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Thermo-Chemical Characterization of Dry Coffee Pulp from *Coffea arabica* L. var. Cenicafé 1 for On-Farm Bioenergy Applications

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Abstract: Coffee production generates significant quantities of by-products during wet processing, particularly coffee pulp. In Colombia, approximately 85% of coffee plantations now consist of disease-resistant varieties such as Coffea arabica L. var. Cenicafé 1, developed by the National Coffee Research Centre (CENICAFÉ) and promoted by the National Federation of Coffee Growers of Colombia (FNC). While coffee husk has been extensively characterized for bioenergy applications, the thermal and chemical properties of coffee pulp (pericarp) from Cenicafé 1 remain largely unexplored, despite its abundance at the farm level. This study aimed to characterize the thermo-chemical properties of dry coffee pulp from the Cenicafé 1 variety and to assess its potential for on-farm bioenergy applications. Fresh coffee pulp (200 kg) was dried in a 3 mm polycarbonate parabolic solar dryer to determine drying kinetics and dry pulp yield, with experiments conducted in triplicate. The dry pulp was subsequently combusted in a three-layer static-bed mechanical dryer to estimate the quantity required to dry 1 kg of coffee beans from 53% to 10% wet basis (wb). Dry coffee pulp exhibited a net calorific value of 16.51 MJ kg^{-1}, a volatile matter content of 87.5%, and a moderate ash content of 3.5%. Elemental analysis revealed favourable combustion properties, with low sulphur and chlorine contents. Experimental combustion tests indicated that the energy contained in the dry pulp produced from two coffee cherries is approximately sufficient to dry one wet coffee bean (assuming a combustion efficiency of 0.5), consistent with values reported for coffee husk. These results demonstrate that dry coffee pulp from Cenicafé 1 is a viable, sustainable, and farm-accessible biofuel for decentralized energy production in coffee-growing regions, supporting circular economy initiatives and rural energy autonomy.

Keywords: agricultural waste; biomass valorisation; renewable energy; circular economy; solid biofuels; combustion properties; smallholder farming

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1. Introduction

Coffee (*Coffea* spp.) is one of the most economically and socially important agricultural commodities worldwide (Freitas et al., 2024), providing livelihoods for over 25 million smallholder farmers, particularly in Latin America, Africa, and Asia (Harvey et al., 2021; Siles et al., 2022). In Colombia, coffee production reached approximately 14 million 60-kg sacks of green coffee in 2024, equivalent to about 840,000 metric tons (FNC, 2024). Beyond its economic role, coffee cultivation has profound cultural, environmental, and social significance, making sustainable production practices essential to maintain quality, yield, and resource efficiency while minimizing environmental impacts (Betancourt et al., 2024; Rahmah et al., 2023).

One critical stage in coffee postharvest processing is drying, which is necessary to ensure bean quality and stability. Mechanical dryers are widely used to accelerate this process, but they often depend on wood or fossil fuels, contributing to deforestation, greenhouse gas emissions, and higher production costs. Replacing these energy sources with biofuels derived from coffee-processing residues offers a promising alternative to speed up drying while reducing environmental impact and production costs. This approach directly supports circular economy principles, transforming waste into energy at the farm level.

Among the processing methods used to transform coffee fruits (cherries) into green coffee beans, the wet method, or fully washed processing, is highly valued for producing coffees with superior sensory profiles (Dong et al., 2017; Elhalis et al., 2021). However, wet processing generates substantial quantities of solid and liquid waste, notably, as seen in Figure 1, coffee pulp, husk, mucilage, and process water, which can cause environmental concerns if not properly managed (Rodríguez-Valencia et al., 2021). It is estimated that approximately 5.5 kg of fresh cherries are required to produce 1 kg of green coffee (Montilla et al., 2008), suggesting that Colombia processed around 4.62 million metric tons of cherries in 2024. Given that fresh coffee pulp constitutes about 42% of the coffee cherry's weight (Esquivel and Jiménez, 2012; Tapingkae et al., 2025), an estimated 1.94 million metric tons of fresh coffee pulp were generated nationwide. This volume of organic residue, concentrated at the farm level, offers a significant yet underexploited opportunity for sustainable waste management and bioenergy production (Rodríguez-Valencia, 2023; Serna-Jiménez et al., 2022). One of the most promising applications of dry coffee pulp as a biofuel is its utilization to generate thermal energy for mechanical coffee dryers, offering farmers an alternative to traditional wood-based or fossil fuel energy sources (Gurram et al., 2016; Remón et al., 2021a; Sugebo, 2022). Integrating dry pulp combustion into drying systems can enhance the energy autonomy and sustainability of coffee postharvest operations, particularly in rural and decentralized contexts (Rodriguez-Valencia and Zambrano-Franco, 2010).

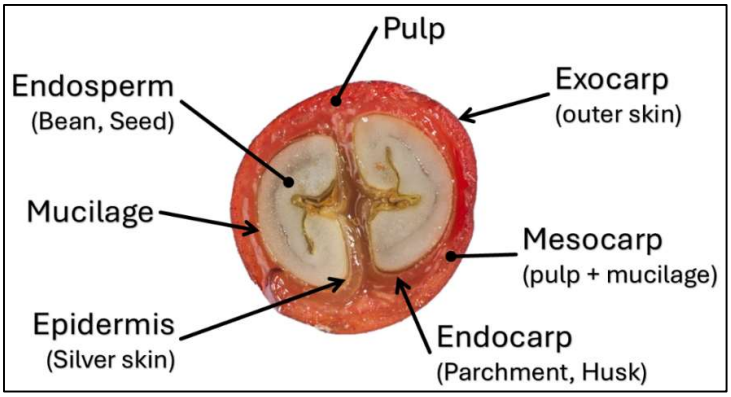

Figure 1. Anatomical cross-section of a ripe *Coffea arabica* L var. Cenicafé 1 fruit, highlighting the main structural components relevant to postharvest processing: pulp, mucilage, endocarp (parchment), and endosperm (bean).

Although coffee husk has been widely recognized for its excellent combustion properties and high energy potential (Oliveros et al., 2009; Tamilselvan et al., 2024), its availability for farmers is limited. Husk is produced during dry milling when the parchment layer is removed at centralized hulling facilities, often distant from coffee farms (Quintero-Yepes et al., 2024), therefore, farmers have little

or no direct access to husk at the farm level, restricting the feasibility of using husk as energy source. This logistical constraint highlights the need to explore alternative biomass feedstocks that are both thermally suitable and readily available at the origin of coffee production (Duque-Dussán et al., 2025; Rahmah et al., 2023).

In Colombia, approximately 85% of coffee plantations are now established with disease-resistant varieties, mainly *Coffea arabica* L. var. Colombia, Castillo and Cenicafé 1, developed by CENICAFÉ and promoted by the FNC through its extension service (FNC, 2023). These varieties combine high productivity with resistance to critical diseases such as coffee leaf rust and coffee berry disease (CBD), ensuring crop resilience and sustainability (Ferrucho et al., 2024; Flórez et al., 2016, 2018, 2021). Despite the share of Cenicafé 1 variety in the national coffee landscape, the thermo-chemical properties of its coffee pulp biomass have not been comprehensively characterized (Duque-Dussán et al., 2025).

Therefore, this study aimed to fill this knowledge gap by evaluating the thermal and chemical properties of dry coffee pulp derived from the Cenicafé 1 variety. In addition to laboratory characterization, experimental drying and combustion tests were performed to assess the energy yield, the biomass conversion efficiency, and the potential of dry coffee pulp as an on-farm sustainable biofuel, contributing to circular economy models and energy autonomy in coffee-growing regions.

2. Materials and Methods

2.1. Study Site and Material Collection

Fresh coffee pulp samples were obtained from the wet processing of *Coffea arabica* L. var. Cenicafé 1 cherries harvested during the first semester harvest of 2025 at CENICAFÉ´s experimental farm "Naranjal", located in Chinchiná, Caldas, Colombia (4.972250, -75.652547). Only ripe cherries, corresponding to stages 4, 5, and 6 of the ripeness scale (Peñuela-Martínez et al., 2022; Pineda et al., 2022; Tinoco & Peña, 2018), were selected to ensure uniformity.

Wet processing involved hydraulic classification, mechanical pulping, mucilage degradation by fermentation, washing, followed by the drying stage (Duque-Dussán and Banout, 2022; Peñuela-Martínez et al., 2022). Immediately after pulping, 200 kg of fresh coffee pulp were collected for drying experiments and subsequent thermo-chemical characterization.

2.2. Drying Process and Yield Determination

The fresh coffee pulp was dried using a parabolic solar dryer with a 3 mm thick solid polycarbonate cover with a drying area of 10 m2 (L = 5 m, W = 2 m), the pulp was laid on 85% thick (15% opening) black mesh, and the unit were lengthwise north-south oriented, in order to take higher advantage of the solar radiation (Duque-Dussán et al., 2023). Drying was conducted under typical ambient conditions of the region with daily average temperatures between 22–28°C and relative humidity between 55-75% (Cenicafé, 2024; Jaramillo-Robledo, 2018). The drying experiments were replicated three times, each involving an initial mass of 200 kg of fresh pulp (Figure 2). To determine the initial moisture content of the fresh pulp, six samples of approximately 10 g per sample were collected and analysed using the oven-drying method (ISO 18134-3:2022, 2022).

Figure 2. Visual comparison of coffee pulp before and after drying. A. Fresh pulp immediately after coffee pulping, moisture content ≈ 79% (wb). B. Dry coffee pulp after solar drying, moisture content ≈ 8.1% (wb).

After the drying process, a composite sample of approximately 60 g was taken from the dried pulp batch to determine the equilibrium moisture content using the same method. The total mass of the dried pulp was recorded to calculate the fresh-to-dry pulp yield and to estimate the quantity of fresh pulp required to produce 1 kg of dry pulp. These values were subsequently used to assess the biomass conversion ratio for combustion analyses (Duque-Dussán et al., 2025).

2.3. Sample Preparation for Characterization

After drying, coffee pulp samples were ground using a laboratory mill (Retsch ZM200, Haan, Germany) until particles passed through a 0.5 mm mesh sieve as seen in Figure 3, according to ISO 14780:2017 (ISO 14780:2017, 2017) and ISO 3310-1:2016 (ISO 3310-1:2016, 2016) standards. The ground material was stored in airtight containers at room temperature until further analysis.

Figure 3. Dry coffee pulp before (A) and after (B) grinding for thermo-chemical characterization.

Approximately 100 g of the ground pulp was separated for thermo-chemical analyses, including moisture content, ash content, gross and net calorific values, elemental composition, and ash behaviour. The remaining quantity of dried pulp was used in combustion trials conducted with a three-layer static bed mechanical dryer to evaluate its practical energy performance as biofuel during coffee drying operations.

2.4. Moisture Content Determination

Moisture content was determined following the ISO 18134-3:2022 (ISO 18134-3:2022, 2022) standard. Approximately 10 g of ground dried pulp sample (6 crucibles) was oven-dried at 105 ± 2°C (Memmert UF30, Schwabach, Germany) until constant mass was achieved. The moisture content W (%, wb) was calculated using Equation (1):

$$W\ (\%) = \frac{m_0 - m_1}{m_0}.100 \quad (1)$$

Where: m_0 is the initial mass of the sample before drying (g) and m_1 is the final mass of the sample after drying (g).

2.5. Ash Content Determination

Ash content was determined according to ISO 18122:2022 (ISO 18122:2022, 2022) using a muffle furnace (Nabertherm LHT 02/17 LB, Lilienthal, Germany). Approximately 1 g of ground dried pulp sample was combusted at 550 ± 10°C until constant mass was achieved and a stable white ash residue remained, in accordance with the requirement of the standard to ensure complete mineralization. Ash content was expressed as a percentage of the initial dry sample mass (dry basis).

2.6. Gross and Net Calorific Value Determination

Gross calorific value (GCV) was determined using a bomb calorimeter (Parr 6400, Moline, IL, USA) following the ISO 18125:2017 standard (ISO 18125:2017, 2017). Net calorific value (NCV) was calculated from the GCV according to Equation (2):

$$NCV = GCV - 24.42\ (W + 8.94H) \quad (2)$$

Where: NCV = Net calorific value (MJ kg^{-1}), GCV = Gross calorific value (MJ kg^{-1}), W = Moisture content of the sample (%) and H = Hydrogen content of the sample (%); all results were expressed on a dry basis.

2.7. Volatile Matter Content

Volatile matter content was determined following the ISO 18123:2023 standard (ISO 18123:2023, 2023) (Equation 3). Approximately 1 g of ground dried pulp sample was placed in a covered crucible and heated at 900 ± 10°C for 7 minutes in a muffle furnace (5 repetitions). The volatile matter content was calculated as the percentage of mass lost during heating relative to the initial dry sample mass.

$$V_d = \left[\frac{100(m_2 - m_3)}{m_2 - m_1} - M_{ad}\right]\left(\frac{100}{100 - M_{ad}}\right) \quad (3)$$

Where: V_d is the volatile matter content % (db), m_1 is the mass of the empty crucible (g), m_2 is the mass of the crucible with sample before heating (g), m_3 is the mass of the crucible with residue after heating (g), and M_{ad} is the moisture content of the sample on air-dry basis (%).

2.8. Elemental Analysis

Carbon (C), hydrogen (H), and nitrogen (N) contents were determined with a CHN analyser (Leco TruSpec, Moline, IL, USA) according to ISO 16948:2015 (ISO 16948:2015, 2015), using ground dried pulp samples. Sulphur (S) and chlorine (Cl) contents were measured by ion chromatography (Dionex ICS-5000+, Thermo Fisher Scientific, USA) according to ISO 16994:2016 (ISO 16994:2016, 2016).
Oxygen (O) content was calculated by difference using Equation (4):

$$O\ (\%) = 100 - (C + H + N + S + Ad) \quad (4)$$

Where: O = Oxygen content (%), C = Carbon content (%), H = Hydrogen content (%), N = Nitrogen content (%), S = Sulphur content (%) and Ad = Ash content expressed on % (db).

2.9. Major and Minor Elements in Ash

Ash samples were digested using a microwave digestion system (Ethos Pro, Milestone, Italy) with acid-assisted digestion protocols.
Major elements as potassium (K), calcium (Ca), magnesium (Mg), phosphorus (P), and silicon (Si) and minor elements: sodium (Na), iron (Fe), aluminium (Al), manganese (Mn), strontium (Sr), zinc (Zn), titanium (Ti), and barium (Ba), were determined by Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) using a Thermo Scientific iCAP 7000 series system, according to ISO 16967:2014 (ISO 16967:2015, 2014).

2.10. Ash Melting Behaviour

Ash melting behaviour was evaluated according to ISO 21404: 2020 (ISO 21404:2020, 2020) using an optical heating microscope system (Hesse Instruments HT15, Osterode, Germany).
Shrinkage temperature (ST), deformation temperature (DT), hemisphere temperature (HT), and flow temperature (FT) were determined during the heating process. The sintering index (I) was calculated using Equation (5):

$$I = \frac{Ca\ O + Mg\ O}{K_2\ O + Na_2\ O} \quad (5)$$

Where: I = Sintering index (dimensionless), CaO = Calcium oxide content (%), MgO = Magnesium oxide content (%) K_2O = Potassium oxide content (%), Na_2O = Sodium oxide content (%).
Values of I>2 indicate a low sintering tendency, whereas I<2 suggests a higher propensity for ash sintering during combustion (Contreras-Trejo et al., 2022; Duque-Dussán et al., 2025; Rodríguez et al., 2021).

2.11. Combustion Requirements Calculations

The theoretical oxygen demand (O_{2min}), theoretical air requirement (L_{min}), and theoretical volume of dry flue gases ($V_{fg,min}$) were calculated using stoichiometric combustion equations for solid biomass fuels, following the methodology described by (Jeníček et al., 2022). Calculations were based on the elemental composition (C, H, N, S, O) of the dry coffee pulp determined in Section 2.8.
Additionally, the volumetric fractions of major combustion gases, carbon dioxide (CO_2), water vapor (H_2O), nitrogen (N_2), sulphur dioxide (SO_2), and excess oxygen (O_2), were estimated to characterize the combustion performance under ideal conditions. These values were used to assess the theoretical air-to-fuel ratio, energy efficiency, and potential environmental emissions associated with the combustion of dry coffee pulp.

2.12. Combustion Tests and Practical Energy Evaluation

Combustion tests were conducted using a mechanical coffee dryer (static bed, three-layer configuration) with a batch capacity of 125 kg of dry parchment coffee (Figure 4). Dry coffee pulp was used as the sole biofuel to generate the hot air necessary for drying coffee beans from an initial moisture content of 53% to a final moisture content of 10% (wb). Drying was conducted with an average air temperature of 50 °C and a specific airflow rate of 0.1 $m^3\ min^{-1}\ kg^{-1}$ of dry parchment coffee (DPC) (Duque-Dussán et al., 2022; Parra-Coronado et al., 2017).

Figure 4. Experimental setup for combustion tests using dry coffee pulp as biofuel. **A.** Static-bed 3-layer mechanical coffee dryer. **B.** Heat exchanger. **C.** Biofuel feed hopper containing dry coffee pulp.

The total amount of dry pulp consumed per batch was measured, and the biomass-to-product ratio was estimated to determine the kilograms of dry pulp required to dry 1 kg of wet coffee. Additionally, a practical energy ratio was calculated, analogous to previous studies on coffee husk, evaluating whether the energy contained in the pulp generated from two coffee cherries would be sufficient to dry one coffee bean (Duque-Dussán et al., 2025; Manrique et al., 2020; Twinomuhwezi et al., 2021).

3. Results and Discussion

3.1. Moisture Content of Fresh and Dried Pulp

The initial moisture content of the fresh coffee pulp was determined to be approximately 79.2% (wb), consistent with values reported for freshly pulped *C. arabica* L. residues (Biratu et al., 2024; Jiamjariyatam et al., 2022). Such high moisture content limits the direct use of pulp as a solid fuel due to combustion inefficiency, microbial instability, and transport difficulties, hence, immediate drying is essential to enable its storage and energetic valorisation (Rahmah et al., 2023; Rodríguez-Valencia, 2023).

After solar drying in a polycarbonate-covered parabolic dryer, the pulp reached an average equilibrium moisture content of approximately 8.09% (wb) within the recommended range for stable biomass storage and efficient combustion according to ISO 18134-3:2022 (Abdel Aal et al., 2023; ISO, 2022; Oladeji and Enweremadu, 2012). Moisture levels below 15% (wb) are critical to reduce energy loss during combustion and prevent fungal growth, ensuring that the biomass maintains its calorific value over time (Antwi-Boasiako and Acheampong, 2016; Zhao et al., 2021).

These findings confirm that coffee pulp can be dried on-farm to a stable moisture level using low-tech systems, providing a practical entry point for its integration into circular and decentralized energy systems. This step is foundational for further processing, such as densification or direct combustion in drying applications.

3.2. Fresh-to-Dry Pulp Yield

Drying experiments conducted with 200 kg batches of fresh coffee pulp resulted in an average dry mass yield of 38.5 kg per batch, corresponding to a 19.25% yield after reducing moisture content from approximately 79% to 8% (wb). This implies that, on average, 5.19 kg of fresh pulp were required to obtain 1 kg of dry pulp.

These outcomes demonstrate the importance of effective moisture management in the valorisation of coffee pulp. The substantial mass reduction emphasises the inherently high-water content of the fresh material and the need of efficient drying to enable its use as a stable energy resource. The yield obtained aligns with drying behaviour reported for other high-moisture agro-industrial residues such as coffee mucilage and fruit peels (García et al., 2021; Kc et al., 2021; Machado and Oliveira, 2023; Suri et al., 2022).

Importantly, the ability to achieve this transformation using on-farm, low-cost parabolic dryers suggests that smallholder coffee producers can independently stabilize pulp biomass without reliance on industrial infrastructure (Duque-Dussán and Banout, 2022; Jiamjariyatam et al., 2022; Jiménez-Ochoa et al., 2022). This represents a critical first step in the integration of coffee pulp into decentralized and circular energy systems, contributing to both environmental sustainability and postharvest energy autonomy.

3.3. Thermo-Chemical Characterization

3.3.1. Moisture Content

In biomass combustion, moisture acts as a thermal sink: a portion of the fuel's energy is consumed to evaporate water before combustion can proceed efficiently (Ion et al., 2021; Milijašević et al., 2025).

Thus, maintaining low moisture content directly improves the net calorific value delivered during combustion, enhancing the energy yield per kilogram of fuel.

In this study, the low final moisture content of the dried pulp enhanced the net calorific value, improving the amount of usable energy per unit of biomass (Jiménez-Ochoa et al., 2022). Moreover, the low moisture content of the coffee pulp, enhances its suitability for long-term storage without risks of microbial degradation or spoilage, ensuring a stable and reliable feedstock supply for biofuel production facilities, a significant advantage in the industry (Rahmah et al., 2023; Shah et al., 2023).

Importantly, the ability to achieve this transformation using on-farm, low-cost parabolic dryers suggests that smallholder coffee producers

3.3.2. Ash Content

The ash content of the dried coffee pulp was measured at 3.5% (db), similar to values obtained in other studies (Rohaya et al., 2023). However, higher than that of coffee husk, previously reported at 0.83% for *C. arabica* L. var. Cenicafé 1 (Duque-Dussán et al., 2025), but remains within acceptable ranges for solid biomass fuels according to ISO 17225-2 (ISO 17225-2:2021, 2021) classification standards.

A higher ash content in biomass can affect combustion behaviour, increasing the frequency of ash removal operations and slightly lowering the overall energy density of the fuel (Díaz-Jiménez and Moya, 2022). In combustion systems, especially those operating with small grates or fixed beds, elevated ash levels necessitate proper ash management strategies to prevent operational inefficiencies and maintain stable heat output (Odzijewicz et al., 2022; Rodríguez et al., 2021).

Nevertheless, the ash content observed in dry coffee pulp is not prohibitive for energy applications. On the contrary, it presents an opportunity for resource recovery: as further analysed in Section 3.2.6, the chemical composition of the ash, rich in potassium, calcium, and phosphorus, suggests its potential use as a soil amendment, contributing to nutrient recycling in coffee farms (Král et al., 2024; Machado et al., 2023; Munirwan et al., 2022; Sánchez-Reinoso et al., 2023).

Overall, while dry coffee pulp contains moderately higher ash levels compared to some woody biomasses, its properties remain compatible with sustainable combustion processes.

3.3.3. Gross and Net Calorific Values

The dry coffee pulp exhibited a gross calorific value (GCV) of 17.33 MJ kg^{-1} and a net calorific value (NCV) of 16.51 MJ kg^{-1}, confirming its strong energy potential as a solid biofuel (Rahmah et al., 2023; Remón et al., 2021b).

Although these values are slightly lower than those reported for coffee husk (18.55 MJ kg^{-1}, Duque-Dussán et al. (2025)), they remain highly competitive when compared to other commonly used agricultural residue as seen in Table 1, such as rice husk and corn cob (Imtiaz-Anando et al., 2023; Wojcieszak et al., 2022; Yiga et al., 2023).

Table 1. Comparison of net calorific values (NCV) of dry coffee pulp and other agricultural biomass fuels.

Biomass Type	Approximate NCV (MJ kg^{-1})	Source / Reference
Dry Coffee Pulp (*Coffea arabica* L. var. Cenicafé 1)	16.51	This study
Coffee pulp – dried powder	13.76	Twinomuhwezi et al., 2021
Coffee Husk (*Coffea arabica* L. var. Cenicafé 1)	18.50	Duque-Dussán et al., 2025
Rice Husk	14.33	Beňová et al., 2021; Imtiaz-Anando et al., 2023

Corn Cob	16.50	Wojcieszak et al., 2022
Wood Chips (Softwood)	~18.5 – 19.0	Kuchler et al., 2024
Sugarcane Bagasse	17.85	Beňová et al., 2021; Kabeyi & Olanrewaju, 2023
Wheat Straw	~17.60	Nath et al., 2023
Palm Kernel Shells	~19.20	Pranolo et al., 2021
Sawdust (general)	~16.50	Obidziński et al., 2024
Sunflower Husk	~19.30	Kienzl et al., 2021
Peanut Shells	~17.0	Bi et al., 2021; Varma et al., 2022
Coconut Husk	~18.6	Pawar et al., 2023; Tanko et al., 2021

Moreover, the relatively narrow ddifference between GCV and NCV, both expressed on a dry basis, reflects the minimal energy loss to water vapor formation due to the low inherent moisture and hydrogen content of the biomass, emphasizing the importance of pre-drying biomass to optimize combustion efficiency (Duque-Dussán et al., 2025; Imtiaz-Anando et al., 2023; Pedišius et al., 2021).

The NCV obtained for dry coffee pulp in this study (16.5 MJ kg^{-1}) was higher than the value reported by Twinomuhwezi et al., (2021), who measured 13.755 MJ kg^{-1} for sun-dried pulp from *C. arabica* using bomb calorimetry. This difference could be attributed to variations in pulp composition, cultivar, growing conditions, and postharvest processing methods, which can influence lignocellulosic content and moisture levels. The higher NCV found in our work suggests a greater potential energy yield. These calorific properties position dry coffee pulp as a promising renewable energy resource for coffee growers seeking to valorise postharvest residues within a circular economy framework (Rodríguez-Valencia, 2023).

3.3.4. Volatile Matter Content

The volatile matter content of the dry coffee pulp was measured at 87.5% (db), a value significantly higher than that of typical woody biomass, which generally ranges from 70% to 80% (Mhilu, 2014). This corresponds to approximately 80.4% on a wet basis, given the final moisture content of 8.09%. High volatile content indicates that the biomass contains a substantial proportion of easily vaporized compounds, such as light hydrocarbons, organic acids, and cellulose derivatives, which ignite and burn rapidly when heated (Syguła et al., 2024; Zhu et al., 2022).

This characteristic is advantageous for small-scale combustion systems, as it allows for quick ignition, sustained flame propagation, and relatively stable combustion at moderate temperatures (Miao et al., 2021; Wan et al., 2024). These properties are especially relevant in rural or farm-based contexts, where combustion systems tend to lack forced air supply, staged combustion chambers, or automated control systems.

However, fuels with high volatile content can also lead to flame instability, incomplete combustion, or increased emissions of unburned hydrocarbons if not properly managed, then, combustion system design, particularly air supply regulation and flame retention must be adapted to accommodate the rapid release of volatiles (Cohen-Sacal et al., 2023; Dai et al., 2019; Pitsch, 2024). In this study, the effective performance of dry pulp in a static-bed mechanical dryer suggests that, despite its high volatile matter, combustion can be controlled effectively under well-insulated and well-calibrated drying conditions.

3.3.5. Elemental Composition

The elemental analysis of the dried coffee pulp revealed a composition of approximately 48.0% carbon (C), 6.3% hydrogen (H), 0.8% nitrogen (N), 0.10% sulphur (S), and 0.05% chlorine (Cl), with oxygen (O) estimated by difference at 44.5% (db).

The relatively high carbon content is consistent with the favourable calorific values observed, as carbon is the primary contributor to energy release during combustion (Tesfaye et al., 2022). A hydrogen content of 6.3% further supports the fuel's thermal reactivity, enhancing flame propagation and contributing to water vapor formation in the flue gases.

The moderate nitrogen and sulphur contents indicate a low tendency for the formation of nitrogen oxides (NO_x) and sulphur dioxide (SO_2) during combustion, which are among the primary gaseous pollutants associated with biomass energy systems (Cohen-Sacal et al., 2023). These levels fall well within the acceptable thresholds for clean combustion and minimize the need for gas treatment technologies.

The chlorine content of 0.05% is particularly relevant, as it remains well below the levels commonly associated with corrosion risks in metallic components of combustion systems (Kaczmarczyk and Mlonka-Mędrala, 2016; Karuana et al., 2024). High chlorine concentrations in biomass, such as in straw or certain industrial residues, can lead to the formation of hydrochloric acid and alkali chlorides, which corrode heat exchangers and reduce system lifespan. The low Cl content in coffee pulp thus increases its technical compatibility with small- to medium-scale dryers and furnaces.

Collectively, the elemental composition of dry coffee pulp supports its viability as a clean, efficient, and low-emission biofuel suitable for decentralized combustion systems, particularly in the context of farm-based coffee processing.

3.3.6. Major and Minor Elements in Ash

The ash obtained from the combustion of dry coffee pulp revealed a high concentration of major plant macronutrients, including potassium (21.0% K_2O) and calcium (18.0% CaO), as well as appreciable amounts of magnesium (4.5% MgO) and phosphorus (3.2% P_2O_5). These oxides are critical for plant growth and soil fertility, highlighting the potential for reusing coffee pulp ash as a soil amendment within circular agricultural systems (Jeníček et al., 2022).

As shown in Table 2, the ash also contained moderate levels of silicon dioxide (2.8% SiO_2), sodium oxide (1.6% Na_2O), iron (III) oxide (1.4% Fe_2O_3), and aluminium oxide (0.9% Al_2O_3), along with trace quantities of other minor oxides. No heavy metals such as cadmium (Cd), lead (Pb), or mercury (Hg) were detected above regulatory thresholds, further supporting the environmental safety and agronomic viability of the ash for use in coffee-growing systems.

Table 2. Major and Minor Oxide Composition of Coffee Pulp Ash (% by mass)

Oxide	Symbol	Content (% by mass)
Potassium oxide	K_2O	21.0%
Calcium oxide	CaO	18.0%
Magnesium oxide	MgO	4.5%
Phosphorus pentoxide	P_2O_5	3.2%
Silicon dioxide	SiO_2	2.8%
Sodium oxide	Na_2O	1.6%
Iron (III) oxide	Fe_2O_3	1.4%
Aluminum oxide	Al_2O_3	0.9%

Titanium dioxide	TiO_2	0.2%
Manganese oxide	MnO	0.1%
Zinc oxide	ZnO	0.05%
Strontium oxide	SrO	0.03%
Barium oxide	BaO	0.02%
Lead, cadmium, mercury	–	< detection limit

These results are consistent with findings from other lignocellulosic biomass residues, where combustion eliminates the organic fraction and concentrates the inorganic mineral matter into a small volume of ash (Ma et al., 2024; Vassilev et al., 2017). Given that dry coffee pulp contains about 3.5% ash by mass, the elements identified in Table 2 represent a concentrated profile of nutrients originally distributed throughout the entire biomass.

However, the high potassium content, while agronomically beneficial, is known to contribute to sintering and slagging tendencies during combustion, especially at high temperatures, recent studies have shown that potassium forms low-melting-point compounds such as potassium silicates (K_2SiO_3), potassium sulfate (K_2SO_4), and potassium chloride (KCl) at elevated temperatures, which promote ash melting, sintering, and deposit formation in combustion systems (Boström et al., 2012; Yuan et al., 2025).This observation correlates with the moderate sintering index calculated in Section 3.3.7 and should be considered when designing combustion systems using coffee pulp as a biofuel.

3.3.7. Ash Melting Behaviour

The ash melting behaviour of dry coffee pulp was characterized using optical heating microscopy. The shrinkage temperature (ST) was observed at 720°C, the deformation temperature (DT) at 850°C, and the flow temperature (FT) exceeded 1400°C, with no visible hemisphere formation during the test. These results indicate that while the ash begins to soften and deform at moderate temperatures, it retains structural stability at higher temperatures, a trait desirable in biomass fuels used for controlled combustion.

The calculated sintering index was 1.4, suggesting a moderate tendency for ash sintering and agglomeration, particularly under combustion conditions exceeding 850°C (Li et al., 2022; Sher et al., 2024). According to Contreras-Trejo et al. (2022), sintering indices below 2 generally indicate an increased risk of slag formation, especially in systems with limited ash removal or temperature control (Rodríguez et al., 2021).

For practical applications, this implies that combustion systems using dry coffee pulp should be designed to operate at temperatures below the deformation threshold or incorporate design strategies that mitigate slagging risks (Chen et al., 2021; Silvennoinen and Hedman, 2013). These may include staged combustion, ash-bed cooling, or the use of grate shaking mechanisms to prevent buildup. In small-scale or farm-based systems, where temperature control is often less precise, using insulated chambers and optimizing airflow can also reduce sintering risk.

3.3.8. Combustion Requirements Calculations

Based on the elemental composition of the dry coffee pulp, the theoretical combustion parameters were calculated using stoichiometric equations for biomass fuels (Jeníček et al., 2022). The results are summarized in Table 3.

Table 3. Theoretical Combustion Parameters for Dry Coffee Pulp

Parameter	**Value ($m^3\ kg^{-1}$)**	**Description**
O_{2min}	2.90	Minimum oxygen required for complete combustion

L_{min}	13.50	Theoretical air requirement for stoichiometric combustion
$V_{fg,min}$	11.50	Theoretical volume of dry flue gas produced
v_{CO2}	0.98	CO_2 in flue gases
v_{H2O}	0.35	Water vapor in flue gases (from H combustion)
v_{N2}	10.90	N_2 from air
v_{O2}	3.10	Residual oxygen in flue gases (with 50% excess air)

Compared to coffee husk and typical woody biomass fuels, dry coffee pulp requires a slightly higher oxygen and air input for complete combustion (Amertet et al., 2021; Cohen-Sacal et al., 2023; Duque-Dussán et al., 2025). This is largely attributed to its higher hydrogen and volatile matter content, which increases both the fuel's reactivity and the volume of water vapour produced during combustion (Czekała et al., 2023; Lionetti et al., 2025).

From a design perspective, these parameters indicate that combustion systems utilizing dry coffee pulp must ensure sufficient and well-distributed air supply to achieve complete oxidation, especially in fixed-bed systems or natural-draft stoves (Duque-Dussán and Banout, 2022; Orosco et al., 2018; Ouedraogo et al., 2025). Fortunately, the total flue gas volume and air demand remain within manageable ranges for conventional small-scale biomass burners and mechanical dryers.

Moreover, the relatively high CO_2 and low SO_2 concentrations in the flue gas, attributed to the low sulphur content of biomass fuels like dry coffee pulp, suggest favourable environmental characteristics with reduced emissions of acid-forming gases. Studies have shown that most biomass fuels possess low sulphur content, resulting in significantly lower SO_2 emissions compared to coal combustion, additionally, the alkaline-earth ash from biomass can retain sulphur during combustion, further decreasing SO_2 emissions (Jomantas et al., 2025; Ren et al., 2017).

The composition of the flue gas is also crucial for the design of heat exchangers in indirect dryers, where water vapor condensation and ash deposition need to be controlled. Research indicates that flue gas condensers (FGCs) must be designed to handle the condensation of water vapor in the presence of inert gases, which affects heat and mass transfer processes, proper design considerations, such as the arrangement of tube bundles and the management of excess air, are essential to minimize ash deposition and optimize heat recovery (Coccia et al., 2024; Coppieters and Blondeau, 2019).

3.4. Practical Combustion Test Results

Combustion tests performed in a static-bed mechanical dryer demonstrated that, under the specific conditions of this study, approximately 0.39 kg of dry coffee pulp were required to dry 1 kg of parchment coffee, reducing its moisture content from 53% to 10% (wb). Drying was conducted with hot air supplied at an average temperature of 50 °C, and a full batch of 125 kg of dry parchment coffee required approximately 22.3 hours to complete the drying process (Figure 5).

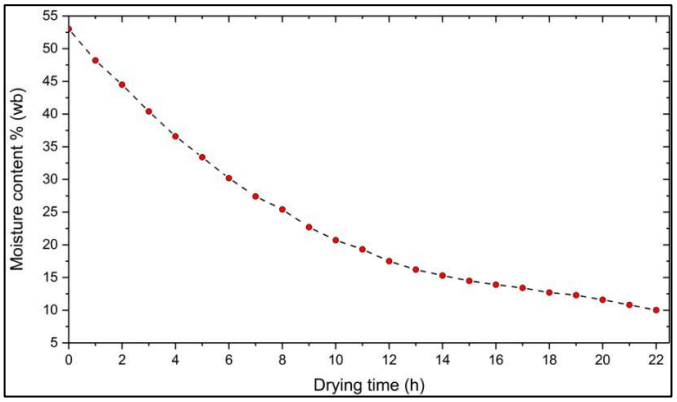

Figure 5. Moisture content reduction curve of parchment coffee during drying using dry coffee pulp as the sole heat source.

These drying kinetics are consistent with reported times for mechanical coffee drying under similar thermal and airflow conditions (Duque-Dussán et al., 2022), confirming the feasibility of using dry coffee pulp combustion for extended drying cycles without compromising product quality. To supply the required energy for a full 125 kg batch at the measured biomass-to-product ratio, approximately 48.75 kg of dry coffee pulp were needed. This reinforces the importance of scalable and replicable drying strategies if pulp is to be consistently used as a renewable energy source.

The experimental ratio reflects relatively efficient energy use under controlled combustion conditions. It aligns conceptually with earlier estimations made for coffee husk, where the energy contained in the husk produced by two beans is considered sufficient to dry one wet bean (Manrique et al., 2020). By analogy, the energy stored in the pulp generated from approximately two and a half coffee cherries could be considered roughly sufficient to dry one corresponding bean.

However, real-world combustion systems may operate with lower efficiencies due to factors such as heat losses, variable airflow, and inconsistent fuel feeding (Duque-Dussán et al., 2023; Parra-Coronado et al., 2017), hence, for practical implementation in rural farm settings, a more conservative estimate of 0.45 kg of dry pulp per 1 kg of DPC is recommended. This adjustment provides a buffer that enhances resilience in decentralized drying systems.

Given the large availability of coffee pulp during harvest, the material can be dried using traditional solar patios, stabilized, and stored for use in subsequent postharvest operations. Once dried, coffee pulp becomes a renewable, on-farm energy resource, capable of supporting low-capacity mechanical dryers and improving smallholder energy self-sufficiency.

In addition to its role in on-farm drying, dry coffee pulp presents an opportunity for economic valorisation. With rising demand for biomass fuels like coffee husk, particularly in industries where husk availability is limited at the farm level, dry pulp offers a viable alternative. It can be marketed directly as loose biomass or densified into briquettes or pellets, improving its transportability, storage life, and market value. These pathways position dry pulp not only as a tool for energy autonomy, but also as a potential economic asset within integrated, sustainable coffee production systems.

5. Conclusions

This study characterized the thermo-chemical properties of dry coffee pulp derived from *C. arabica* L. var. Cenicafé 1, one of the predominant varieties planted in Colombia, and evaluated its potential for on-farm bioenergy applications. The pulp exhibited a net calorific value of 16.51 MJ kg^{-1}, a volatile matter content of 87.5%, and a moderate ash content of 3.5%, with elemental analysis confirming low sulphur and chlorine concentrations, supporting its viability as a clean and environmentally compatible biomass fuel.

Drying trials demonstrated that coffee pulp can be effectively stabilized on-farm using low-tech solar dryers, achieving a final moisture content of approximately 8% (wb). Combustion tests confirmed that, under controlled conditions, 0.39 kg of dry pulp were sufficient to dry 1 kg of coffee beans, with drying conducted at 50 °C, over 22.3 hours for a 125 kg batch. Given potential variations in field efficiency, a conservative estimate of 0.45 kg of dry pulp per kg of coffee is recommended for practical applications.

These results confirm that dry coffee pulp is a technically feasible and accessible fuel for decentralized thermal energy systems. The pulp's abundance during harvest allows for solar drying, storage, and reuse as a renewable energy source across harvest cycles, promoting energy resilience and circular economy practices on coffee farms.

In addition to its energetic value, dry pulp holds economic potential. With increasing demand for biomass fuels such as coffee husk, and limited husk availability at the farm level, dry coffee pulp offers an alternative biomass that can be commercialized in bulk form or densified into briquettes or pellets, opening the possibility for additional income streams, contributing to the economic sustainability of smallholder coffee systems.

Future research should focus on optimizing combustion system designs, improving fuel handling logistics, and evaluating the long-term stability and performance of stored pulp under real farm conditions.

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6. References

1. Abdel Aal A, Ibrahim O, Al-Farga A, El Saeidy E (2023). Impact of Biomass Moisture Content on the Physical Properties of Briquettes Produced from Recycled *Ficus nitida* Pruning Residuals. Sustainability 15(15), Article 15. https://doi.org/10.3390/su151511762

2. Amertet S, Mitiku Y, Belete G (2021). Analysis of a Coffee Husk Fired Cogeneration Plant in South Western Ethiopia Coffee Processing Industries. Low Carbon Economy 12(1), Article 1. https://doi.org/10.4236/lce.2021.121003

3. Antwi-Boasiako C, Acheampong BB (2016). Strength properties and calorific values of sawdust-briquettes as wood-residue energy generation source from tropical hardwoods of different densities. Biomass and Bioenergy 85, 144–152. https://doi.org/10.1016/j.biombioe.2015.12.006

4. Beňová D, Mareš K, Hutla P, Ivanova T, Banout J, Kolaříková M (2021). Energy Potential of Agri Residual Biomass in Southeast Asia with the Focus on Vietnam. Agronomy 11(1), 169. https://doi.org/10.3390/agronomy11010169

5. Betancourt JA, Florez-Yepes GY, Garcés-Gómez YA (2024). Agricultural Productivity and Multidimensional Poverty Reduction in Colombia: An Analysis of Coffee, Plantain, and Corn Crops. Earth 5(4), Article 4. https://doi.org/10.3390/earth5040032

6. Bi H, Wang C, Jiang X, Jiang C, Bao L, Lin Q (2021). Thermodynamics, kinetics, gas emissions and artificial neural network modeling of co-pyrolysis of sewage sludge and peanut shell. Fuel 284, 118988. https://doi.org/10.1016/j.fuel.2020.118988

7. Biratu G, Gonfa G, Bekele M, Woldemariam HW (2024). Extraction and characterization of pectin from coffee (*Coffea arabica* L.) pulp obtained from four different coffee producing regions. International Journal of Biological Macromolecules 274, 133321. https://doi.org/10.1016/j.ijbiomac.2024.133321

8. Boström D, Skoglund N, Grimm A, Boman C, Öhman M, Broström M, Backman R (2012). Ash Transformation Chemistry during Combustion of Biomass. Energy & Fuels 26(1), 85–93. https://doi.org/10.1021/ef201205b

9. Cenicafé. (2024). Anuario meteorológico cafetero 2023. Anuario Meteorológico Cafetero. https://doi.org/10.38141/10782/anu2023

10. Chen C, Bi Y, Huang Y, Huang H (2021). Review on slagging evaluation methods of biomass fuel combustion. Journal of Analytical and Applied Pyrolysis 155, 105082. https://doi.org/10.1016/j.jaap.2021.105082

11. Coccia V, Barros Lovate Temporim R, Lunghi L, Tryboi O, Cotana F, Magrini A, Dondi D, Vadivel D, Cartesegna M, Nicolini A (2024). Design and Performance Analysis of a Small-Scale Prototype Water Condensing System for Biomass Combustion Flue Gas Abatement. Sustainability 16(12), Article 12. https://doi.org/10.3390/su16125164

12. Cohen-Sacal D, Khan MS, Broumand M, Thomson MJ, Ellis N, Kirchen P (2023). Combustion and emission characterization of upgraded biomass fast pyrolysis oil in a swirl burner. Applications in Energy and Combustion Science 13, 100118. https://doi.org/10.1016/j.jaecs.2023.100118

13. Contreras-Trejo JC, Vega-Nieva DJ, Heya MN, Prieto-Ruíz JA, Nava-Berúmen CA, Carrillo-Parra A (2022). Sintering and Fusibility Risks of Pellet Ash from Different Sources at Different Combustion Temperatures. Energies 15(14), Article 14. https://doi.org/10.3390/en15145026

14. Coppieters T, Blondeau J (2019). Techno-Economic Design of Flue Gas Condensers for Medium-Scale Biomass Combustion Plants: Impact of Heat Demand and Return Temperature Variations. Energies 12(12), Article 12. https://doi.org/10.3390/en12122337

15. Czekała W, Łukomska A, Pulka J, Bojarski W, Pochwatka P, Kowalczyk-Juśko A, Oniszczuk A, Dach J (2023). Waste-to-energy: Biogas potential of waste from coffee production and consumption. Energy 276, 127604. https://doi.org/10.1016/j.energy.2023.127604

16. Dai G, Wang K, Wang G, Wang S (2019). Initial pyrolysis mechanism of cellulose revealed by in-situ DRIFT analysis and theoretical calculation. Combustion and Flame 208, 273–280. https://doi.org/10.1016/j.combustflame.2019.07.009

17. Díaz-Jiménez E, Moya R (2022). The Effects of *Jatropha curcas* and *Ricinus communis* Seeds Addition on Coffee Pulp Waste Pellets as Fuel. Waste and Biomass Valorization 13(6), 3071–3084. https://doi.org/10.1007/s12649-022-01701-4

18. Dong W, Hu R, Chu Z, Zhao J, Tan L (2017). Effect of different drying techniques on bioactive components, fatty acid composition, and volatile profile of robusta coffee beans. Food Chemistry 234, 121–130. https://doi.org/10.1016/j.foodchem.2017.04.156

19. Duque-Dussán E, Banout, J (2022). Improving the drying performance of parchment coffee due to the newly redesigned drying chamber. Journal of Food Process Engineering 45(12), e14161. https://doi.org/10.1111/jfpe.14161

20. Duque-Dussán E, Bappah M, Sanz-Uribe JR., Nainggolan EA (2025). Thermo-Chemical Characterization of Coffee Husk from a New Variety (*Coffea arabica* L. var. Cenicafé 1) for Biofuel Production. Scientia Agriculturae Bohemica 56(1). https://doi.org/10.7160/sab.2025.560101

21. Duque-Dussán E, Sanz-Uribe JR., Banout J (2023). Design and evaluation of a hybrid solar dryer for postharvesting processing of parchment coffee. Renewable Energy 215, 118961. https://doi.org/10.1016/j.renene.2023.118961

22. Duque-Dussán E, Villada-Dussán A, Roubik H, Banout J (2022). Modeling of Forced and Natural Convection Drying Process of a Coffee Seed. Journal of the ASABE 65(5), 1061–1070. https://doi.org/10.13031/ja.15156

23. Elhalis H, Cox J, Frank D, Zhao J (2021). The role of wet fermentation in enhancing coffee flavor, aroma and sensory quality. European Food Research and Technology 247(2), 485–498. https://doi.org/10.1007/s00217-020-03641-6

24. Esquivel P, Jiménez VM (2012). Functional properties of coffee and coffee by-products. Food Research International 46(2), 488–495. https://doi.org/10.1016/j.foodres.2011.05.028

25. Ferrucho RL, Marín-Ramírez GA, Gaitan A (2024). Integrated Disease Management for the Sustainable Production of Colombian Coffee. Agronomy 14(6), Article 6. https://doi.org/10.3390/agronomy14061286

26. Flórez CP, Arias JC, Cortina H, Moncada-Botero M, Quiroga-Cardona J, Molina DM, García-López JC (2018). Variedades Castillo ® Zonales. Resistencia a la roya con mayor productividad. Avances Técnicos Cenicafé 1–8. https://doi.org/10.38141/10779/0489

27. Flórez CP, Maldonado CE, Cortina HA, Moncada M. del P, Montoya EC, Ibarra LN, Unigarro CA, Rendón JR, Orrego HD (2016). Cenicafé 1: Nueva variedad de porte bajo altamente productiva resistente a la roya y al CBD con mayor calidad física del grano. Avances Técnicos Cenicafé 1–8. https://doi.org/10.38141/10779/0469

28. Flórez CP, Quiroga-Cardona J, Arias JC (2021). Variedades del Café. In Guía+Agronomía+Productividad+Calidad(Vol. 1). https://publicaciones.cenicafe.org/index.php/libros_manuales/article/view/823

29. FNC (2023). Informe del Gerente General 2023. Informes del Gerente General FNC. https://doi.org/10.38141/10801/2023

30. FNC (2024). Informe del Gerente General 2024. Informes del Gerente General FNC, 1–66. https://doi.org/10.38141/10801/2024

31. Freitas VV, Borges LR, Vidigal MR, dos Santos MH, Stringheta PC. (2024). Coffee: A comprehensive overview of origin, market, and the quality process. Trends in Food Science & Technology 146, 104411. https://doi.org/10.1016/j.tifs.2024.104411

32. García ML, Carrión MH, Escobar S, Rodríguez A, Cortina JR (2021). Optimization of the antioxidant capacity of mangosteen peels (*Garcinia mangostana* L.) extracts: Management of the drying extraction processes. Food Science and Technology International 27(5), 404–412. https://doi.org/10.1177/1082013220962630

33. Gurram R, Al-Shannag M, Knapp S, Das T, Singsaas E, Alkasrawi M (2016). Technical possibilities of bioethanol production from coffee pulp: A renewable feedstock. Clean Technologies and Environmental Policy 18(1), 269–278. https://doi.org/10.1007/s10098-015-1015-9

34. Harvey CA, Pritts AA, Zwetsloot MJ, Jansen K, Pulleman MM, Armbrecht I, Avelino J, Barrera JF, Bunn C, García JH, Isaza C, Munoz-Ucros J, Pérez-Alemán CJ, Rahn E, Robiglio V, Somarriba E, Valencia V (2021). Transformation of coffee-growing landscapes across Latin America. A review. Agronomy for Sustainable Development 41(5), 62. https://doi.org/10.1007/s13593-021-00712-0

35. Imtiaz-Anando A, Ehsan MM, Karim MR, Bhuiyan AA, Ahiduzzaman M, Karim A (2023). Thermochemical pretreatments to improve the fuel properties of rice husk: A review. Renewable Energy 215, 118917. https://doi.org/10.1016/j.renene.2023.118917

36. Ion IV, Popescu F, Mahu R, Rusu E (2021). A Numerical Model of Biomass Combustion Physical and Chemical Processes. Energies 14(7), Article 7. https://doi.org/10.3390/en14071978

37. ISO 3310-1:2016. (2016). Test sieves—Technical requirements and testing Part 1: Test sieves of metal wire cloth. International Organization for Standardization.

38. ISO 14780:2017. (2017). Solid biofuels—Determination of moisture content Part 3: Moisture in general analysis sample. International Organization for Standardization.

39. ISO 16948:2015. (2015). Solid biofuels—Determination of total content of carbon, hydrogen and nitrogen. International Organization for Standardization.

40. ISO 16967:2015. (2014). Solid biofuels—Determination of major elements—Al, Ca, Fe, Mg, P, K, Si, Na and Ti. International Organization for Standardization.

41. ISO 16994:2016. (2016). Solid biofuels—Determination of total content of sulfur and chlorine. International Organization for Standardization.

42. ISO 17225-2:2021. (2021). Solid biofuels—Fuel specifications and classes Part 2: Graded wood pellets. International Organization for Standardization.

43. ISO 18122:2022. (2022). Solid biofuels—Determination of ash content. International Organization for Standardization.

44. ISO 18123:2023. (2023). Solid biofuels—Determination of volatile matter. International Organization for Standardization.

45. ISO 18125:2017. (2017). Solid biofuels—Determination of calorific value. International Organization for Standardization.

46. ISO 18134-3:2022. (2022). Solid Biofuels—Determination of Moisture Content—Oven Dry Method Part 3: Moisture in General Analysis Sample. International Organization for Standardization.

47. ISO 21404:2020. (2020). Solid biofuels—Determination of ash melting behaviour. International Organization for Standardization.

48. Jaramillo-Robledo A (2018). El clima de la caficultura en Colombia. Colección Libros 80 años Cenicafé. https://doi.org/10.38141/cenbook-0031

49. Jeníček L, Tunklová B, Malaťák J, Neškudla M, Velebil J (2022). Use of Spent Coffee Ground as an Alternative Fuel and Possible Soil Amendment. Materials 15(19), Article 19. https://doi.org/10.3390/ma15196722

50. Jiamjariyatam R, Samosorn S, Dolsophon K, Tantayotai P, Lorliam W, Krajangsang S (2022). Effects of drying processes on the quality of coffee pulp. Journal of Food Processing and Preservation, 46(10), e16876. https://doi.org/10.1111/jfpp.16876

51. Jiménez-Ochoa JP, Barrios-Rodríguez YF, Bahamón-Monje AF, Gutiérrez-Gúzman N (2022). Physicochemical and sensory characteristics of dehydrated coffee pulp in function of drying temperature. Revista Brasileira de Engenharia Agrícola e Ambiental 26, 894–900. https://doi.org/10.1590/1807-1929/agriambi.v26n12p894-900

52. Jomantas G, Buinevičius K, Šereika J (2025). Sulfur Emission Dependence on Various Factors During Biomass Combustion. Energies 18(7), Article 7. https://doi.org/10.3390/en18071701

53. Kabeyi MB, Olanrewaju OA (2023). Bagasse Electricity Potential of Conventional Sugarcane Factories. Journal of Energy 2023(1), 5749122. https://doi.org/10.1155/2023/5749122

54. Kaczmarczyk R, Mlonka-Mędrala A (2016). Chloride corrosion in biomass-fired boilers – Fe-O-Cl system thermodynamic analysis. E3S Web of Conferences, 10, 00060. https://doi.org/10.1051/e3sconf/20161000060

55. Karuana F, Prismantoko A, Jatisukamto G, Tambunan B, Suhendra N, Syahril M, Rahayu S, Darmawan A, Darmadi DB, Aziz M., Muflikhun MA, Hariana H (2024). Degradation of the protective layer on stainless steel by chlorine variation under high-temperature conditions. Materials Today Communications 40, 109981. https://doi.org/10.1016/j.mtcomm.2024.109981

56. Kc Y, Subba R, Shiwakoti LD, Dhungana PK, Bajagain R, Chaudhary DK, Pant BR, Bajgai TR, Lamichhane J, Timilsina S, Upadhyaya J, Dahal RH (2021). Utilizing Coffee Pulp and Mucilage for Producing Alcohol-Based Beverage. Fermentation 7(2), Article 2. https://doi.org/10.3390/fermentation7020053

57. Kienzl N, Margaritis N, Isemin R, Zaychenko V, Strasser C, Kourkoumpas DS, Grammeli P, Klimov D, Larina O, Sytchev G, Mikhalev A (2021). Applicability of Torrefied Sunflower Husk Pellets in Small and Medium Scale Furnaces. Waste and Biomass Valorization 12(5), 2579–2596. https://doi.org/10.1007/s12649-020-01170-7

58. Král E, Rukov JL, Mendes AC (2024). Coffee Cherry on the Top: Disserting Valorization of Coffee Pulp and Husk. Food Engineering Reviews 16(1), 146–162. https://doi.org/10.1007/s12393-023-09352-4

59. Kuchler C, Schön C, Kuptz D, Dietz E, Zimmermann D, Rist E, Mack R, Riebler M, Blum U, Borchert H, Hartmann H (2024). Fuel upgrade and soil contamination effects on wood chip quality and combustion behaviour. Biomass and Bioenergy 183, 107150. https://doi.org/10.1016/j.biombioe.2024.107150

60. Li J, Wei J, Reinmöller M, Liang C, Li S, Xiao R, Xu J (2022). Comparative observation of the flow behavior of low- and high-temperature ashes of biomass. Fuel 327, 125232. https://doi.org/10.1016/j.fuel.2022.125232

61. Lionetti V, Bartucci S, Poselle Bonaventura C, Conte G, Desiderio G, Policicchio A, Agostino RG (2025). Optimized activation of coffee-ground carbons for hydrogen storage. International Journal of Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2025.03.188

62. Ma P, Li B, Diao R, Liu X, Cheng Z, Qi F (2024). Demineralization effects on physicochemical and combustion characteristics of biomass: Insights into distributed kinetics, flue gas evolution, and slag formation. Fuel 370, 131836. https://doi.org/10.1016/j.fuel.2024.131836

63. Machado DB, Oliveira RA de (2023). Functional and technological properties of coffee mucilage (*Coffea arabica*) and its application in edible films. Química Nova 46, 778–784. https://doi.org/10.21577/0100-4042.20230052

64. Machado M, Espírito Santo L, Machado S, Lobo JC, Costa AG, Oliveira MP, Ferreira H, Alves RC (2023). Bioactive Potential and Chemical Composition of Coffee By-Products: From Pulp to Silverskin. Foods 12(12), Article 12. https://doi.org/10.3390/foods12122354

65. Manrique R, Vásquez D, Chejne F, Pinzón A (2020). Energy analysis of a proposed hybrid solar–biomass coffee bean drying system. Energy 202, 117720. https://doi.org/10.1016/j.energy.2020.117720

66. Mhilu CF (2014). Analysis of Energy Characteristics of Rice and Coffee Husks Blends. International Scholarly Research Notices 2014(1), 196103. https://doi.org/10.1155/2014/196103

67. Miao M, Deng B, Kong H, Yang H, Lyu J, Jiang X, Zhang M (2021). Effects of volatile matter and oxygen concentration on combustion characteristics of coal in an oxygen-enriched fluidized bed. Energy 220, 119778. https://doi.org/10.1016/j.energy.2021.119778

68. Milijašević M, Stojiljković D, Manić N (2025). Computational Fluid Dynamics Study of Biomass Moisture Content Impact on Particle Matter Emissions. Environmental Modeling & Assessment 30(1), 193–218. https://doi.org/10.1007/s10666-024-09991-9

69. Montilla J, Arcila J, Aristizabal M, Montoya EC, Puerta GI, Oliveros CE, Cadena G (2008). Propiedades físicas y factores de conversión del café en el proceso de beneficio [Technical Report]. Centro Nacional de Investigaciones de Café (Cenicafé). https://biblioteca.cenicafe.org/handle/10778/358

70. Munirwan RP, Mohd Taib A, Taha MR, Abd Rahman N, Munirwansyah M (2022). Utilization of coffee husk ash for soil stabilization: A systematic review. Physics and Chemistry of the Earth, Parts A/B/C, 128, 103252. https://doi.org/10.1016/j.pce.2022.103252

71. Nath B, Chen G, Bowtell L, Mahmood RA (2023). Assessment of densified fuel quality parameters: A case study for wheat straw pellet. Journal of Bioresources and Bioproducts 8(1), 45–58. https://doi.org/10.1016/j.jobab.2022.10.001

72. Obidziński S, Cwalina P, Kowczyk-Sadowy M, Sienkiewicz A, Krasowska M, Szyszlak-Bargłowicz J, Zając G, Słowik T, Mazur J, Jankowski M (2024). Physical and Energy Properties of Fuel Pellets Produced from Sawdust with Potato Pulp Addition. Energies 17(16), Article 16. https://doi.org/10.3390/en17163960

73. Odzijewicz JI, Wołejko E, Wydro U, Wasil M, Jabłońska-Trypuć A (2022). Utilization of Ashes from Biomass Combustion. Energies 15(24), Article 24. https://doi.org/10.3390/en15249653

74. Oladeji JT, Enweremadu CC (2012). The Effects of Some Processing Parameters on Physical and Densification Characteristics of Corncob Briquettes. International Journal of Energy Engineering 2(1), 22–27.

75. Oliveros CE, San JR, Ramirez CA, Peñuela AE (2009). Aprovechamiento eficiente de la energía en el secado mecánico del café [Technical Report]. Centro Nacional de Investigaciones de Café (Cenicafé). https://biblioteca.cenicafe.org/handle/10778/370

76. Orosco J, Patiño FJ, Quintero MJ, Rodríguez L (2018). Residual biomass gasification on a small scale and its thermal utilization for coffee drying. Livestock Research for Rural Development 30(1). https://www.lrrd.cipav.org.co/lrrd30/1/jair30005.html

77. Ouedraogo H, Sadio Sidibe SD, Richardson Y (2025). Advancing small-scale biomass gasification (10–200 kW) for energy access: Syngas purification, system modeling and the role of artificial intelligence-A review. Energy Conversion and Management: X, 101059. https://doi.org/10.1016/j.ecmx.2025.101059

78. Parra-Coronado A, Roa-Mejía G, Oliveros-Tascón CE, Sanz-Uribe JR (2017). Optimización operacional de secadores mecánicos para café pergamino (Vol. 1). Cenicafé. https://www.cenicafe.org/es/index.php/nuestras_publicaciones/libros/publicaciones_optimizacion_operacional_de_secadores_mecanicos_para_cafe

79. Pawar A, Panwar NL, Jain S, Jain NK, Gupta T (2023). Thermal degradation of coconut husk waste biomass under non-isothermal condition. Biomass Conversion and Biorefinery 13(9), 7613–7622. https://doi.org/10.1007/s13399-021-01657-w

80. Pedišius N, Praspaliauskas M, Pedišius J, Dzenajavičienė EF (2021). Analysis of Wood Chip Characteristics for Energy Production in Lithuania. Energies 14(13), Article 13. https://doi.org/10.3390/en14133931

81. Peñuela-Martínez AE, Guerrero A, Sanz-Uribe JR (2022). Cromacafé ® Herramienta para identificar los estados de madurez de las variedades de café de fruto rojo. Avances Técnicos Cenicafé 1–8. https://doi.org/10.38141/10779/0535

82. Peñuela-Martínez AE, Sanz-Uribe JR, Guerrero A, Ramírez CA (2022). Siete prácticas en el beneficio para obtener café de buena calidad—Proceso 7P®. Avances Técnicos Cenicafé 1–8. https://doi.org/10.38141/10779/0546

83. Pineda MF, Tinoco HA, Lopez-Guzman J, Perdomo-Hurtado L, Cardona CI, Rincon-Jimenez A, Betancur-Herrera N (2022). Ripening stage classification of *Coffea arabica* L. var. Castillo using a Machine learning approach with the electromechanical impedance measurements of a contact device. Materials Today: Proceedings 62, 6671–6678. https://doi.org/10.1016/j.matpr.2022.04.669

84. Pitsch H (2024). The transition to sustainable combustion: Hydrogen- and carbon-based future fuels and methods for dealing with their challenges. Proceedings of the Combustion Institute 40(1), 105638. https://doi.org/10.1016/j.proci.2024.105638

85. Pranolo SH, Waluyo J, Setiawan A, Hidayat H, Hati WP (2021). The study of palm kernel shell updraft gasification for supplying heat to an asphalt mixing plant. IOP Conference Series: Materials Science and Engineering 1098(2), 022003. https://doi.org/10.1088/1757-899X/1098/2/022003

86. Quintero-Yepes L, Verú-Torres A, Esguerra AO (2024). Guía de sostenibilidad ambiental para las centrales de transformación y beneficio de café cereza. Libros y Manuales. https://doi.org/10.38141/cenbook-0054

87. Rahmah DM, Mardawati E, Kastaman R, Pujianto T, Pramulya R (2023). Coffee Pulp Biomass Utilization on Coffee Production and Its Impact on Energy Saving, CO2 Emission Reduction, and Economic Value Added to Promote Green Lean Practice in Agriculture Production. Agronomy 13(3), Article 3. https://doi.org/10.3390/agronomy13030904

88. Remón J, Ravaglio-Pasquini F, Pedraza-Segura L, Arcelus-Arrillaga P, Suelves I, Pinilla JL (2021). Caffeinating the biofuels market: Effect of the processing conditions during the production of biofuels and high-value chemicals by hydrothermal treatment of residual coffee pulp. Journal of Cleaner Production 302, 127008. https://doi.org/10.1016/j.jclepro.2021.127008

89. Ren X, Sun R, Meng X, Vorobiev N, Schiemann M, Levendis YA (2017). Carbon, sulfur and nitrogen oxide emissions from combustion of pulverized raw and torrefied biomass. Fuel 188, 310–323. https://doi.org/10.1016/j.fuel.2016.10.017

90. Rodríguez JL, Álvarez X, Valero E, Ortiz L, de la Torre-Rodríguez N, Acuña-Alonso C (2021). Influence of ashes in the use of forest biomass as source of energy. Fuel 283, 119256. https://doi.org/10.1016/j.fuel.2020.119256

91. Rodríguez-Valencia N (2023). Aplicación de la bioeconomía circular en el proceso de beneficio de café con cero residuos. Colección Libros 85 años Cenicafé. https://doi.org/10.38141/cenbook-0032

92. Rodríguez-Valencia N, Sanz-Uribe JR, Ramírez CA, Quintero-Yepes L, Tibaduiza-Vianchá CA (2021). Tipificación del beneficio del café en Colombia. Boletín Técnico Cenicafé 1–40. https://doi.org/10.38141/10781/046

93. Rodriguez-Valencia N, Zambrano-Franco DA (2010). Los subproductos del café: Fuente de energía renovable [Technical Report]. Centro Nacional de Investigaciones de Café (Cenicafé). https://biblioteca.cenicafe.org/handle/10778/351

94. Rohaya S, Anwar SH, Amhar AB, Sutriana A, Muzaifa M (2023). Antioxidant activity and physicochemical composition of coffee pulp obtained from three coffee varieties in Aceh, Indonesia. IOP Conference Series: Earth and Environmental Science 1182(1), 012063. https://doi.org/10.1088/1755-1315/1182/1/012063

95. Sánchez-Reinoso AD, Ávila-Pedraza EÁ, Lombardini L, Restrepo-Díaz H (2023). The Application of Coffee Pulp Biochar Improves the Physical, Chemical, and Biological Characteristics of Soil for Coffee Cultivation. Journal of Soil Science and Plant Nutrition 23(2), 2512–2524. https://doi.org/10.1007/s42729-023-01208-4

96. Serna-Jiménez JA, Siles JA, de los Ángeles Martín M, Chica AF (2022). A Review on the Applications of Coffee Waste Derived from Primary Processing: Strategies for Revalorization. Processes 10(11), Article 11. https://doi.org/10.3390/pr10112436

97. Shah MA, Hayder G, Kumar R, Kumar V, Ahamad T, Kalam MA, Soudagar MM, Mohamed Shamshuddin SZ, Mubarak NM (2023). Development of sustainable biomass residues for biofuels applications. Scientific Reports 13(1), 14248. https://doi.org/10.1038/s41598-023-41446-1

98. Sher F, Smječanin N, Khan MK, Shabbir I, Ali S, Hatshan MR, Ul Hai I (2024). Agglomeration behaviour of various biomass fuels under different air staging conditions in fluidised bed technology for renewable energy applications. Renewable Energy 227, 120479. https://doi.org/10.1016/j.renene.2024.120479

99. Siles P, Cerdán CR, Staver C (2022). Smallholder Coffee in the Global Economy—A Framework to Explore Transformation Alternatives of Traditional Agroforestry for Greater Economic, Ecological, and Livelihood Viability. Frontiers in Sustainable Food Systems 6. https://doi.org/10.3389/fsufs.2022.808207

100. Silvennoinen J, Hedman M (2013). Co-firing of agricultural fuels in a full-scale fluidized bed boiler. Fuel Processing Technology 105, 11–19. https://doi.org/10.1016/j.fuproc.2011.05.019

101. Sugebo B (2022). A review on enhanced biofuel production from coffee by-products using different enhancement techniques. Materials for Renewable and Sustainable Energy 11(2), 91–103. https://doi.org/10.1007/s40243-022-00209-0

102. Suri S, Singh A, Nema PK, Malakar S, Arora VK (2022). Sweet lime (*Citrus limetta*) peel waste drying approaches and effect on quality attributes, phytochemical and functional properties. Food Bioscience 48, 101789. https://doi.org/10.1016/j.fbio.2022.101789

103. Syguła E, Ciolkosz D, Białowiec A (2024). The significance of structural components of lignocellulosic biomass on volatile organic compounds presence on biochar—A review. Wood Science and Technology 58(3), 859–886. https://doi.org/10.1007/s00226-024-01557-y

104. Tamilselvan K, Sundarajan S, Ramakrishna S, Amirul A, Vigneswari S (2024). Sustainable valorisation of coffee husk into value added product in the context of circular bioeconomy: Exploring potential biomass-based value webs. Food and Bioproducts Processing 145, 187–202. https://doi.org/10.1016/j.fbp.2024.03.008

105. Tanko J, Ahmadu U, Sadiq U, Muazu A (2021). Characterization of Rice Husk and Coconut Shell Briquette as an Alternative Solid Fuel. Advanced Energy Conversion Materials 1–12. https://doi.org/10.37256/aecm.212021608

106. Tapingkae W, Srinual P, Khamtavee P, Pintalerd N, Chaiyaso T, Yachai M, Kanmanee C, Lumsangkul C, Srinual O (2025). The Use of Coffee Cherry Pulp Extract as an Alternative to an Antibiotic Growth Promoter in Broiler Diets. Animals 15(2), Article 2. https://doi.org/10.3390/ani15020244

107. Tesfaye A, Workie F, Kumar VS (2022). Production and Characterization of Coffee Husk Fuel Briquettes as an Alternative Energy Source. Advances in Materials Science and Engineering 2022(1), 9139766. https://doi.org/10.1155/2022/9139766

108. Tinoco HA, Peña FM (2018). Finite Element Analysis of Coffea arabica L. var. Colombia Fruits for Selective Detachment Using Forced Vibrations. Vibration 1(1), Article 1. https://doi.org/10.3390/vibration1010015

109. Twinomuhwez H, Wozeyi P, Igwe VS, Amagwula IO, Awuchi CG (2021). Heat of Combustion of Coffee Pulp and Husks as Alternative Sources of Renewable Energy. European Journal of Agriculture and Food Sciences 3(2), Article 2. https://doi.org/10.24018/ejfood.2021.3.2.241

110. Varma AK, Singh S, Rathore AK, Thakur LS, Shankar R, Mondal P (2022). Investigation of kinetic and thermodynamic parameters for pyrolysis of peanut shell using thermogravimetric analysis. Biomass Conversion and Biorefinery 12(11), 4877–4888. https://doi.org/10.1007/s13399-020-00972-y

111. Vassilev SV, Vassileva CG, Song YC, Li WY, Feng J (2017). Ash contents and ash-forming elements of biomass and their significance for solid biofuel combustion. Fuel 208, 377–409. https://doi.org/10.1016/j.fuel.2017.07.036

112. Wan L, Wang H, Mo X, Wang Y, Song L, Liu L, Liang W (2024). Applying HS-SPME-GC-MS combined with PTR-TOF-MS to analyze the volatile compounds in coffee husks of Coffea *arabica* with different primary processing treatments in Yunnan. LWT 191, 115675. https://doi.org/10.1016/j.lwt.2023.115675

113. Wojcieszak D, Przybył J, Czajkowski Ł, Majka J, Pawłowski A (2022). Effects of Harvest Maturity on the Chemical and Energetic Properties of Corn Stover Biomass Combustion. Materials 15(8), Article 8. https://doi.org/10.3390/ma15082831

114. Yiga VA, Nuwamanya A, Birungi A, Lubwama M, Lubwama HN (2023). Development of carbonized rice husks briquettes: Synergy between emissions, combustion, kinetics and thermodynamic characteristics. Energy Reports 9, 5977–5991. https://doi.org/10.1016/j.egyr.2023.05.066

115. Yuan M, Guo J, He C, Ilyushechkin A, Li X, Lu H, Fan F, Wang Z, Qin Y, Wei Y, Bai J, Li W (2025). Structure-governed potassium retention mechanism in the slagging and non-slagging gasification condition of corn straw. Renewable Energy 239, 122181. https://doi.org/10.1016/j.renene.2024.122181

116. Zhao N, Li B, Ahmad R, Ding F, Zhou Y, Li G, Zayan AMI, Dong R (2021). Dynamic relationships between real-time fuel moisture content and combustion-emission-performance characteristics of wood pellets in a top-lit updraft cookstove. Case Studies in Thermal Engineering 28, 101484. https://doi.org/10.1016/j.csite.2021.101484

117. Zhu X, Han Y, Feng Y, Cheng P, Peng Y, Wang J, Cai J, Chen Y (2022). Formation and emission characteristics of intermediate volatile organic compounds (IVOCs) from the combustion of biomass and their cellulose, hemicellulose, and lignin. Atmospheric Environment 286, 119217. https://doi.org/10.1016/j.atmosenv.2022.119217

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