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Thermo-Chemical Characterization of Coffee Husk from a New Variety (*Coffea arabica* L. var. Cenicafé 1) for Biofuel Production

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Abstract: *Coffea arabica* L. var. Cenicafé 1, developed by the National Coffee Research Center of Colombia (Cenicafé), offers improved productivity, quality, and disease resistance, but its processing generates coffee husk, a by-product often considered waste. This study explores the thermo-chemical properties of the husk from this new variety to assess its potential for biofuel production. By utilizing this husk, waste management challenges were addressed while providing a sustainable energy source. Key properties measured include calorific value, ash content, elemental composition, and ash behavior. The calorific value was found to be 18.55 MJ kg^{-1}, higher than many other coffee husks, suggesting strong energy potential. The ash content was notably low at 0.83%, and the minimal presence of nitrogen, sulfur, and chlorine reduces the risk of harmful emissions during combustion. The ash composition also indicates that it can be safely used as fertilizer, promoting a circular economy. Overall, the husk from Cenicafé 1 displays characteristics comparable to wood but with even lower ash content, making it an ideal candidate for biofuel. This study underscores the dual benefits of improving waste management and generating renewable energy from coffee husks, contributing to sustainable agricultural practices.

Keywords: Agricultural Waste; Bioenergy; Biomass Conversion; Cellulosic Biomass; Sustainable Energy

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1. Introduction

The wet method, also known as washing processing, is a widely used coffee bean processing technique that encompasses multiple phases that significantly influence the quality and characteristics of the end product of green coffee beans (Figueroa Campos et al., 2020; Kamal et al., 2008). In this method, harvested and sorted coffee beans undergo pulping to remove the outer skin of the coffee fruit and expose the beans within. The pulped beans are then fermented for 12–48 hours (Raveendran & Murthy, 2022; Vinícius de Melo Pereira et al., 2017); during this process, mucilage is degraded, producing ethanol, acetic acid, and lactic acids which impact the development of the

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distinctive flavor profile of the coffee beans (Avallone et al., 2001; Tamilselvan et al., 2024). The fermented coffee beans are then washed to remove any remaining mucilage and carefully dried to an optimal moisture content of 10–12% wet basis (wb); the removal of mucilage aims to prevent excessive or uneven drying, which can adversely affect the quality of the coffee (Elhalis et al., 2021; Kleinwächter et al., 2015; Serna-Jiménez et al., 2022). Following the drying stage, the coffee beans undergo hulling, which removes the parchment layer (endocarp); once removed, it is known as husk (Duque-Dussán et al., 2023; Muzaifa et al., 2021; Serna-Jiménez et al., 2022). Upon completion of this stage, the product is referred to as "green coffee" representing the final stage before export and effectively encompassing the unprocessed state of the beans, prepared for the process of roasting.

Although the wet process is globally recognized for providing control and consistency across various stages of coffee production, allowing for more predictable and uniform outcomes (Firdissa et al., 2022; Hall et al., 2022; Kleinwächter et al., 2015; Kleinwächter & Selmar, 2010), it also generates significant amounts of solid and liquid waste, exceeding 10 million tons annually (de Almeida et al., 2023; Mendoza Martinez et al., 2019), the liquid waste originates from various production processes, requiring approximately 40–45 liters of water for every kilogram of coffee fruit processed (Oller et al., 2011; Ribeiro et al., 2024). Meanwhile, solid waste emanates from various components of the coffee fruit itself. The mature coffee fruit, as depicted in Figure 1, comprises the following components: fruit skin, which accounts for an estimated 29–43% (w/w); endocarp (parchment), which constitutes approximately 12% (w/w); silverskin, which accounts for around 4.2% (w/w); and coffee beans, which comprise approximately 55% (w/w) of the fruit weight (Esquivel & Jiménez, 2012; Muzaifa et al., 2021; Serna-Jiménez et al., 2022; Shah et al., 2023; Suraj et al., 2024).

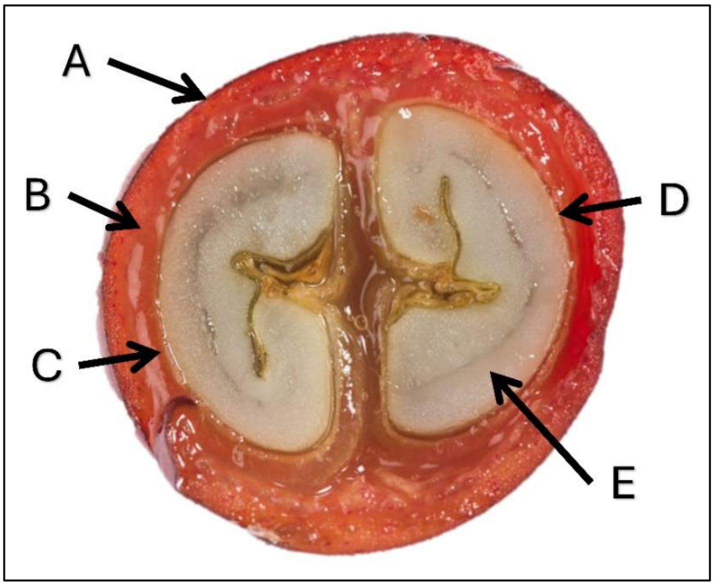

Figure 1. Coffee fruit structure: A. Exocarp (outer skin); B. Mesocarp (pulp); C. Mesocarp (mucilage); D. Endocarp (Parchment); E. Endosperm (seed).

According to data from FAOSTAT (2020), global coffee production in 2020 reached 10,688,153 tons, with approximately 40% being processed using the wet method (Campuzano-Duque et al., 2021; Scariot et al., 2024). This implies that about 1,154,320 tons of pulp, 513,031 tons of mucilage, and 256,515 tons of husk are generated from these processes. For example, Colombia, one of the leading coffee producers, produced approximately 14.1 million bags of coffee during the 2020–2021 period (Campuzano-Duque et al., 2021; Yang et al., 2024). Each bag contains about 60 kg of green coffee, meaning Colombia alone produced around 50,760 tons of husk during that period.

The high content of carbohydrates, proteins, pectin, and bioactive compounds (polyphenols) in coffee wastes and by-products makes them suitable for utilization in food, cosmetics, pharmaceuticals, bioenergy, and bioremediation (Figueroa Campos et al., 2020; Jeníček et al., 2022;

Serna-Jiménez et al., 2022; Tamilselvan et al., 2024), some of the main by-products in the coffee agricultural industry include the husks, peels, and pulp of the coffee fruit, which collectively represent nearly 45% of the coffee fruit. On the other hand, considering that husks undergo a drying process while still attached to the beans, there is a growing trend to dispose of these by-products for biomass applications in various thermal processes (Afessa et al., 2024; Ribeiro et al., 2024; Saenger et al., 2001; Setter & Oliveira, 2022). Coffee husks, rich in organic matter (Pandey et al., 2000), serve as an environmentally friendly and sustainable energy source, with one of its most common uses being as biofuel for biomass steam boilers (Adams & Ghaly, 2007; Oliveira & Franca, 2015; Yang et al., 2024) and hybrid coffee dryers (Duque-Dussán et al., 2023; Manrique et al., 2020), either used directly, in pellet form, or as briquettes (Tesfaye et al., 2022). This not only addresses waste management issues but also contributes to the development of environmentally friendly and efficient energy solutions (Bamisile et al., 2020; Rivera & Ortega-Jimenez, 2019).

Seeing that coffee, as any other crop, is naturally susceptible to certain diseases and pests (Poyilil et al., 2022; Saenger et al., 2001), the National Coffee Research Centre (Cenicafé) of Colombia has been breeding new coffee varieties resistant to certain diseases such as coffee leaf rust (Castro Caicedo et al., 2013; Flórez et al., 2016, 2018) and the coffee berry disease (CBD) (Ferrucho et al., 2024; Flórez et al., 2016; Gonzales et al., 2023), which diminish the coffee production. The latest developed variety, the so-called "Cenicafé 1", displayed high resistance to the diseases mentioned above and better physical grain attributes (Duque-Dussán et al., 2023). Due to the positive characteristics shown by *Coffea arabica* L. var. Cenicafé 1, the National Coffee Federation of Colombia has been carrying out extensive crop renewal strategies and campaigns throughout their extension service (Aguirre Cuellar et al., 2022; Duque-Dussán, 2023; Rendón, 2021), which transmits to the coffee growers the research and scientific results attained by Cenicafé to increase the grower's profitability and crop yield. Therefore, the country is rapidly transitioning towards this coffee variety (Avelino et al., 2015; Duque-Dussán et al., 2023; Ferrucho et al., 2024).

Although research has been carried out to calculate the energy value of other coffee varieties' husk (Cangussu et al., 2021; de Almeida et al., 2023; Pandey et al., 2000; Poyilil et al., 2022; Rivera & Ortega-Jimenez, 2019; Shah et al., 2023; Solomon & Gopal, 2024; Tesfaye et al., 2022; Twinomuhwezi et al., 2021), and there is also a record of the calculation of the thermal and physical properties of parchment coffee of the latest developed coffee varieties by Cenicafé (Duque-Dussán et al., 2023; Pineda et al., 2022; Tinoco et al., 2014), the information available in the literature is relatively scarce. There are no reports related to the physical and chemical characterization of the coffee husk of *Coffea arabica* L. var. Cenicafé 1 to understand its potential as a biofuel, and, based on them, design different processes to use this byproduct (Manrique et al., 2019; Serna-Jiménez et al., 2022; Tesfaye et al., 2022; Yang et al., 2024).

Therefore, this study aimed to comprehensively assess the energy potential of *Coffea arabica* L. var. Cenicafé 1 husks by analysing their moisture content, elemental composition, ash content, net and gross calorific values, as well as volatiles and combustion properties. By determining these parameters, the research sought to understand the suitability of coffee husks as a biomass energy source and their potential for applications such as waste management and renewable energy production. This characterisation is crucial for informing decisions regarding using coffee husks as a sustainable fuel source and the design of machinery and processes involving this biomass, contributing to energy efficiency and environmental sustainability efforts.

2. Materials and Methods

80 kg of *Coffea arabica* L. var. Cenicafé 1 coffee berries in ripe stages 4, 5 and 6 (Pineda et al., 2022; Tinoco et al., 2014; Tinoco & Peña, 2017) were collected from the Colombian National Coffee Research Center's (Cenicafé) experimental farm Naranjal (GPS coordinates: 4.972250, -75.652547) located in the municipality of Chinchiná, Colombia. Then, the berries were processed in Cenicafé's seed processing facility (GPS Coordinates: 4.991873, -75.597159) in the municipality of Manizales, Colombia, through the wet method, characterized by the following steps: Hydraulic classification, pulping, mucilage

degradation (fermentation), washing and drying (Duque-Dussán & Banout, 2022; Figueroa Campos et al., 2020; Pereira et al., 2020).

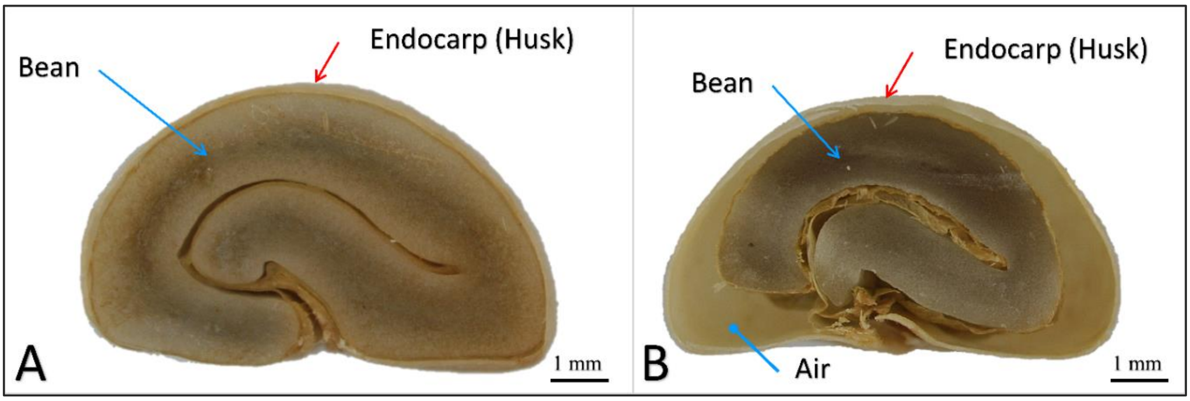

Figure 2. A. Wet coffee bean at 53% (wb). B. Dry coffee bean at 10% (wb).

Once the coffee beans reached their equilibrium moisture content of 10-12% (wb), the hulling process continued to remove the husk, also known as endocarp or parchment (de Oliveira e Silva et al., 2023; Dias et al., 2020), which separated already from the bean due to the shrinking effect that drying has on the bean (Burmester & Eggers, 2010; Duque-Dussán et al., 2022; Nilnont et al., 2012; Phitakwinai et al., 2019; Sfredo et al., 2005) as seen in Figure 2b. From the generated husk, 2 kg were taken to perform the evaluations.

2.1 Sample preparation

An analytical sample was prepared by grinding the received coffee husk (Figure 3A) until attaining a particle size capable of fitting through a 0.5mm sieve fraction (Figure 3B), as ISO 14780:2017/AMD 1:2019 prescribed.

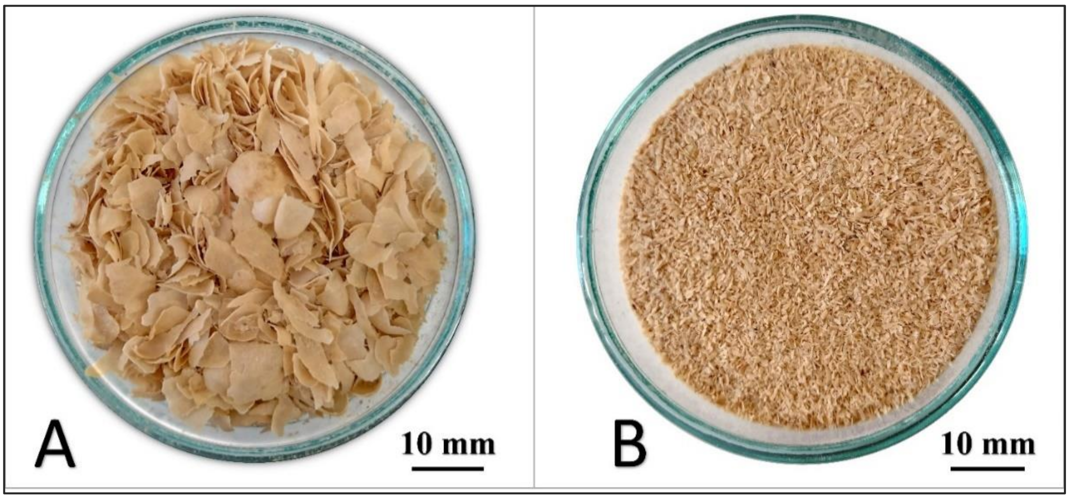

Figure 3. A. Coffee husk as received. **B.** Sieved and ground coffee husk.

During the sieving process, a 0.5 mm PRECISELEKT Stainless Steel wire cloth sieve calibrated following the ISO 3310-1:2016 was used.

2.2 Moisture content

The moisture content of the received coffee husk was measured by drying a 10 g sample using a Memmerth UF 30 (Schwabach, Germany) laboratory oven at 105±2ºC until uniform mass is attained. Afterwards, the moisture content was calculated using Equation (1), as indicated in ISO 18134-3:2022 for solid biofuels.

$$W = \left(\frac{m_0 - m_1}{m_0}\right)100$$

(1)

Where W stands for the moisture content as received in % (wb); m_0 represents the mass of the sample before drying in g and m_1 depicts the mass of the sample after drying in g.

2.3 Ash Content

The ash content of the dry basis (w=0%) of the husk was measured using a laboratory muffle furnace (LecoSpec CHN analyser, St. Joseph, MI, USA), and calculated with Equation (2) according to ISO 18122:2022.

$$A_d = \left(\frac{m_3 - m_1}{m_2 - m_1}\right)\left(\frac{100}{100 - W_{ad}}\right)100$$

(2)

Where, m_1: mass of empty dish (g); m_2: mass of the dish (g) + test sample portion (g); m_3: mass of the dish (g) + ash (g); W_{ad}: moisture content of the test sample portion (g).

2.4 Gross and Net Calorific Value

Temperature jump was measured using a Laget MS-10A (Beijing, China) bomb calorimeter. Then, the gross calorific value (GCV) was calculated using Equation (3) based on the specifications of EN ISO 18125:2017.

$$GCV = \frac{(dTk\ Tk) - c}{m}$$

(3)

Where GCV stands for the gross calorific value (J g^{-1}); dTk is the temperature jump (°C); Tk represents the mean value of the effective heat capacity of the calorimeter as determined in the calibrations (9161 J $°C^{-1}$); *c* depicts the total repair on burning spark fine wire (J) and m denotes the mass of the material sample (g).

Afterwards, the dry basis net calorific value (NCV) of the coffee husk was calculated by using Equation (4) also as described in the EN ISO 18125:2017.

$$NCV = GCV - (24.42\ (W + 8.94H))$$

(4)

Where NCV is the net calorific value (J g^{-1}); GCV stands for gross calorific value (J g^{-1}); W is the moisture content (%) and H represents the hydrogen content (%).

2.5 Volatiles

The content of volatile matter (V_d) of the coffee husk was determined using a Nabertherm LT-40/12 (Lilienthal, Germany) laboratory muffle furnace at 900 °C as indicated in ISO 18123:2023 and calculated using Equation (5)

$$V_d = \left[\frac{100(m_2 - m_3)}{m_2 - m_1} - M_{ad}\right]\left(\frac{100}{100 - M_{ad}}\right)$$

(5)

2.6 Elemental Analysis

The composition of Carbon, Hydrogen, and Nitrogen, in the coffee husk were measured according to ISO 16948:2015, using a LecoSpec CHN analyser (St. Joseph, MI, USA). Sulphur and Chlorine contents were measured according to ISO 16994, using Basic IC Plus chromatography. Oxygen proportion in the combustible matter of the coffee husk was calculated using Equation (6).

$$O = 100 - C - H - N - S - A_d$$

(6)

Where, *O*: Oxygen content (%); *C*: Carbon content (%); *H*: Hydrogen content (%); *N*: Nitrogen content (%); *S*: Sulphur content (%) and A_d: Ash content (%).

2.7 Major and Minor Elements in Ash

The content of major elements in the ash were determined according to the ISO 16967:2015 standard using microwave digestion (Ethos Pro, Milestone, Sorisole, Italy) and ICP-OES (Jarrell ash, model IRIS AP, Thermo Fisher Scientific, Waltham, Massachusetts, USA).

2.8 Ash Melting Behaviour

The ash melting behaviour was determined using a Hesse instrument HT15 optical heating microscope (Osterode am Harz, Germany) with an automated analyser as prescribed by ISO 21404. The shrinkage, deformation, hemisphere and flow temperatures of the ash were determined.

$$I = \frac{(CaO + MgO)}{K_2O + Na_2O}$$

(7)

The ash sintering was also determined by considering the relationship between alkaline earth oxides and alkaline oxides, using Equation (7). When the I index is greater than 2, the biomass is said to have no risk of sintering during combustion (Fernández Llorente & Carrasco García, 2005).

2.9 Combustion

The combustion properties of the coffee husk were determined from the relationship provided by Jeníček et al. (2022).The theoretical amount of oxygen for perfect combustion was determined based on Equation (8)

$$O_{2,min} = V_m(O_2)\left(\frac{C}{M(C)} + \frac{H}{M(H)} + \frac{S}{M(S)} + \frac{O}{M(O_2)}\right)$$

(8)

Where $O_{2,min}$ is the theoretical amount of oxygen; $V_m\ (O_2)$ represents the molar volume of oxygen at Standard Temperature and Pressure (STP) (22.39 m^3 $kmol^{-1}$); *C* is the carbon content (%); *H* is the hydrogen content (%); *S* is the sulphur content (%); *O* is the oxygen content (%); *M(C)* stands for the molar mass of carbon that combines with O_2 (kg $kmol^{-1}$); *M(H)* represents the molar mass of hydrogen that combines with O_2 (kg $kmol^{-1}$); *M(S)* is the molar mass of sulphur that combines with O_2 (kg $kmol^{-1}$) and M(O) symbolizes the molar mass of oxygen that combine with O_2 (kg $kmol^{-1}$)

The theoretical amount of dry air L_{min} (m^3_N kg^{-1}) for perfect combustion was calculated using Equation (9).

$$L_{min} = \frac{O_{2,min}}{C_{atm}(O_2)} \times 100$$

(9)

Where: $O_{2,min}$ as above-mentioned, is the theoretical amount of oxygen and $C_{atm}(O_2)$ represents the volumetric concentration of oxygen in air (21% vol).

In order to achieve complete combustion, it is imperative to maintain an optimal surplus of air to prevent a reduction in combustion temperature, which can result from the removal of heat by the flue gas (Al-Kayiem, 2016; Malaťák et al., 2013). The optimal air quantity falls within a range greater than the theoretical excess air and less than the actual excess air, as indicated by Sadaka & Johnson (2011). The excess air coefficient (n) represents the ratio between the actual air consumption ($O_{2,skut}$) and the theoretical one ($O_{2,min}$), this relationship is mathematically expressed in Equation (10).

$$n = \frac{O_{2,skut}}{O_{2,min}} = \frac{20.95}{20.95 - O_2} = \frac{CO_{2,min}}{CO_2}$$

(10)

The real amount of air for perfect combustion L_{skut} can be determined as displayed in Equation (11).

$$L_{skut} = O_{2,min}\left(\frac{100n}{21}\right) \quad (11)$$

Equation (12) was then used in determining the theoretical amount of dry flue gasses $V_{fg,min}$.

$$V_{fg,min} = \left(\frac{V_m(CO_2)}{M(C)} \times \mathrm{C}\right) + \left(\frac{V_m(SO_2)}{M(S)} \times \mathrm{S}\right) + \left(\frac{V_m(N_2)}{M(N_2)} \times \mathrm{N}\right) + \left(\frac{C_{atm}(N_2)}{100} \times L_{min}\right) \quad (12)$$

Where $C_{atm}(N_2)$ represents the nitrogen concentration in the air (75.474% vol).

The volumetric amounts of combustion products, CO_2, H_2O, N_2, SO_2, and O_2 were calculated using Equations (13) to (17) (Bappah et al., 2022; Malaťák et al., 2013).

$$v(CO_2) = \left(\frac{V_m(CO_2)}{M(C)} \times C\right) + \left(\frac{C_{atm}(CO_2)}{100} \times L_{min}\right) \quad (13)$$

$$v(H_2O) = \left(\frac{V_m(H_2O)}{M(H_2)} \times H\right) + \left(\frac{V_m(H_2O)}{M(H_2O)} \times W\right) \quad (14)$$

$$v_{N_2} = \left(\frac{V_m(N_2)}{M(N_2)} \times N\right) + \left(O_{2,min} \times \frac{C_{atm}(N_2)}{C_{atm}(O_2)}\right) \quad (15)$$

$$v_{SO_2} = \left(\frac{M(C)}{M(S)} \times S\right) \quad (16)$$

$$v_{O_2} = O_{2,min} \times (n-1) \quad (17)$$

Where, W represents the moisture % (wb) content in the fuel.

An analytical sample was prepared by grinding the received coffee husk (Figure 3A) until attaining a particle size capable of fitting through a 0.5 mm sieve fraction (Figure 3B), as ISO 14780:2017/AMD 1:2019 prescribed.

3. Results and Discussion.

3.1 Moisture Content

The moisture content of the coffee husk, a novel finding in our research, was W=7.14% (wb). This discovery is significant as the moisture content can influence various aspects of the coffee husk, including its potential as a biofuel and its suitability for pelleting and briquetting (Bekalo & Reinhardt, 2010; Poyilil et al., 2022; Tesfaye et al., 2022); the wet processing method employed results in husks with a relatively high lignin content (Kumari & Gupta, 2023; Shah et al., 2023; Tun et al., 2020), which enhances their binding properties, promoting the cohesion and structural integrity of the densified biofuel products, hence reducing the need for additional binders or additives (Anggono et al., 2023; Tun et al., 2020).

It is reported in the literature that the moisture content of coffee husks for other varieties widely varies from 7-18% (wb) to 13% (wb) as the average moisture content of wet-processed coffee husks (Bekalo & Reinhardt, 2010; Cangussu et al., 2021; Oliveira & Franca, 2015). A moisture content within this range indicates a favourable condition for biofuel processing, as the husks have undergone a drying process, reducing the energy required for further moisture removal steps, thereby reducing energy consumption and processing costs (Cangussu et al., 2021; Scariot et al., 2024), conducive to efficient conversion processes, such as pyrolysis or gasification, which typically require biomass feedstocks with moisture content below certain thresholds to optimize energy yield and process efficiency (Conesa et al., 2016; Nam et al., 2021; Poyilil et al., 2022; Rivera & Ortega-Jimenez, 2019).

Moreover, the low moisture content of the coffee husks, enhances their suitability for long-term storage without the risk of microbial degradation or spoilage, ensuring a stable and reliable feedstock supply for biofuel production facilities, a significant advantage in the industry (Rivera & Ortega-Jimenez, 2019; Serna-Jiménez et al., 2022; Shah et al., 2023). Additionally, the consistent moisture content observed in the husks of the new coffee variety facilitates standardized processing protocols and enhances the scalability of biofuel production operations.

3.2 Ash Content

The ash content A_d of the evaluated coffee husks, measuring at 0.83%, holds a significantly lower difference with other studies (Cangussu et al., 2021; Mhilu, 2014; Nam et al., 2021; Poyilil et al., 2022; Saenger et al., 2001; Tesfaye et al., 2022; Yang et al., 2024) in evaluating the quality and potential applications of the husk evaluated in this study since a low ash content in coffee husks indicates minimal mineral impurities and inert materials, highlighting their purity and suitability for different applications in the industry (Pandey et al., 2000; Rivera & Ortega-Jimenez, 2019; Shah et al., 2023) as it reduces the formation of ash during combustion (Fernández Llorente & Carrasco García, 2005; Poyilil et al., 2022), ensuring cleaner emissions and minimizes equipment maintenance requirements, enhancing the overall efficiency of the combustion process (Manrique et al., 2019, 2020; Sadaka & Johnson, 2011). This ash content can be compared with that of the best solid biofuel used in combustion devices (ISO 17225-2).

Additionally, in agricultural applications such as composting or soil conditioning, coffee husks' low ash content is beneficial and holds a promising potential (Fagundes et al., 2020; Jeníček et al., 2022; Torrez et al., 2023). Excessive ash can alter soil pH levels and nutrient availability, potentially affecting plant growth (Peña-Quiñones et al., 2011; Szara-Bąk et al., 2023; Teutscherová et al., 2023; Usman et al., 2022). By having a low ash content, these coffee husks can be incorporated into soil amendments without compromising soil quality, providing organic matter to significantly improve soil structure and its fertility, which refers to the soil's ability to support plant growth by providing essential nutrients and optimal conditions for plants to thrive (De la Rosa et al., 2023), offering an optimistic outlook for their use in agriculture.

3.3 Gross and Net Calorific Value

The gross calorific value (GCV) and net calorific value (NCV) of the evaluated coffee husks were determined to be 19.78 MJ kg^{-1} and 18.55 MJ kg^{-1}, respectively. This study's findings indicate a higher calorific value than previous studies focusing on coffee husks. For instance, Twinomuhwezi et al. (2021) reported a gross calorific value of 15.39 MJ kg^{-1}, while Poyilil et al. (2022) reported a GCV value of 19.67 MJ kg^{-1}. Additionally, Anggono et al. (2023) documented GCV values ranging from 18 to 20 MJ kg^{-1} for coffee husks from diverse regions, implying that the new Colombian variety exhibits competitive or superior energy content. Moreover, the attained NCV value of 18.55 MJ kg^{-1} exceeds the averages reported in the literature. For instance, Twinomuhwezi et al. (2021) found NCV values ranging from 16 to 18 MJ kg^{-1} for coffee husks, highlighting the favourable energy characteristics of our new Colombian variety. The husks evaluated in this study also demonstrated superior performance compared with other biomass sources commonly used for energy production as seen in Figure 4.

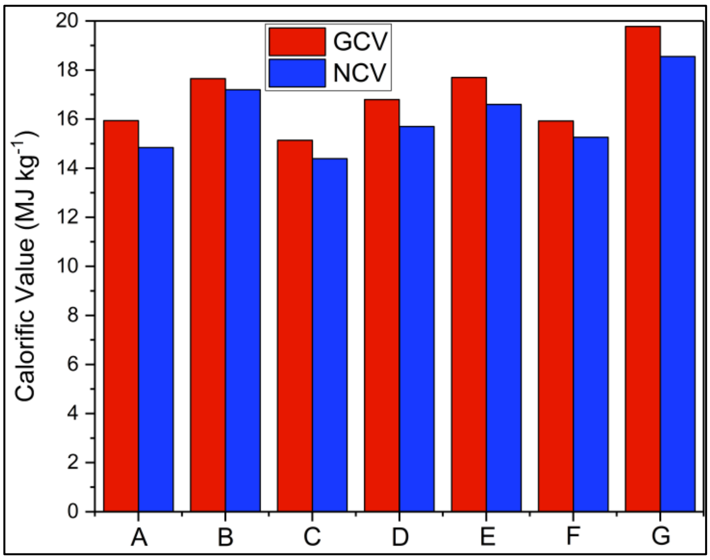

Figure 4. Comparative GCV and NCV values for different crop residues. **A.** Raw rice husk (Imtiaz Anando et al., 2023). **B.** Torrefied rice husk at 234.4°C (Imtiaz Anando et al., 2023). **C.** Corn cob (Kumari & Gupta, 2023). **D.** Peanut shell (Kumari & Gupta, 2023). **E.** *Coffea canephora* coffee husk (Scariot et al., 2024). **F.** *Coffea arabica* L. var. Colombia (Manrique et al., 2019). **G.** *Coffea arabica L*. var. Cenicafé 1 (This study).

Rice husks, for instance, typically exhibit GCV and NCV values ranging from 14 to 17 MJ kg^{-1} and 13 to 16 MJ kg^{-1}, respectively (Imtiaz Anando et al., 2023; Inegbedion & Ikpoza, 2022; Kumari & Gupta, 2023; Mhilu, 2014), which are notably lower than those of our coffee husks. Similarly, corn cobs and wood chips, which have reported GCV and NCV values ranging from 15 to 19 MJ kg^{-1} and 14 to 17 MJ kg^{-1}, respectively (Pedišius et al., 2021), show comparable or lower energy potential than the evaluated coffee husks. Coffee husks offer a valuable biofuel source, especially for isolated coffee growers in Colombia, where it can be used in biomass burning coffee dryers. These results suggest that the new coffee variety has increased energy content, making the husks a more efficient biomass energy source with a higher Net Calorific Value (NCV). This makes husks a cost-effective alternative to external fuels, reducing energy costs for growers. The practice supports a circular economy by repurposing waste and lowering disposal costs. Additionally, burning coffee husks is carbon neutral, reducing the carbon footprint of coffee production. Similar to initiatives in Brazil, using coffee husks as biofuel not only boosts economic resilience for small-scale farmers but also promotes sustainable energy solutions.

3.4 Volatiles

The proximate analysis of the new coffee husk variety revealed a volatile matter content of 82.68%, significantly higher than the volatile matter content found in other studies, which reported values around 69.8% (Nam et al., 2021; Poyilil et al., 2022). The volatile matter content is a crucial parameter in evaluating biomass for energy production. It represents the portion of the biomass converted into volatile gases during pyrolysis (Mhilu, 2014; Nam et al., 2021); combusting these gases is done to generate heat or electricity (Conesa et al., 2016; Elhalis et al., 2021). Therefore, a higher volatile matter content implies that the evaluated coffee husk could yield more energy than other varieties or biomass types.

However, it is essential to note that other factors, such as ash content and heating value, also play a crucial role in determining the overall energy potential of a biomass source (Wan et al., 2024). For instance, a high ash content can negatively impact the energy yield as it does not contribute to energy production but instead leads to operational issues such as slagging and fouling (Cangussu et al., 2021; Manrique et al., 2019, 2020; Poyilil et al., 2022). Nevertheless, as mentioned above, the ash content in this coffee husk variety is lower than others, and the calorific value is also higher than other husks, potentially improving the combustion properties of this biomass.

3.5 Elemental Analysis

The elemental analysis of coffee husks reveals key information about their chemical composition, as outlined in Table 1.

Table 1. *Coffea arabica* L. var. Cenicafé 1. Elemental Composition.

Element	Content
C (% db)	51.11
H (% db)	6.10
N (% db)	0.38
S (% db)	<0.03
O (% db)	41.53
Cl (%db)	<0.01

The elemental composition of biomass material is a crucial factor in determining its potential as a biofuel (de Almeida et al., 2023; Poyilil et al., 2022). The elemental analysis of the coffee husks revealed a unique composition, with a predominant presence of carbon (*C*), followed by oxygen (*O*) and hydrogen (*H*). Nitrogen (*N*) was detected at a relatively low percentage, while sulphur (*S*) and chlorine (*Cl*) were found to be minimal at 0.03% and 0.01% respectively. Additionally, the ash content was recorded at 0.83%. The coffee husk's high carbon content (51.11%) indicates a high energy content, which is desirable for biofuel and biochar production, contributing to carbon sequestration and soil improvement (Aurell et al., 2017; Tesfaye et al., 2022). The relatively low nitrogen and sulphur contents (0.38% and 0.05%, respectively) are also advantageous, as it reduces the emission of harmful gases during combustion (de Almeida et al., 2023).

Compared to other studies, the elemental composition of this new coffee variety husk is quite similar to those reported in the literature (Manrique et al., 2020). However, the Cenicafé 1 husks hold 8.43% more carbon than those published by Poyilil et al. (2022) while evaluating Robusta husks. Also, the variety evaluated in this study displayed 1.54% less nitrogen and 0.38% less sulphur (Cangussu et al., 2021; Manrique et al., 2020; Poyilil et al., 2022), improving the combustion gas composition. It will, therefore, present less risk of emitting oxides of Nitrogen, Sulphur and Chlorine during combustion than husks from other coffee varieties. This coffee husk fulfilled all the elemental requirements for use as solid biofuel judging by the ultimate analysis as indicated in the ISO 17225-2.

3.6 Major and Minor Elements in Ash

The microwave digestion of the new coffee husk ash at 550 °C and atomic emission spectrometry revealed the presence of several major and minor inorganic elements in the ash. Calcium is the predominant element in the ash, with a percentage of 21% (db) and 29% as CaO, suggesting that the sample likely contains significant amounts of calcium-based minerals or compounds common in many natural materials. Potassium (*K*): Potassium is also in substantial quantities, with 18% (db) and 21% as K_2O.

Other elements present relevant content, such as magnesium *Mg* with percentages of 2.6% (db) and 4.4% as MgO, phosphorus (*P*) with percentages of 1.5% (db) and 3.4% as P2O5, sulphur (*S*) with a moderate content of 1.1%, and silicon (*Si*) with a reasonable content of 1.4% were also detected in significant amounts (Table 2), further highlighting the potential of coffee husk ash as a source of essential nutrients (Cangussu et al., 2021; Tolessa et al., 2022).

Table 2. *Coffea arabica* L. var. Cenicafé 1. Husk Ash Major and Minor Element Composition.

Ash Elements	% (DB)
Al	0.11
Ba	0.063
Ca	21
Fe	0.14
K	18
Mg	2.6
Mn	0.073
Na	0.22
P	1.5
S	1.1
Si	1.4
Sr	0.20
Ti	0.012
Zn	0.085

The ash compositions were measured in the form of oxides of the respective elements as displayed in Table 3.

Table 3. *Coffea arabica* L. var. Cenicafé 1. Ash composition.

Ash Elements	%(db)
Al_2O_3	0.20
BaO	0.070
CaO	29
Fe_2O_3	0.21
K_2O	21
MgO	4.4
Mn_2O_3	0.10
Na_2O	0.30
P_2O_5	3.4
SO_3	4.1
SiO_2	3.0
SrO	0.24
TiO_2	0.021
ZnO	0.11

These findings are consistent with previous studies that have reported high levels of these elements in coffee husks (Cangussu et al., 2021; Harsono, 2024; Poyilil et al., 2022; Tolessa et al., 2022; H. Wang et al., 2024). The high calcium content is particularly noteworthy as it can neutralise acidic soils, thereby improving soil fertility as explained in section 3.2. Similarly, potassium is an essential nutrient for plant growth, and its high concentration in coffee husk ash suggests potential applications in agriculture as a soil amendment (Jeníček et al., 2022; Tolessa et al., 2022).

All the measured ash compositions were discovered to be less than the maximum error (Reinmöller et al., 2021). The high content of calcium oxide (*CaO*), potassium oxide (K_2O), and magnesium oxide (*MgO*) suggests that the ash could serve as an effective soil amendment and improve wastewater treatment applications (de Almeida et al., 2023; Poyilil et al., 2022) since these oxides are often associated with the alkalinity of ashes and also help improve soil structure, enhance nutrient availability, and promote plant growth. At the same time, the moderate levels of sulphur (*S*) in the ash indicate that it contains sulphur-containing compounds, which can contribute to soil fertility and plant nutrition. Additionally, the presence of silicon (Si) can enhance plant resistance to abiotic stresses such as drought and disease (Irfan et al., 2023; Şener et al., 2023).

Trace elements such as aluminium (*Al*), iron (*Fe*), manganese (*Mn*), sodium (*Na*), strontium (*Sr*), barium (*Ba*), titanium (*Ti*), and zinc (*Zn*) were present in smaller amounts, which is essential since the high presence of certain elements like aluminium (*Al*), iron (*Fe*), and sodium (*Na*) in the ash could pose challenges in specific applications due to their potential environmental impacts (de Almeida et al., 2023; De la Rosa et al., 2023; Poyilil et al., 2022; Saenger et al., 2001; Tolessa et al., 2022; Usman et al., 2022). For instance, high sodium levels can lead to soil salinisation, adversely affecting plant growth (Cangussu et al., 2021; de Almeida et al., 2023; Poyilil et al., 2022; Şener et al., 2023).

On the other hand, the analysis shows that coffee husk ash contains relatively low concentrations of heavy metals such as lead (*Pb*), cadmium (*Cd*), and mercury (*Hg*), suggesting that coffee husk ash may be suitable for use in agricultural and environmental applications without posing significant risks to human health or the environment.

3.7 Ash Melting Behaviour

Initially, the observation of the shrinkage temperature (ST) marked the initiation of the test process; at this critical stage, the moisture and other volatiles evaporate, thereby reducing the area of the ash pellet by about 5% (Figure 5a) (ISO 21404). The subsequent determination of the deformation temperature (DT) indicates the temperature at which the ash starts to deform under its weight, a critical transition in the material's state, where the first structural alterations occur, indicative of pronounced softening and deformation (Figure 5b) (ISO 21404).

Notably, the behaviour at hemisphere temperature (HT) was not recorded (Table 4), precluding an assessment of any discernible changes or transitions within this specific temperature range. However, the absence of observable alterations indicates that there is no hemisphere formation throughout the test process (Figure 5c), therefore higher temperature is required for the ash pellet to form a hemisphere. The hemisphere temperature (HT) is the temperature at which the ash forms hemispherical shape, thereby reducing the height of the test pellet to half of its diameter (ISO 21404).

Table 4. Ash Melting Behaviour Phases. ST: Sintering temperature (°C); DT: Deformation temperature (°C); HT: Hemisphere temperature (°C); FT: Flow temperature (°C).

Phase	Temperature °C
ST	760
DT	870
HT	-
FT	>1450

Finally, the attainment of the flow temperature (FT) represents the culmination of the melting process, signifying the complete transformation of the ash into a molten state. At this temperature, the material transitions from solid to fluid, facilitating its flow and conformation to the surrounding environment. The high FT of over 1450°C observed for the new coffee variety suggests that the ash of this coffee variety has a high resistance to deformation and flow at high temperatures; this could potentially influence the efficiency of energy conversion processes when using this biomass as a biofuel.

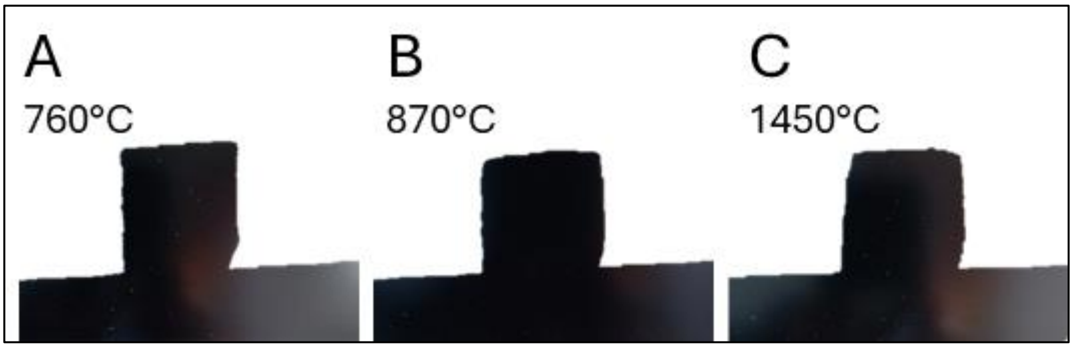

Figure 5. Ash melting behaviour at different phases. **A.** ST: Sintering temperature; **B.** DT: Deformation temperature; **C.** FT: Flow temperature (°C).

The relationship between alkaline earth oxides and alkaline oxides reveals a low I index of the coffee husk ash (1.57), which is less than 2, indicating a possibility of sintering formation during combustion inside the combustion chamber (Fernández Llorente & Carrasco García, 2005). The I index is usually lower for most non-woody biomass, and that of the new coffee variety was discovered to be similar or higher than many herbaceous biomass (H. Zhou et al., 2023; T. Zhou et al., 2023).

These findings offer crucial insights into the thermal stability and behaviour of the *Coffea arabica* L. var. Cenicafé 1 variety's ash, providing a comprehensive framework for understanding its potential applications across diverse industrial sectors. The observed melting behaviour sets the ash derived from the new coffee variety apart from other husks typically used in industrial applications (de Oliveira e Silva et al., 2023; Harsono, 2024). Unlike other husks with less favourable melting characteristics, the ash from the new coffee variety exhibits a lower sintering temperature, indicating an earlier onset of melting, and a relatively lower flow temperature, facilitating a more effortless transformation into a molten state (Fernández Llorente & Carrasco García, 2005; H. Wang et al., 2024). These attributes make the ash derived from the new coffee variety suitable for processing and utilization in various industries, potentially enhancing efficiency and reducing production costs (Dippong et al., 2022).

Moreover, the lower melting temperatures suggest a higher content of alkali metals (H. Wang et al., 2024; Y. Wang et al., 2024; T. Zhou et al., 2023), offering improved reactivity or binding capabilities in specific applications. Leveraging these findings can lead to refining machinery and equipment utilized in biomass conversion processes, thereby enhancing overall efficiency and performance (Rivera & Ortega-Jimenez, 2019; Sadaka & Johnson, 2011; Shah et al., 2023). Additionally, while specific ash melting temperatures for different coffee varieties are not readily available in the literature, further research would be beneficial to compare these results with them and explore the implications of these ash melting temperatures on practical applications, such as bioenergy production.

3.8 Combustion

Efficient oxygen utilization is paramount for optimizing combustion performance, impacting energy output and emissions profiles (Harsono, 2024; Manrique et al., 2020; Sadaka & Johnson, 2011; Saenger et al., 2001). As seen in Table 5, our study determined the O_{2min} at 2.62 m^3 kg^{-1}, indicating a significant reduction compared to conventional fuels (Oliveira & Franca, 2015; Shah et al., 2023). This reduction suggests enhanced combustion efficiency and energy yield, as evidenced by the lower O_{2min} than other coffee varieties (Dippong et al., 2022; Pérez-Sariñana & Saldaña-Trinidad, 2017; Sharma, 2020), indicative of a more efficient combustion process. The calculated L_{min} parameter, stood at 12.48 m^3 kg^{-1}, underscoring the balanced air-fuel ratio characteristic of the new coffee variety's combustion process. These reduced requirements imply that the new coffee variety can achieve comparable combustion levels with less oxygen and air, potentially enhancing efficiency and cost-effectiveness (Dippong et al., 2022; Pérez-Sariñana & Saldaña-Trinidad, 2017).

Table 5. Combustion properties. O_{2min} - Theoretical amount of oxygen for perfect combustion; L_{min} - Theoretical amount of air for perfect combustion; $V_{fg,min}$ - Theoretical volumetric amount of dry flue gas; v_{CO2} - Volumetric amount of CO_2; v_{H2O} -Volumetric amount of H_2O; v_{N2} - Volumetric amount of N_2; v_{O2} - Volumetric amount of O_2.

Sample	O_{2min} (m^3.kg^{-1})	L_{min} (m^3.kg^{-1})	$V_{fg,min}$ (m^3.kg^{-1})	v_{CO2} (m^3.kg^{-1})	v_{H2O} (m^3.kg^{-1})	v_{N2} (m^3.kg^{-1})	v_{O2} (m^3.kg^{-1})
Coffea arabica L. var. Cenicafé 1 Husks	2.62	12.48	10.69	0.95	0.31	10.04	2.88

Notably, the theoretical volumetric amount of dry flue gas ($V_{fg, min}$) was determined to be 10.69 m^3 kg^{-1}, indicative of its ability to generate substantial energy output while mitigating environmental impact through reduced flue gas emissions (Al-Kayiem, 2016; Aurell et al., 2017). Additionally, the volumetric amounts of CO_2 and H_2O were recorded at 0.95 m^3 kg^{-1} and 0.31 m^3 kg^{-1}, respectively, highlighting significant reductions in greenhouse gas emissions and effective moisture control during combustion (Harsono, 2024; Tesfaye et al., 2022).

Furthermore, comparing these results with published data underscored the superior combustion properties of the new coffee variety. These findings, including lower oxygen requirements, reduced carbon dioxide emissions, and optimal air utilization compared to existing biomass-derived fuels, accentuate its potential as a renewable energy source (Rivera & Ortega-Jimenez, 2019; Sonthikun et al., 2016).

Moreover, the higher nitrogen content (v_{N2}) observed in the combustion residues of the new coffee variety could enrich the soil if used as a soil amendment, further enhancing its sustainability profile (De la Rosa et al., 2023; Jeníček et al., 2022). Its efficient combustion process, reduced emissions, and potential soil enrichment benefits position it as an environmentally friendly and economically viable alternative to conventional fuels.

4. Conclusions

The physical and chemical properties of new coffee variety *Coffea arabica* L. var. Cenicafé 1 were investigated using standard laboratory equipment, according to International Organization for Standardization (ISO).

The new coffee variety was discovered to have a high calorific value and low ash content of 81.55 MJ kg^{-1} and 0.83 % respectively, which can be compared with that of wood or woody biomass, thereby exploring its potential for possible utilization for solid biofuel production, which can be used as an energy source for processing the coffee instead of present utilization of wood. Its elemental composition indicates a low risk of emitting harmful gases during the combustion process due to its low Nitrogen, Sulphur, and Chlorine contents, which are optimum for the best solid biofuel production (graded woody pellet A1).

The ash obtained from the coffee husks presents no risk of heavy metals contamination when used as a fertilizer on the farm. Despite its slightly low ash sintering index, the husk from the new coffee variety has favourable sintering possibilities, and it can withstand higher temperatures without flowing on the combustion device. While not directly related to the ash analysis results, coffee husk ash is typically produced as a byproduct of biomass combustion. This suggests that coffee husk biomass may have potential as a renewable energy source, with the resulting ash containing valuable nutrients for agricultural use.

Coffea arabica L. var. Cenicafe 1 husk can be considered as superior to other varieties due to its high calorific value, low ash content, low content of heavy metals and low tendency of harmful gas emission during combustion. This husk can therefore be considered as a good feedstock for solid fuel (briquette and pellets) production.

Furthermore, the superior Net Calorific Value (NCV) of this husk not only enhances its efficiency as a biofuel but also aligns with global trends in sustainable energy solutions. As a carbon-neutral fuel, it offers environmental benefits by reducing the carbon footprint of coffee production. Its use in biofuel applications can contribute to a circular economy, where waste is repurposed for energy, thereby benefiting both local economies and the global push for cleaner, renewable energy sources.

Declaration of Competing Interest

The authors have no conflicts of interest to disclose.

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Author Contributions CRediT

EDD: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft, Writing – review and editing. **MB**: Data curation, Formal analysis, Investigation, Validation, Writing – original draft. **JRSU**: Funding acquisition, Resources, Supervision, Writing – review and editing. **EAN**: Formal analysis, Investigation, Writing – original draft.

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