

Resumo

Introdução: Este artigo é resultado da pesquisa intitulada "Análise Energética de Sonhos da Biomassa Agrícola e Florestal", desenvolvida pela Universidad América, em conjunto com a Fundação Universitária Minuto de Dios e a Universidade Politécnica Grancolombiana, em 2024.

Problema: A Colômbia é um dos maiores produtores de café; no entanto, sua biomassa, além do fruto, é subutilizada, tornando-a uma excelente fonte de biomassa.

Objetivo: Neste contexto, foi realizada uma análise dendroenergética de pellets de biomassa de Coffea arabica L., avaliando cinco fatores: % de umidade, % de cinzas, voláteis, termogravimetria e poder calorífico.

Metodologia: O poder calorífico foi avaliado utilizando um calorímetro CAL3K e um analisador termogravimétrico TGA 8000. O teor de umidade foi determinado utilizando uma balança de umidade RADWAG (±0,0001 g), e as porcentagens de cinzas e compostos orgânicos voláteis foram determinadas utilizando uma balança analítica RADWAG (±0,0001 g).

Resultados: Em todos os casos, foram obtidos resultados energéticos interessantes, mas o carvão é uma das melhores opções devido ao seu alto poder calorífico, baixo teor de compostos orgânicos voláteis e boa resistência à umidade. Assim, a biomassa de Coffea arabica L. é uma matéria-prima potencial para o desenvolvimento de biocombustíveis densificados de alto poder calorífico.

Conclusão: A ampla disponibilidade desse tipo de biomassa na Colômbia, juntamente com o alto poder calorífico da madeira e do carvão de pirólise, tornam essa biomassa um material ideal para essa finalidade.

Originalidade: Dados sobre a energia da madeira da biomassa de Coffea arabica L. sob condições específicas são relatados.

Limitações: A análise da energia da madeira é realizada em uma única variedade de café.

Palavras-chave: Biomassa florestal, biochar, energia térmica, energia renovável.

1. INTRODUCTION

Colombia is one of the world's largest coffee producers, with approximately 4,570 million coffee trees planted across about 877,000 hectares [1].

The Colombian coffee production system comprises six stages, as illustrated in Figure 1. The first stage involves seedbeds, where coffee seeds germinate in fine sand to protect the roots from damage during transplantation (Figure 1A). In the second stage, the seedlings develop individually in bags until they reach a height of around 30 cm (Figure 1B). The third stage is the field planting of the seedlings, which remain non-productive for at least two years (Figure 1C).

The fourth stage (Figure 1E) is the productive development phase of the coffee bush, lasting approximately four years. Following this, in the fifth stage (Figure 1D), the plant undergoes a cutting process known as "Zoca," where the coffee bush is cut approximately 15 cm above the ground [2]. This stage generates a significant amount of biomass (Figure 1F), as does the final phase of plantation rehabilitation when coffee plants are cut or uprooted at ground level, producing up to 13 tons of dry biomass per hectare [1].

Each year, around 75,000 hectares of coffee plantations are renewed in Colombia, positioning the coffee sector as a major source of biofuels. This estimate does not include the continuous biomass generated by productive coffee plants throughout their lifecycle.

Figure 1. Coffee production system in Colombia. A: Coffee seedling nursery, B: Seedling nursery, C: Field planting, D: Zoca, E: Coffee trees in production, F: Renovation of coffee plantations.
Source: own work

However, the current high energy demand is largely sustained by fossil fuels, which are in continuous decline [3]. Despite their widespread use, fossil fuels are the primary contributors to increased air pollution through greenhouse gas emissions such as carbon dioxide, nitrogen oxides, and sulfur compounds [4]. This pollution leads to severe environmental and health issues, including acid rain, bronchitis, lung and skin cancer, eye irritation, and vomiting. Consequently, there is an urgent need to develop alternative fuels that can mitigate these problems.

Renewable energy sources present an efficient solution to these challenges. Among them, biomass energy stands out as a low-cost and readily available form of renewable energy produced by the decomposition of natural waste materials. Biomass fuels are derived from organic waste and represent a renewable, sustainable energy source that can generate electrical or thermal energy [5]. Examples of biomass materials include forestry and wood waste, manure, agricultural residues, and others. With a steady supply of non-paper construction and demolition waste as well as municipal solid waste, green energy production from biomass can be sustained indefinitely.

Agricultural residues such as rice husks, coconut fiber, sawdust, and various plant leaves are abundant resources. However, these residues generally have low bulk density and high moisture content, which pose challenges for direct use as fuel. Fortunately, these materials can be compressed into briquettes or pellets with high calorific value, which offers benefits such as volume reduction, ease of handling, lower transportation costs, complete combustion, and convenient storage without significant degradation [6].

Charcoal, a light residue produced by removing water and volatile substances from animal and plant matter—usually through slow pyrolysis—is another important biomass fuel. Compared to raw wood, charcoal burns at higher temperatures due to the removal of moisture and volatiles and achieves near-complete combustion, producing primarily carbon dioxide with minimal smoke. Charcoal's composition includes carbon, hydrogen, oxygen, ash, and impurities, and is often empirically represented as C_7H_4O [7]. To obtain high-purity charcoal, the raw material must be free of non-volatile compounds [8]–[11].

Various research efforts have focused on enhancing biomass utilization efficiency by converting it into high-calorific-value materials through methods such as gasification, briquetting [11]–[13], bioconversion [13], [14], thermal modification, and fuel synthesis [15], [16]. Pelletizing, in particular, is a technology that densifies loose materials into solid composite forms by applying pressure and suitable binders. Pelletizing methods vary depending on the equipment used, including manual press, piston press, screw press, and roller press pelletizing.

Producing pellets from biomass and charcoal is crucial for improving the properties and combustion characteristics of solid fuels. Wood energy, derived from agricultural or forest biomass waste, holds great potential as a sustainable alternative fuel source. Compressing biomass residues into briquettes or pellets creates a homogeneous, processed fuel that can effectively substitute fossil fuels.

Briquetting is a non-carbonized biomass compaction process applicable on scales ranging from households to industries. To improve briquette calorific value, composite materials have been developed by incorporating coal dust from carbonization or biocarbon (biochar) production [17], [18]. Pyrolysis, a thermal decomposition process, converts biomass into biofuels with high energy density, yielding three main products: liquid bio-oil, gas, and solid biochar [19]. The proportions and properties of these products depend on pyrolysis conditions.

Currently, research focuses primarily on optimizing bio-oil and gas production [20], [21]. However, the chemical complexity of bio-oil necessitates refining before use, and difficulties in purifying the gaseous fraction limit its large-scale application [22]. Under these conditions, biochar stands out as a promising product due to its stability and high calorific value. Slow pyrolysis, in particular, is an effective method for transforming biomass into solid fuels with enhanced energy content [23].

2. MATERIALS AND METHODS

The biomass used in this study was obtained from Coffea arabica L. (coffee) wood waste. Charcoal derived from the pyrolysis of Coffea arabica L. was ground into a fine powder prior to pellet preparation. The powdered raw materials were then packed into a mold and compressed using a hydraulic jack applying a load ranging from approximately 3 to 7 tons to form the pellets. The equipment utilized in this process is shown in Figure 2.

For the preparation of charcoal pellets, starch was added as a binder, with a mass ratio of 0.75 charcoal to 0.25 starch. Three samples of each pellet type were prepared for experimental analysis.

The analytical instruments used during the investigation included a moisture balance RADWAG with a precision of ±0.0001 g, an analytical balance RADWAG with the same precision, a CAL3K calorimeter, a TGA 8000 thermogravimetric analyzer, and a muffle furnace.

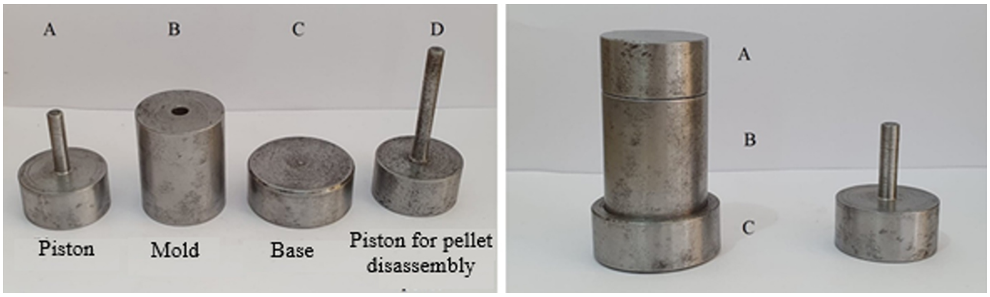

Figure 2. Steel equipment for pellet production.
Source: own work

3. RESULTS AND DISCUSSION

Moisture, ash and volatile matter.

Moisture analysis was performed by taking approximately 5 grams of each sample and placing them on the pan of the moisture analyzer. The apparatus increased the sample temperature to 120 °C and maintained it until a constant mass was achieved. This procedure was carried out in triplicate, and the results are presented as the average of the three measurements plus or minus the standard deviation. As shown in Figure 3, the highest moisture content was observed in the charcoal and starch composite material (3:1 ratio), with 16.45±0.35%, while the lowest moisture content was found in the dry wood at 6.68±0.51%. The increased moisture in the composite material is likely due to the starch, which tends to absorb water. Additionally, compared to wood, charcoal has a much larger surface area and a porous structure that may contribute to water adsorption.

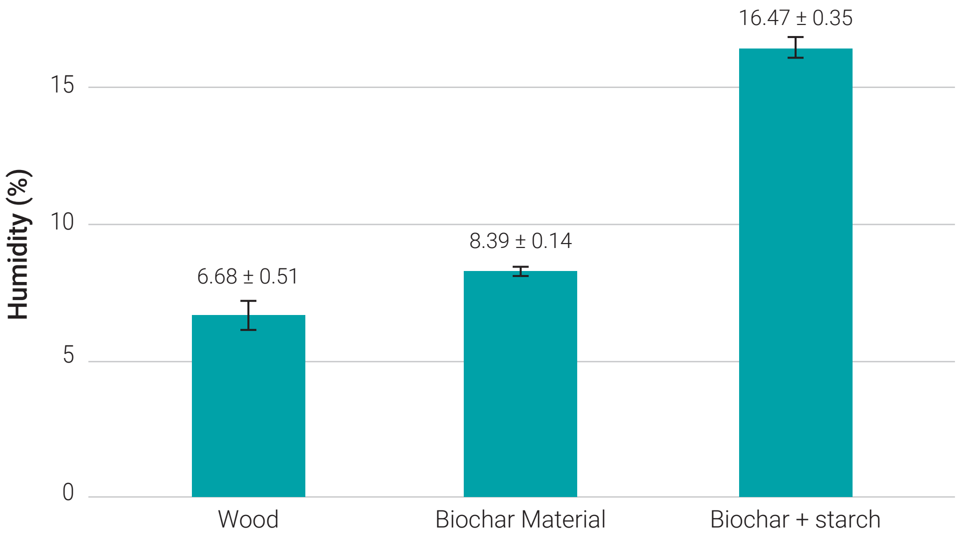

Figure 3. Moisture content of wood, charcoal and charcoal + starch samples.
Source: own work

To determine the percentage of ash, approximately 5 grams of each sample, weighed to four decimal places on an analytical balance, were placed in a previously weighed crucible. The crucible was then heated in a muffle furnace at 600 °C until white or grayish-white ash was obtained. This process was repeated until a constant weight was achieved. After calcination, the material was allowed to cool in a desiccator to prevent ash hydration. The ash content is expressed as a percentage and calculated using the following equation [25].

$$\% \text{ Ashes} = 100\frac{w_c}{w_i} \qquad \text{Equation 1}$$

Where w_c is the mass in grams of the ash and w_i is the initial mass of the sample.

Figure 4 shows the percentage of ash in the materials studied. Wood has the lowest ash content, with 11.58 ± 0.40%, reflecting a lower ratio between initial mass and ash amount. Charcoal shows a higher ash percentage because it has lost many of its volatile components, resulting in an ash content approximately 40% greater than that of wood. The charcoal + starch composite exhibits the highest ash content at 16.47 ± 0.35%. Similar to the moisture behavior, this approximately 200% increase compared to charcoal is attributed to the starch content.

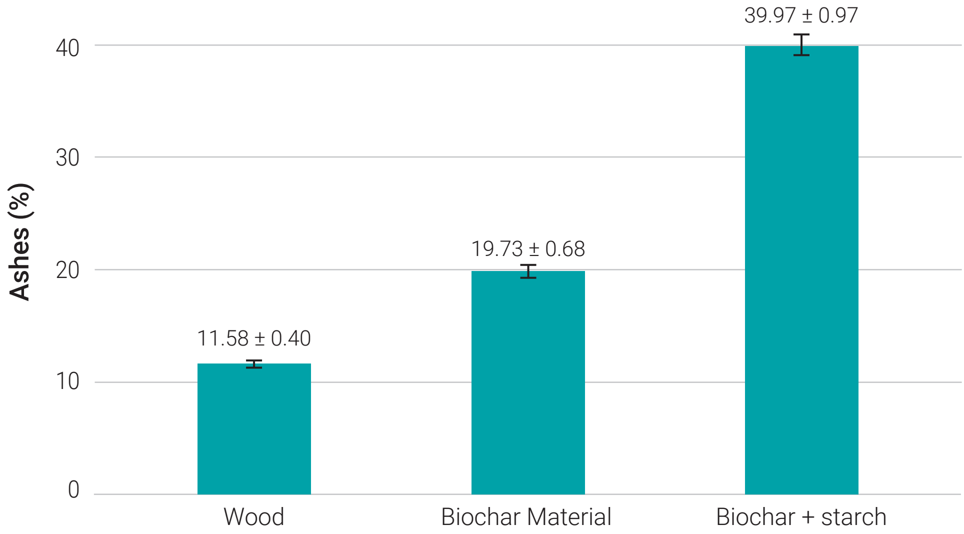

Figure 4. Ash content of wood samples, charcoal and charcoal + starch mixture 3:1.
Source: own work

The procedure for determining volatile content is similar to that for ash analysis, with the difference that the sample is placed in a crucible and heated to 300 °C for 10 minutes. After heating, the crucible is removed from the muffle, cooled in a desiccator until it reaches room temperature, and then weighed on an analytical balance with four decimal places.

Figure 5 presents the percentage of volatile material in each sample. As expected, wood exhibits a higher volatile content at 21.70 ± 0.92%, compared to charcoal at 9.73 ± 0.72%, reflecting the loss of volatiles during pyrolysis. Interestingly, the mixture of charcoal and starch shows a significant increase in non-volatile material, reaching 35.25 ± 0.97%.

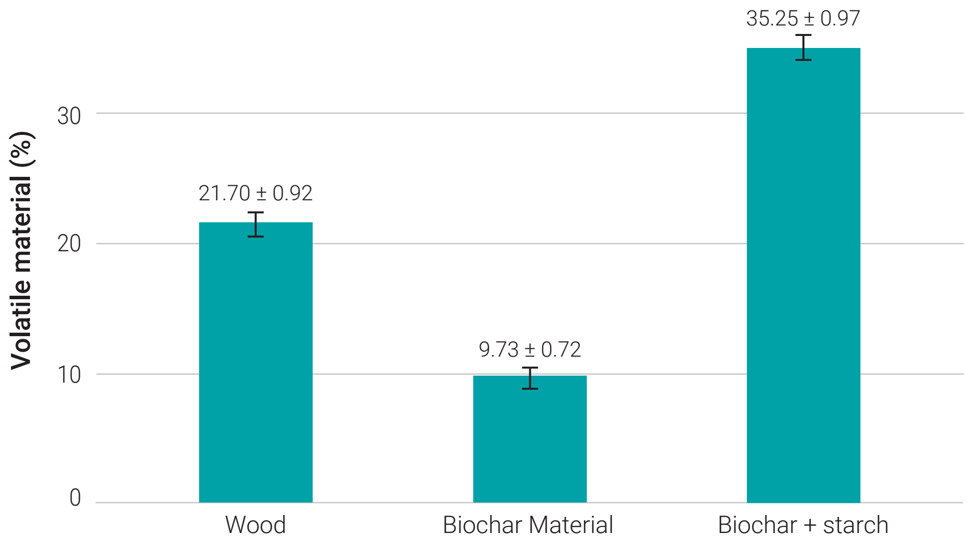

Figure 5. Volatile material content of wood samples, charcoal and charcoal + starch mixture 3:1.
Source: own work

TGA results (Thermogravimetric analysis)

The TGA results for biomass (wood), coal, and coal with starch are shown in Figures 6, 7, and 8, along with the corresponding DTGA plots (derivatives of the thermogravimetric analysis).

In Figure 6, two significant mass loss events can be observed as temperature increases. The first occurs between approximately 56 °C and 167 °C, during which about 10% of the sample's mass is lost, likely due to the evaporation of surface water and some volatile compounds. The second major mass loss takes place between 277 °C and 417 °C, where around 70% of the sample decomposes. This corresponds to the breakdown of volatile matter, primarily from the decomposition of hemicellulose (around 300 °C) and cellulose (approximately 393 K or 120 °C), which may continue between 523 K (250 °C) and 713 K (440 °C) [26]. Finally, between 393 °C and 726 °C, the mass decreases by an additional 10%, possibly attributed to the decomposition of lignin, which begins decomposing near 326.85 °C and accelerates its decomposition rate above 500 °C [26].

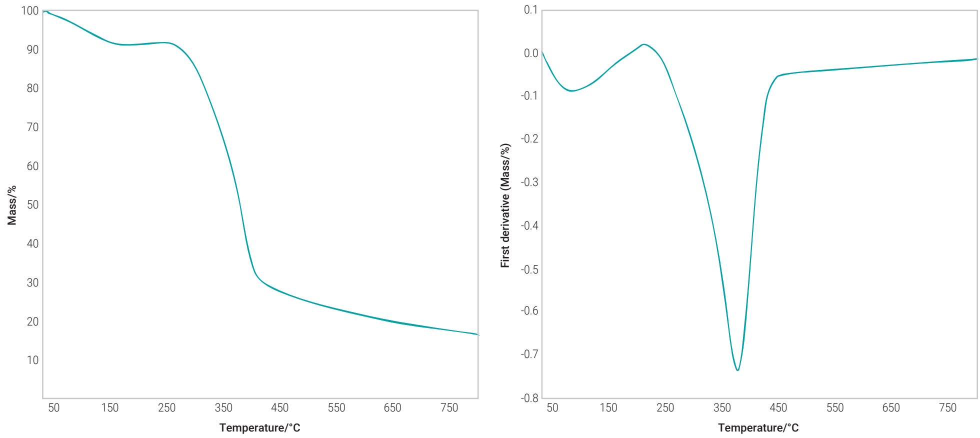

Figure 6. Thermogravimetric analysis of *Coffea arabica* L. wood.
Source: own work

Figure 7 presents the thermogravimetric analysis of charcoal. Unlike dry wood, which loses slightly over 80% of its mass within a temperature range up to 770 °C, charcoal loses only about 15% of its mass. This difference occurs because charcoal has already lost most of its volatile matter during the pyrolysis process, which also enables it to burn at higher temperatures than wood and to have a longer combustion duration. The mass lost during the analysis likely corresponds to moisture, water, and a small amount of volatile substances absorbed in the porous structure of the charcoal.

Additionally, the first derivative of the thermogravimetric curve for charcoal (Figure 7) shows no abrupt changes in mass, indicating a relatively homogeneous composition throughout the temperature range.

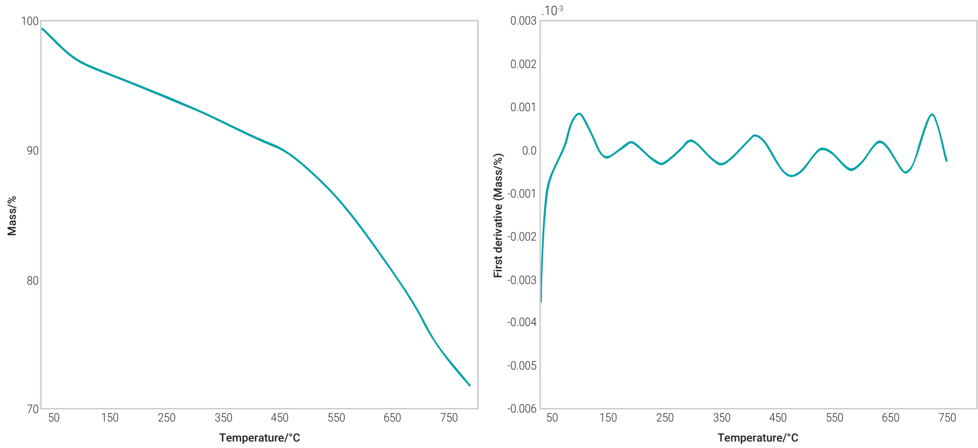

Figure 7. Thermogravimetric analysis of pyrolysis charcoal from *Coffea arabica* L.
Source: own work

Regarding the 3:1 mixture of charcoal and starch shown in Figure 8, two distinct mass loss events are observed. The first occurs at temperatures below 120 °C and corresponds to the loss of water. The second significant change happens between 300 and 400 °C and is associated with the decomposition of volatile material. This variation in behavior compared to pure charcoal is attributed to the presence of starch, which decomposes mainly between 250 and 350 °C [27], precisely in the temperature range where the most pronounced difference from the charcoal TGA curve is observed.

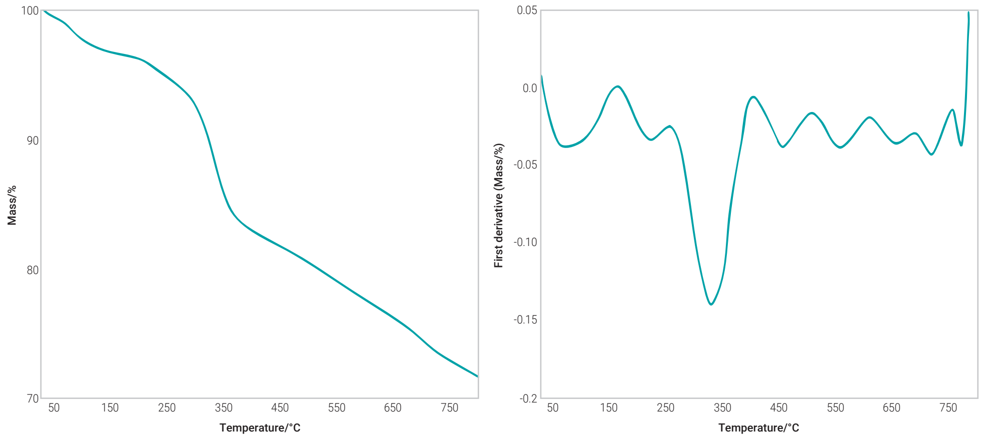

Figure 8. Thermogravimetric analysis of charcoal + starch from *Coffea arabica* L.
Source: own work

Figure 9 presents a comparison of the thermogravimetric analysis (TGA) curves for the three materials studied. Wood is identified as the most thermolabile material, showing decomposition at the lowest temperatures, while coal is the most thermally stable. When starch is added to coal to enhance the mechanical properties of the pellets, the resulting mixture begins to decompose at lower temperatures compared to pure coal. Additionally, the incorporation of starch increases the ash content of the pellet, which may pose challenges for combustion. Specifically, higher ash production can lead to increased residue buildup in furnaces, necessitating more frequent maintenance to prevent corrosion and ensure efficient operation.

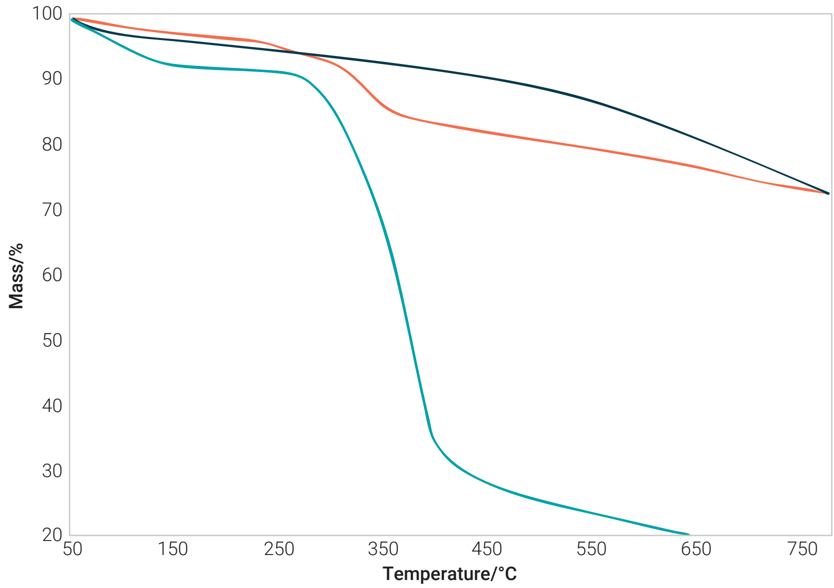

Figure 9. Thermogravimetric analysis of wood (black line), charcoal (blue line) and 3:1 charcoal:starch mixture (red line).
Source: own work

Heating power

The calorific values of the samples were measured using a CAL3K oxygen bomb calorimeter, with the results shown in Figure 5. Charcoal exhibited the highest calorific value at 27.62 ± 0.51 J/g, while wood showed the lowest at 18.57 ± 0.50 J/g. When charcoal was mixed with starch in a 3:1 ratio, the calorific value decreased to 22.39 ± 0.51 J/g, which is lower than that of pure charcoal.

Charcoal not only offers a higher calorific value but also greater durability (as seen in Figure 4), contributing to improved fuel efficiency. Compared to wood, charcoal increases the calorific value by approximately 48.73%, and the charcoal-starch mixture improves it by 20.6%. However, adding starch to charcoal reduces its thermal stability, decreases the calorific value, and consequently affects the overall fuel efficiency.

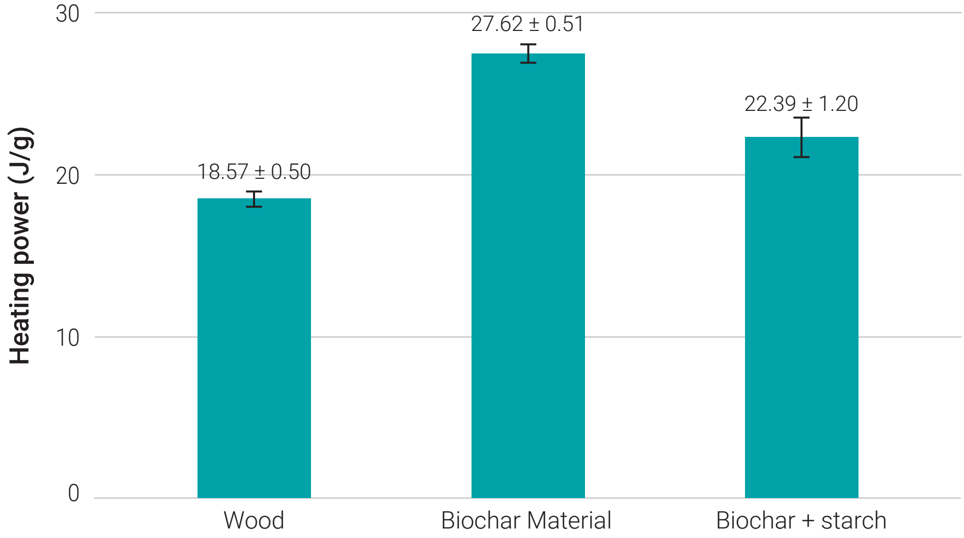

Figure 10. Heating power of wood samples, charcoal and charcoal + starch mixture 3:1.
Source: own work

According to the figure, the calorific value of charcoal is higher than that of biomass (wood), and the addition of starch as a binder reduces the calorific value of charcoal. Additionally, adding starch to charcoal decreases the ash content, moisture content, and volatile matter compared to charcoal without a binder. Producing briquettes in a hollow form rather than solid may also reduce ash, moisture, and volatile content in the coal. Although this reduction in calorific value may lower furnace efficiency, the decrease in ash, moisture, and volatiles can help reduce corrosion.

4. CONCLUSIONS

Coffea arabica L. biomass is a promising raw material for developing densified biofuels with high calorific value. The abundant availability of this biomass in Colombia, combined with the high calorific values of both wood and pyrolysis charcoal, makes it an ideal candidate for such applications.

Pyrolysis biochar represents the best option for producing biofuel pellets from coffee biomass, as it tends to retain less moisture, enhances energy efficiency, and reduces residue production during combustion. Compared to untreated biomass, biochar provides more energy per mass unit of biofuel, facilitating more efficient transport by eliminating the energy costs associated with transporting non-energy materials like water and ash.

Finally, the addition of starch offers minimal benefits energetically and particularly regarding combustion residues.

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