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Research Article

Tea (*Camellia sinensis*) processing residues: Thermochemical characterization of stalks and off-grade leaves for renewable energy

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Abstract. Tea (*Camellia sinensis*) processing generates significant quantities of solid residues, particularly stalks and off-grade leaves, which remain underutilized despite their potential as renewable energy resources. Valorization of these residues as solid biofuels could support waste reduction, local energy supply, and circular economy strategies in tea-producing regions. This study presents a thermochemical characterization of tea processing residues with emphasis on stalks and off-grade leaves. Representative samples were collected from a commercial tea processing facility in Bandung, Indonesia, and analyzed through proximate analysis to determine moisture, volatile matter, ash, and fixed carbon, and ultimate analysis to quantify carbon, hydrogen, nitrogen, sulfur, and oxygen. Higher heating value was determined by bomb calorimetry, and net calorific value was calculated to assess practical energy availability under combustion conditions. Thermal behavior was evaluated using thermogravimetric analysis and differential scanning calorimetry to characterize degradation stages and combustion stability. Results showed volatile matter contents above 70%, carbon contents between 45% and 50%, and higher heating values ranging from 16 to 19 MJ·kg^{-1}. Corresponding net calorific values ranged from 15 to 18 MJ·kg^{-1}, comparable to widely used lignocellulosic biomasses such as coffee husk and sugarcane bagasse. Thermogravimetric profiles revealed distinct devolatilization and char oxidation stages. Differences between stalks and off-grade leaves confirmed the relevance of fraction-specific evaluation. These findings demonstrate that tea processing residues represent a viable solid biofuel resource for renewable energy applications in tea-producing regions.

Keywords: Biomass conversion; Calorific value; Lignocellulosic materials; Solid biofuel; Thermal degradation

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1. Introduction

Tea (*Camellia sinensis*) is the world's second-most popular beverage, consumed less frequently only than water (Dou, 2019; Zhao et al., 2022). The worldwide production is more than six million tons per year, and the cultivated areas are increasing in Asia, Africa and Latin America to meet the increasing demand (Duarah *et al.*, 2024; Mandal *et al.*, 2024). In addition to its economic and cultural value, tea production generates large quantities of solid waste. Substantial quantities of stalks, fibres, dust and off-grade leaves are removed from the finished product during processing operations like withering, rolling, drying and grading (Powrel *et al.,* 2025; Unyay *et al.,* 2025).

These materials are abundant but often underutilized, either discarded or diverted to low value applications. Annually, millions of tons of tea residues are produced globally, posing logistical challenges for producers, but also a substantial and underutilized biomass source (Guo *et al.*, 2021). In addition to factory generated fractions, other organic matter is derived from complementary streams such as pruning materials and field sweepings, but these are rarely quantified or incorporated in formal management plans (Aung Zaw O *et al.*, 2018; Pramanik & Phukan, 2020). In certain areas, the lack of organized routes for use can result in environmental effects like uncontrolled decomposition, methane emissions, and leachate production (Seth *et al.*, 2025). With the global demand for tea increasing, finding sustainable valorization routes for these by-products is becoming increasingly important to align production systems with international goals for waste minimization, renewable energy transition and circular economy implementation (Kumar *et al.*, 2023; Sadh *et al.*, 2023). Figure 1 shows the tea processing chain and the major steps of residue generation.

The shift to low-carbon energy systems has led to interest in the energy use of crop-derived residues. Biomass resources like coffee husks, sugarcane bagasse, rice husks, and palm residues have been extensively studied and widely used as renewable fuels for thermal and power generation (Abdullah *et al.,* 2021; Duque-Dussán *et al.*, 2025; Saleem, 2022). These materials are already in use in the practical energy systems of many producing areas. In sugar mills, bagasse is commonly used in cogeneration facilities, rice husks are converted into pellets and briquette and coffee husks are burnt to produce heat for drying processes (Cavalcanti *et al.*, 2020a; Manrique *et al.*, 2019; Mofijur *et al.*, 2019). These examples show the possibility of enhancing local energy security, reducing reliance on fossil fuels and

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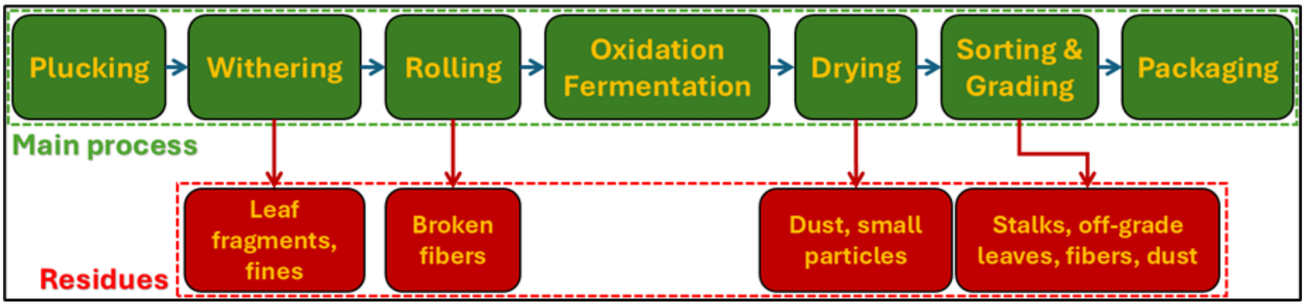

Fig 1. Schematic representation of the tea processing chain and principal stages of residue generation. Residues are produced during withering (leaf fragments), rolling (fibers), drying (dust), and sorting and grading (stalks, off-grade leaves, fibers, and fine particles).

contributing to efforts to mitigate greenhouse gases by using agricultural by-products (Kaniapan *et al.*, 2022; Quispe *et al.*, 2019).

In contrast, residues generated during tea manufacture have received comparatively limited attention in the context of energy recovery. Current practices within the tea sector primarily involve composting, organic fertilizer production, extraction of bioactive compounds, or adsorption applications for environmental remediation (Miao *et al.*, 2023; Seth *et al.,* 2025). While beneficial, these uses do not fully exploit the inherent energy potential of tea-derived biomass. Establishing reliable data on their calorific properties and combustion behavior is therefore essential to evaluate their feasibility as renewable fuel sources and to inform technological and investment decisions related to decentralized energy integration in tea-producing regions (Tunklová *et al.*, 2022; Unyay *et al*., 2025).

While the potential appears to exist, there is little scientific knowledge on the fuel characteristics of tea residues. Only a handful of studies have reported the proximate composition, ultimate analysis, calorific values or thermal degradation profiles of these materials, most of them considering these as a homogeneous stream rather than separate fractions (Cai *et al.*, 2018; Muhammed *et al.*, 2026). The generalized approach ignores the heterogeneity of the processing outputs. For example, stalks and off-grade leaves may differ significantly in ash content, elemental composition, volatile matter fraction, and energy density (Alashmawy *et al.*, 2023; Unyay et al., 2025). Such differences have a direct impact on combustion efficiency, slagging and fouling tendencies, emission profiles and the overall performance of the system (Royo *et al.,* 2019). Variations in the concentrations of hydrogen and oxygen will influence the net calorific value and the stoichiometric air requirements, whereas high silica or alkali content in ash may lead to deposition during combustion (Lachman *et al.*, 2021; Míguez *et al.,* 2021). The absence of fraction-specific characterization constrains the utilization of tea residues in combustion or thermochemical conversion systems, leading to unreliable data for energy planners and equipment designers to predict operational performance and environmental impacts (Chavhan et al., 2024). Moreover, systematic comparisons with other well characterized biomass resources like coffee husks, rice husks and sugarcane bagasse are still limited. Such a lack of comparative assessment limits the potential to place tea residues in the larger picture of renewable biomass and prevents them from being acknowledged as potential energy feedstocks in academic and policy discussions (Chavhan et al., 2024; M. Kumar et al., 2019; Shah et al., 2023). Addressing these knowledge gaps is therefore essential to enable evidence-based decisions supporting sustainable biomass utilization strategies.

The potential use of tea waste for composting, adsorption, bioactive compound recovery, and thermochemical conversion has been reported in previous studies (Duarah et al., 2024; Guo *et al.,* 2021; Miao *et al.*, 2023; Seth *et al.*, 2025). However, most of these studies consider tea waste as a homogenous material, while the industrial processing leads to different fractions with different physicochemical and thermal properties (Alashmawy *et al.*, 2023; Cai *et al.*, 2018; Unyay *et al.*, 2025). Existing data are not directly applicable to energy system design because ash content, volatile matter, fixed carbon, elemental composition, calorific value and degradation behavior directly impact combustion stability, char formation, slagging risk, emissions and conversion efficiency (Chavhan *et al.,* 2024; Lachman *et al.,* 2021; Míguez *et al.,* 2021; Royo *et al.,* 2019). Hence, in the present work, we are going to go beyond general evaluations of the waste produced by the tea industry, and we are going to provide a thermochemical characterization for stalks and for off-grade leaves, two residues generated in the sorting and grading steps of the industry, respectively. This work integrates proximate and ultimate analyses, determination of calorific value, thermogravimetric analysis, differential scanning calorimetry and comparison with existing agricultural biofuels, providing more applicable evidence for decentralized renewable energy use and circular economy strategies in tea producing regions (Duque-Dussán *et al.,* 2025; V. Kumar *et al.,* 2023; Sadh *et al.,* 2023; Tunklová *et al.*, 2022).

Accordingly, the objective of this study was to conduct systematic thermochemical characterization of tea processing residues, with emphasis on differentiating stalks and off-grade leaves. Proximate and ultimate analyses were performed to determine their physicochemical properties, while higher and net calorific values were measured to assess gross and practical energy potential under combustion conditions. Thermal behavior was further evaluated using thermogravimetric analysis and differential scanning calorimetry to characterize degradation stages and combustion stability. By providing fraction-specific fuel data and situating the results within the broader context of agricultural biomass resources, this study contributes technical evidence to support the integration of tea processing residues into renewable energy systems and advances their valorization within circular economy frameworks.

2. Materials and Methods

2.1 Study Area and Sample Collection

Tea processing residues were obtained from a commercial tea processing facility located at the Riung Gunung plantation

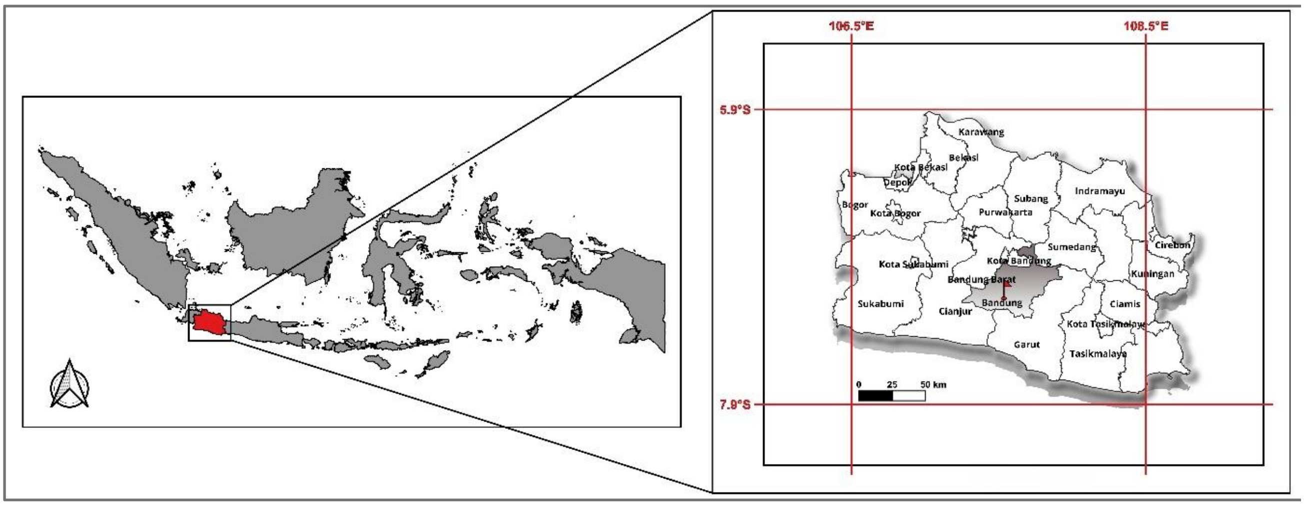

Fig 2. Geographic location of the Riung Gunung tea plantation in the Pangalengan district, West Java Province, Indonesia, where samples of tea processing residues were collected.

(7.177595° S, 107.531070° E) in the Pangalengan district, West Java Province, Indonesia (Figure 2). The facility processes freshly harvested *Camellia sinensis* leaves using standard industrial operations, including withering, rolling, drying, and mechanical sorting and grading. During the sorting stage, non-commercial fractions such as stalks and off-grade leaves are separated from the final product stream. These fractions were selected for analysis due to their availability and relevance as potential solid biofuel feedstocks.

Sampling was conducted directly at the discharge point of the sorting system to ensure representative collection under normal operating conditions. Separate batches of stalks and off-grade leaves were collected and handled independently. The collected materials were placed in airtight polyethylene containers immediately after separation to minimize moisture exchange with the environment and prevent contamination. Samples were transported to the laboratory for subsequent preparation and physicochemical characterization.

2.2 Sample Preparation

2.2.1 Pre-treatment and Drying

Collected residues were subjected to pre-treatment prior to laboratory analyses to ensure sample consistency. Stalks and off-grade leaves were manually inspected and cleaned to remove visible foreign materials such as soil particles, stones, and other impurities. The samples were then air-dried under controlled laboratory conditions to reduce initial moisture content and stabilize the biomass prior to further processing. This step allowed moisture equilibration while minimizing thermal alteration of the material.

2.2.2 Size Reduction and Storage

After drying, the samples were milled using a laboratory grinder to obtain a homogeneous particle size suitable for analytical measurements. The ground material was subsequently sieved through a 1 mm mesh to ensure uniform particle distribution. The prepared samples were stored in airtight containers at ambient laboratory conditions to prevent moisture uptake prior to physicochemical characterization.

2.3 Proximate Analysis

Proximate analysis was conducted to determine the moisture content, volatile matter, ash content, and fixed carbon of the tea processing residues. These parameters provide essential information on the fuel characteristics and combustion behavior of biomass materials. All analyses were carried out following standardized procedures, and measurements were performed in triplicate to ensure reproducibility. Results were expressed on a dry basis unless otherwise specified.

2.3.1 Moisture Content Determination

Moisture content was determined using the oven-drying method in accordance with ISO 18134-3 for solid biofuels. Approximately 10 g of sample was placed in a Memmert UF110 drying oven (Memmert GmbH + Co. KG, Schwabach, Germany) at 105 ± 2 °C and dried until constant mass was achieved. Moisture content was calculated on a wet basis from the mass difference before and after drying as stated in Equation 1.

$$MC_{\text{wb}}\,(\%) = \frac{m_{\text{initial}} - m_{\text{dry}}}{m_{\text{initial}}}\,100 \tag{1}$$

Where $m_{initial}$ represents the mass before drying and m_{dry} the mass after drying.

2.3.2 Volatile Matter

Volatile matter (VM) content was determined following the procedure described in ISO 18123 for solid biofuels. Approximately 1 g of oven-dried sample was placed in a covered crucible to limit oxygen access during heating. The crucible containing the sample was introduced into a preheated Memmert muffle furnace model L9/11 (Memmert GmbH + Co. KG, Schwabach, Germany) at 900 ± 10 °C and maintained at this temperature for 7 minutes.

After heating, the crucible was carefully removed from the furnace, allowed to cool in a desiccator to ambient temperature, and then weighed. The loss in mass during heating, excluding the previously determined moisture content, was attributed to the release of volatile compounds present in the biomass. Volatile matter content was calculated on a dry basis using the mass difference before and after thermal treatment.

2.3.3 Ash Content

Ash content was determined following the procedure described in ISO 18122 for solid biofuels. Approximately 1 g of oven-dried sample was placed in a pre-weighed ceramic crucible and introduced into a muffle furnace. The sample was heated at 550 ± 10 °C until constant mass was achieved to ensure complete combustion of organic material.

After combustion, the crucible containing the residual inorganic material was removed from the furnace, cooled in a desiccator to room temperature, and weighed. The remaining residue was considered ash. Ash content was calculated on a dry basis from the ratio of the mass of the remaining inorganic residue to the initial dry mass of the sample

2.3.4 Fixed Carbon

Fixed carbon content was calculated by difference from the results obtained in the proximate analysis. Since moisture content was determined separately on a wet basis, fixed carbon was calculated on a dry basis according to Equation 2:

$$FC_{\mathrm{db}}(\%) = 100 - (VM_{\mathrm{db}} + Ash_{\mathrm{db}}) \quad (2)$$

where FC_{db} is the fixed carbon content on a dry basis (%), VM_{db} is the volatile matter content on a dry basis (%), and Ash_{db} is the ash content on a dry basis (%).

2.4 Ultimate Analysis

Ultimate analysis was performed to determine the elemental composition of the tea processing residues, including carbon (C), hydrogen (H), nitrogen (N), and sulfur (S). The measurements were conducted using an elemental analyzer (CHNS analyzer) following standard procedures for solid biofuels (ISO 16948:2015) (ISO, 2015). Approximately 2 mg of finely ground sample was used for each analysis.

During the analysis, samples were combusted at high temperature in an oxygen-rich environment, and the resulting gases were quantified to determine the elemental composition. Oxygen (O) content was calculated by difference according to Equation 3:

$$O_{\mathrm{db}}(\%) = 100 - (C + H + N + S + Ash) \quad (3)$$

where C, H, N, S, and Ash represent the mass fractions (%) of carbon, hydrogen, nitrogen, sulfur, and ash, respectively. All elemental concentrations were expressed on a dry basis.

2.5 Calorific Value Determination

2.5.1 Higher Heating Value (HHV)

The higher heating value (HHV) of the tea processing residues was determined using an isoperibol IKA C2000 Bomb Calorimeter (IKA-Werke GmbH & Co. KG, Staufen, Germany) in accordance with ISO 18125 for solid biofuels. Approximately 1.0 ± 0.01 g of oven-dried and finely ground sample was placed in the combustion crucible and combusted in an oxygen atmosphere under controlled conditions.

The heat released during complete combustion was measured calorimetrically, and the HHV was calculated from the temperature rise of the calorimetric system. Calibration of the calorimeter was performed using benzoic acid as a reference standard. Results were expressed in $MJ \cdot kg^{-1}$ on a dry basis. All calorimetric measurements were performed in triplicate.

2.5.2 Net Calorific Value (NCV)

The net calorific value (NCV) was calculated from the higher heating value by accounting for the latent heat of vaporization of water produced during combustion. The calculation considered the hydrogen content of the biomass obtained from the ultimate analysis and was determined using Equation 4:

$$NCV = HHV - 2.442\,(9H) \quad (4)$$

where NCV is the net calorific value ($MJ \cdot kg^{-1}$), HHV is the higher heating value ($MJ \cdot kg^{-1}$), and H is the hydrogen content (%) determined from the ultimate analysis.

The calculated NCV represents the effective energy available during practical combustion processes where the water formed during combustion remains in vapor form.

2.6 Thermogravimetric and Calorimetric Analysis

Thermal degradation behavior of the tea processing residues was evaluated using thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC). These techniques were employed to assess mass loss patterns, thermal stability, and heat flow associated with the thermal decomposition of the biomass samples.

2.6.1 Thermogravimetric Analysis (TGA)

Thermogravimetric analysis was performed using a STA 449 F3 Jupiter simultaneous thermal analyzer (NETZSCH-Gerätebau GmbH, Selb, Germany). Approximately 10 mg of finely ground sample was placed in a platinum crucible and heated from ambient temperature to 800 °C at a constant heating rate of 10 $°C \cdot min^{-1}$.

The analysis was conducted under a controlled nitrogen atmosphere to evaluate the devolatilization behavior of the samples and minimize oxidative reactions during heating. The mass change of the sample was continuously recorded as a function of temperature and time. Derivative thermogravimetric (DTG) curves were obtained from the primary TGA data to identify the principal stages of thermal degradation.

2.6.2 Differential Scanning Calorimetry (DSC)

Differential scanning calorimetry was conducted using the DSC module integrated in the STA 449 F3 Jupiter system (NETZSCH-Gerätebau GmbH, Selb, Germany) to evaluate heat flow associated with thermal transitions occurring during biomass decomposition. Approximately 5–10 mg of sample was placed in an aluminum crucible and subjected to a controlled heating program.

Samples were heated from ambient temperature to 800 °C at a constant heating rate of 10 $°C \cdot min^{-1}$ under a controlled atmosphere. Heat flow signals were recorded as a function of temperature, allowing identification of endothermic and exothermic events associated with devolatilization and oxidation processes.

2.7 Statistical and Comparative Analysis

All experimental measurements were performed in triplicate, and results were expressed as mean ± standard deviation. Statistical analysis was conducted to evaluate differences between the two residue fractions analyzed in this study, namely stalks and off-grade leaves.

Differences in proximate composition, elemental composition, and calorific values between the two residue types were assessed using one-way analysis of variance (ANOVA). When statistically significant differences were detected, mean comparisons were performed using Tukey's honestly significant difference (HSD) test at a 95% confidence level ($p < 0.05$).

Given that the study compared only two residue fractions, stalks and off-grade leaves, with triplicate measurements, one-way ANOVA followed by Tukey's HSD test was considered appropriate to evaluate statistically significant differences between materials. Multivariate analysis was not applied because the number of residue types was limited and would not provide robust statistical interpretation. Future studies including a larger number of residue fractions, production sites, and seasonal samples should incorporate correlation or multivariate analyses to better model relationships among biomass composition and energy performance.

All statistical analyses were performed using R statistical software (R Foundation for Statistical Computing, Vienna, Austria). In addition to statistical evaluation, the obtained results were compared with values reported in the literature for other lignocellulosic biomasses, including coffee husks, rice husks, and sugarcane bagasse, to contextualize the energetic potential of tea processing residues.

3. Results and Discussion

3.1 Proximate Composition of Tea Processing Residues

The proximate composition of the analyzed tea processing residues is presented in Table 1. These parameters provide essential information regarding the combustion behavior and energy potential of biomass fuels (Racero-Galaraga et al., 2024). Moisture content for both residue fractions ranged between 8.4% and 9.1% (wet basis) after sample preparation. Such relatively low moisture levels are favorable for thermochemical conversion processes, as high moisture contents reduce combustion efficiency and increase the energy required for water evaporation during thermal processing (Motta et al., 2018; Ramos et al., 2022).

Volatile matter represented the largest fraction of the biomass composition for both residue types, with values of 71.8% for stalks and 74.6% for off-grade leaves on a dry basis. High volatile matter content is characteristic of lignocellulosic materials and generally promotes rapid ignition and flame propagation during combustion (Y. Jia et al., 2021; S. Wang et al., 2020). Similar volatile matter ranges have been reported for other agricultural residues such as coffee husks, rice husks, and sugarcane bagasse, which are widely used as solid biofuels in decentralized energy systems (Duque-Dussán et al., 2025). However, high volatile matter content is not universally advantageous. Although it may favor ignition and flame development, rapid volatile release can also cause flame instability, incomplete oxidation, smoke formation, and higher emissions if air supply and residence time are not properly controlled. In gasification and pyrolysis, it may also increase tar formation under insufficient temperature control or vapor residence time (Alashmawy et al., 2023; Aniza et al., 2024; Cai et al., 2018). Therefore, tea processing residues should preferably be used in controlled combustion, gasification, or pyrolysis systems rather than in open or poorly controlled combustion units.

Ash content showed moderate values, ranging from 5.6% for stalks to 6.9% for off-grade leaves. Ash is an important parameter in biomass fuel evaluation because high mineral content may lead to slagging, fouling, and deposition problems in combustion systems (Lachman et al., 2021; Míguez et al., 2021). The ash levels observed in the present study fall within the range commonly reported for many agricultural residues and remain lower than those observed in certain biomass types such as rice husk, which typically contains elevated silica concentrations (Kamruzzaman et al., 2024; M. Kumar et al., 2019).

Fixed carbon contents were 22.6% for stalks and 18.5% for off-grade leaves, indicating differences in structural composition between the two residue fractions. Fixed carbon represents the solid combustible fraction remaining after the release of volatile components and contributes to char formation during the later stages of combustion (Yan et al., 2019). The higher fixed carbon content observed in stalks suggests a slightly greater proportion of lignified structural material compared with leaf-derived residues.

The proximate composition also provides insight into the expected combustion behavior and thermal reactivity of tea processing residues. The high volatile matter content observed in both fractions, 71.8% for stalks and 74.6% for off grade leaves, suggests that these materials would exhibit rapid devolatilization and relatively easy ignition during combustion or pyrolysis. Biomass fuels with high volatile matter generally release combustible gases at lower temperatures, which can enhance flame propagation but also requires adequate air supply and residence time to ensure complete oxidation (Y. Jia et al., 2021; S. Wang et al., 2020). In contrast, the fixed carbon fraction, which was higher in stalks, contributes to char formation and sustained heat release during the later stages of combustion. This indicates that stalks may provide slightly more stable char combustion, while off grade leaves may be more reactive during the initial devolatilization stage. The moderate ash contents measured in this study, 5.6% for stalks and 6.9% for off grade leaves, also indicate the need to consider ash behavior during combustion, since inorganic matter can promote slagging, fouling, and deposition in boilers or burners, particularly when alkali metals and silica are present (Lachman et al., 2021; Míguez et al., 2021).

The fuel ratio, calculated as the fixed carbon to volatile matter ratio, was 0.31 for stalks and 0.25 for off-grade leaves. These low values are typical of highly volatile lignocellulosic biomass and indicate rapid ignition and devolatilization

Table 1
Proximate composition of tea processing residues (stalks and off-grade leaves). Values are expressed as mean ± standard deviation ($n = 3$). Different letters within the same row indicate statistically significant differences according to Tukey's HSD test ($p < 0.05$).

Parameter	Stalks	Off-grade leaves
Moisture content (%, wb)	8.4 ± 0.3^{a}	9.1 ± 0.4 a
Volatile matter (%, db)	71.8 ± 0.7^{a}	74.6 ± 0.8 b
Ash (%, db)	5.6 ± 0.2^{a}	6.9 ± 0.3 b
Fixed carbon (%, db)	22.6 ± 0.5^{b}	18.5 ± 0.4 a

behavior. The higher fuel ratio of stalks suggests a slightly greater contribution to char formation and sustained combustion, while the lower ratio of off-grade leaves indicates higher initial reactivity during thermal conversion.

Overall, the proximate composition indicates that tea processing residues possess physicochemical characteristics comparable to other lignocellulosic biomass resources commonly used for renewable energy generation (Muhammed et al., 2026; Schmitt et al., 2020). These results support their potential suitability as solid biofuel feedstocks in tea-producing regions.

3.2 Elemental Composition of Tea Processing Residues

The elemental composition of the analyzed tea processing residues is presented in Table 2. Ultimate analysis provides essential information regarding the chemical structure of biomass and its suitability as a fuel for thermochemical conversion processes (Sher et al., 2020).

Carbon content ranged from 46.7% in off-grade leaves to 48.2% in stalks, values that are typical of lignocellulosic biomass materials (Charis *et al.*, 2020; Chavhan et al., 2024). Higher carbon content generally contributes to increased calorific value, since carbon is the primary element responsible for heat release during combustion (X. Qian et al., 2021). The slightly higher carbon concentration observed in stalks may therefore contribute to marginally greater energy density compared with leaf-derived residues.

Hydrogen contents were relatively similar between both fractions, ranging between 6.1% and 6.3%. Hydrogen plays an important role in biomass combustion because it contributes to the formation of water vapor during oxidation and influences the net calorific value of the fuel (Fajobi *et al.,* 2022; X. Qian *et al.*, 2021). Values observed in this study are consistent with those reported for other agricultural residues such as coffee husks, rice husks, and sugarcane bagasse (Camargo et al., 2020; Poyilil et al., 2022).

Nitrogen content was significantly higher in off-grade leaves (2.1%) compared with stalks (1.4%). This difference likely reflects the higher concentration of proteins and nitrogen-containing compounds typically present in leaf tissues (Chavhan *et al.*, 2024; Riaza *et al.*, 2019). Elevated nitrogen levels in biomass fuels may contribute to the formation of nitrogen oxides (NOx) during combustion, which is an important environmental consideration in bioenergy applications (Anca-Couce et al., 2018; Proto et al., 2021).

Sulfur concentrations were very low in both residue fractions, remaining below 0.12%. Low sulfur content is advantageous for biomass fuels because it reduces the potential formation of sulfur oxides (SOx) during combustion and minimizes the risk of corrosion in thermal systems (Yanik *et al.*, 2018). Assuming complete conversion of fuel sulfur to SO_2, the measured sulfur contents would correspond to theoretical SO_2 emissions of approximately 1.8 g kg^{-1} for stalks and 2.2 g kg^{-1} for off-grade leaves on a dry biomass basis. These low values support the environmental advantage of tea processing residues as solid biofuels, particularly when compared with sulfur-containing fossil fuels. However, actual SOx emissions would depend on combustion temperature, sulfur retention in ash, air supply, and the presence of emission control systems.

Oxygen content, calculated by difference, accounted for approximately 44% of the biomass composition. Oxygen is a major component of lignocellulosic materials and influences the overall reactivity of biomass during thermal decomposition (Sher *et al.*, 2020). Although high oxygen content generally reduces energy density compared with fossil fuels, it also contributes to enhanced reactivity during combustion and gasification processes (Ivanovski *et al.,* 2022; Tian *et al.*, 2022).

To further interpret fuel quality, atomic H/C and O/C ratios were calculated from the ultimate analysis. Stalks showed H/C and O/C ratios of 1.51 and 0.68, respectively, while off-grade leaves presented values of 1.61 and 0.72. These values are typical of oxygen-rich lignocellulosic biomass and indicate a lower energy density than fossil fuels. The slightly lower O/C ratio of stalks is consistent with their higher carbon content and higher calorific value, supporting their slightly better fuel quality compared with off-grade leaves.

Overall, the elemental composition of the analyzed tea residues is comparable to that of other agricultural biomass resources widely used for energy generation (Chavhan *et al.*, 2024; M. Kumar *et al.*, 2019). These results further support the potential of tea processing residues as suitable feedstocks for renewable energy applications in tea-producing regions.

3.3 Calorific Value and Energy Potential

The higher heating value (HHV) and net calorific value (NCV) of the analyzed tea processing residues are presented in

Table 2
Ultimate analysis of tea processing residues (stalks and off-grade leaves). Values are expressed as mean ± standard deviation (n = 3) on a dry basis. Different letters within the same row indicate statistically significant differences according to Tukey's HSD test ($p < 0.05$)

Parameter	Stalks	Off-grade leaves
Carbon (C, %)	48.2 ± 0.6 [a]	46.7 ± 0.5 [b]
Hydrogen (H, %)	6.1 ± 0.1 [a]	6.3 ± 0.1 [a]
Nitrogen (N, %)	1.4 ± 0.1 [a]	2.1 ± 0.1 [b]
Sulfur (S, %)	0.09 ± 0.01 [a]	0.11 ± 0.01 [a]
Oxygen* (O, %)	43.7 ± 0.7 [a]	44.8 ± 0.6 [a]

*Oxygen calculated by difference.

Table 3
Higher heating value (HHV) and net calorific value (NCV) of tea processing residues (dry basis). Values are expressed as mean ± standard deviation (n = 3). Different letters within the same row indicate statistically significant differences according to Tukey's HSD test ($p < 0.05$).

Parameter	Stalks	Off-grade leaves
HHV (MJ·kg^{-1})	18.7 ± 0.2 [a]	17.9 ± 0.2 [b]
NCV (MJ·kg^{-1})	17.3 ± 0.2 [a]	16.6 ± 0.2 [b]

Table 3. The HHV ranged from 17.9 to 18.7 MJ·kg⁻¹, indicating that both residue fractions possess energy densities typical of lignocellulosic biomass fuels (Shah *et al.*, 2023). The slightly higher HHV observed for stalks can be attributed to their marginally higher carbon content, which directly contributes to heat release during combustion (Huang & Lo, 2020; X. Qian et al., 2021).

The measured HHV values ranged between 17.9 and 18.7 $MJ \cdot kg^{-1}$, with stalks exhibiting slightly higher energy content than off-grade leaves. This difference is consistent with the elemental composition discussed in Section 3.2, where stalks presented marginally higher carbon content. Carbon is the primary contributor to heat release during combustion, and therefore biomass with higher carbon fractions typically exhibits greater calorific values (Chavhan *et al.*, 2024; Esteves *et al.,* 2023; Huang & Lo, 2020).

The calculated NCV values ranged from 16.6 to 17.3 $MJ \cdot kg^{-1}$, representing the effective energy available during practical combustion processes where water formed during hydrogen oxidation remains in vapor form (C. Qian *et al.*, 2020). The difference between HHV and NCV reflects the latent heat associated with water vaporization during combustion (Gani *et al.,* 2024; Huang & Lo, 2020). To contextualize the energy potential of tea residues, Table 4 compares the obtained values with calorific values reported for other agricultural biomass fuels commonly used in renewable energy applications.

The comparison indicates that the calorific values of tea processing residues are comparable to those reported for coffee husks and corn stalk, which are widely used as biomass fuels in agricultural energy systems (Duque-Dussán *et al.*, 2025; Gao *et al.*, 2024). In contrast, materials such as rice husk typically exhibit lower calorific values due to higher ash and silica contents, which reduce the overall energy density of the biomass (Beidaghy Dizaji *et al.*, 2022).

The HHV values obtained in this study are also similar to those reported for sugarcane bagasse, a well-established biomass fuel commonly used in cogeneration systems in the sugar industry (Cavalcanti *et al.,* 2020b). These comparisons demonstrate that tea residues possess energy densities within the typical range of lignocellulosic biomass resources used for renewable energy generation. For additional context, the HHV values obtained for tea processing residues, 17.9–18.7 $MJ \cdot kg^{-1}$, are comparable to the lower range reported for low-rank fossil fuels such as lignite, although they remain below the typical values of higher-rank coals. This comparison highlights the practical thermal potential of tea residues as renewable solid fuels, while recognizing that their combustion behavior, ash composition, moisture sensitivity, and emissions profile differ from those of fossil fuels

Overall, the calorific performance of tea processing residues indicates that these materials can serve as viable feedstocks for thermochemical energy conversion processes such as combustion, gasification, and pyrolysis (Duarah *et al.*, 2024; Zhou *et al.*, 2021). Considering the large quantities of residues generated during tea processing, their utilization as solid biofuels could contribute to waste reduction and support decentralized renewable energy production in tea-growing regions.

3.4 Thermogravimetric Analysis of Tea Processing Residues

The thermal degradation behavior of tea processing residues was investigated using thermogravimetric analysis (TGA). The resulting TGA and derivative thermogravimetric (DTG) curves are presented in Figure 3. These curves provide insight into the mass loss patterns and thermal stability of the biomass during controlled heating (Aniza *et al.,* 2024).

The thermal decomposition profiles of both residue fractions exhibited the typical behavior of lignocellulosic biomass, characterized by three main degradation stages (G. Jia, 2021). The first stage, occurring between approximately 50 °C and 150 °C, corresponds primarily to the removal of physically bound moisture and light volatile compounds. This stage is associated with relatively small mass losses and reflects the evaporation of residual water remaining in the biomass structure (El-Sayed *et al.,* 2024; Emiola-Sadiq *et al.*, 2021).

The second stage, which represents the most significant mass loss, occurred between approximately 200 °C and 380 °C. This region corresponds to the thermal decomposition of hemicellulose and cellulose components within the biomass matrix. Hemicellulose typically decomposes at temperatures between 200 and 300 °C, while cellulose degradation generally occurs between 300 and 370 °C (Apaydın Varol & Mutlu, 2023; Volli *et al.,* 2021). The pronounced DTG peaks observed in this temperature range indicate rapid volatilization and release of combustible gases. The DTG curves further confirmed that the main decomposition event occurred within this temperature interval, where the maximum degradation rate was associated with the rapid devolatilization of hemicellulose and cellulose. Off-grade leaves showed a slightly more intense DTG response, indicating faster volatile release and higher thermal reactivity, which agrees with their higher volatile matter content. In contrast, stalks exhibited a less intense but broader degradation profile and retained slightly higher residual mass at elevated temperatures, consistent with their higher fixed carbon content and more lignified structure. These differences indicate that off-grade leaves may be more reactive during the initial thermal conversion stage, while stalks may contribute more to char formation and sustained combustion.

The third stage, extending from approximately 380 °C to 600 °C, is associated with the gradual degradation of lignin and the formation of char residues. Lignin decomposes over a broader temperature range due to its complex aromatic structure, which results in slower and more progressive mass loss compared with hemicellulose and cellulose (Yogalakshmi K *et al.*, 2022).

Table 4
Comparison of calorific values of tea processing residues with selected agricultural biomass fuels reported in the literature.

Biomass	HHV ($MJ \cdot kg^{-1}$)	NCV ($MJ \cdot kg^{-1}$)	Reference
Tea stalks	18.7	17.3	This study
Tea off-grade leaves	17.9	16.6	This study
Coffee husk	18–19	16.8–17.5	(Duque-Dussán et al., 2025)
Sugarcane bagasse	16–18	15–17	(Camargo et al., 2020)
Rice husk	14–16	13–15	(Kamruzzaman et al., 2024)
Corn stalk	17–19	16–18	(Gao et al., 2024)

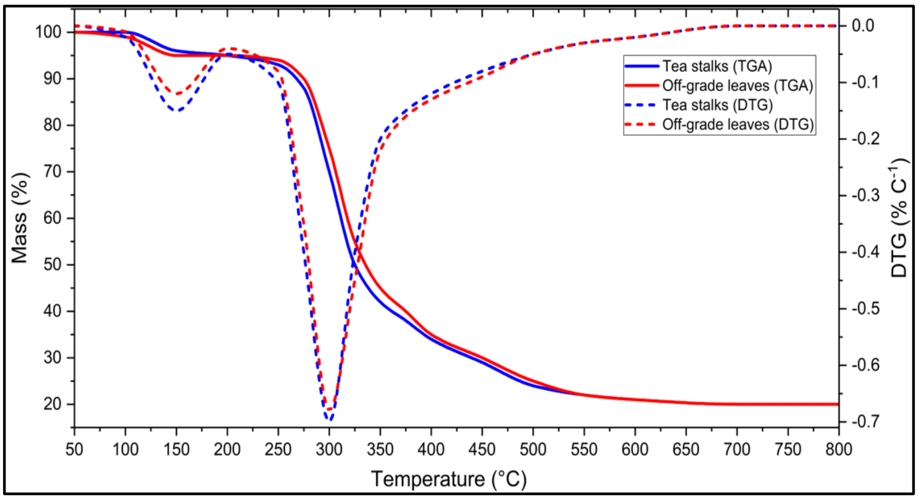

Fig 3. Thermogravimetric (TGA) and derivative thermogravimetric (DTG) curves of tea processing residues (stalks and off-grade leaves) obtained at a heating rate of 10 °C·min⁻¹ under nitrogen atmosphere. The curves show the characteristic three-stage thermal degradation behavior of lignocellulosic biomass.

Although both residue fractions displayed similar degradation patterns, slight differences were observed in the intensity and position of the DTG peaks. Off-grade leaves showed slightly higher volatile release rates, consistent with the higher volatile matter content reported in the proximate analysis. In contrast, stalk samples exhibited marginally higher residual mass at elevated temperatures, reflecting their higher fixed carbon content and more lignified structural composition.

Overall, the thermogravimetric results confirm that tea processing residues exhibit thermal decomposition characteristics comparable to those of other lignocellulosic biomass fuels commonly used in thermochemical energy conversion processes (Ben Abdallah *et al.,* 2023; Sermyagina *et al.*, 2021). These properties suggest that tea residues are suitable feedstocks for applications such as combustion, pyrolysis, and gasification.

3.5 Differential Scanning Calorimetry Analysis

Differential scanning calorimetry (DSC) was performed to evaluate the thermal transitions and heat flow associated with the decomposition of tea processing residues. The resulting DSC curves for stalks and off-grade leaves are presented in Figure 4. DSC analysis provides complementary information to thermogravimetric analysis by identifying endothermic and exothermic processes occurring during thermal degradation of biomass materials (Kristanto *et al*., 2021).

The DSC profiles exhibited characteristic thermal events associated with the decomposition of lignocellulosic biomass. An initial endothermic peak observed below approximately 150 °C corresponds to the evaporation of residual moisture and the release of physically bound water within the biomass structure (El-Sayed *et al*., 2024). This behavior is consistent with the first stage of mass loss identified in the thermogravimetric analysis.

A pronounced exothermic peak between approximately 250 °C and 360 °C was associated with the thermal degradation of hemicellulose and cellulose components. These polysaccharides decompose through complex reactions involving depolymerization, volatilization, and the formation of combustible gases (Apaydın Varol & Mutlu, 2023; Zhang *et al.,* 2024) The intensity of this exothermic region reflects the release of chemical energy stored in the biomass matrix.

At higher temperatures, typically between 380 °C and 500 °C, a broader thermal event was observed, which can be attributed to the gradual decomposition of lignin and the oxidation of intermediate char structures (Babinszki *et al*., 2021; Volli *et al*., 2021). Lignin degradation occurs over a wider temperature range due to its highly aromatic and cross-linked molecular structure.

Although both residue fractions exhibited similar DSC patterns, slight differences in peak intensity and thermal response were observed. Off-grade leaves showed somewhat stronger exothermic signals, which may be related to their higher volatile matter content as determined in the proximate analysis. This suggests a more intense release of energy during devolatilization and decomposition of hemicellulose and cellulose. In contrast, stalk samples exhibited slightly broader peaks, suggesting a slower and more progressive thermal response, probably associated with a greater contribution from lignin-rich structural components and fixed carbon. Although quantitative enthalpy changes were not calculated in this study, the DSC profiles provide useful comparative information on the relative energy release behavior of both residue fractions. Future work should include DSC peak integration to determine enthalpy changes more rigorously.

Overall, the DSC results confirm that tea processing residues undergo thermal transformations typical of lignocellulosic biomass materials (Alashmawy *et al.,* 2023). The observed exothermic reactions indicate that these residues possess favorable thermal characteristics for energy recovery through thermochemical processes such as combustion and pyrolysis.

3.6 Implications for Renewable Energy Utilization

The thermochemical characterization results obtained in this study indicate that tea processing residues possess properties consistent with those of conventional lignocellulosic biomass fuels. The proximate analysis revealed high volatile matter contents exceeding 70%, moderate ash concentrations, and fixed carbon levels typical of plant-derived biomass materials. These characteristics are favorable for thermochemical conversion processes such as combustion, gasification, and pyrolysis (Y. Wang & Wu, 2023).

The ultimate analysis further demonstrated carbon contents approaching 47–48% and low sulfur concentrations, which are desirable attributes for biomass fuels. High carbon fractions contribute to increased calorific values, while low sulfur content reduces the potential formation of sulfur oxides during

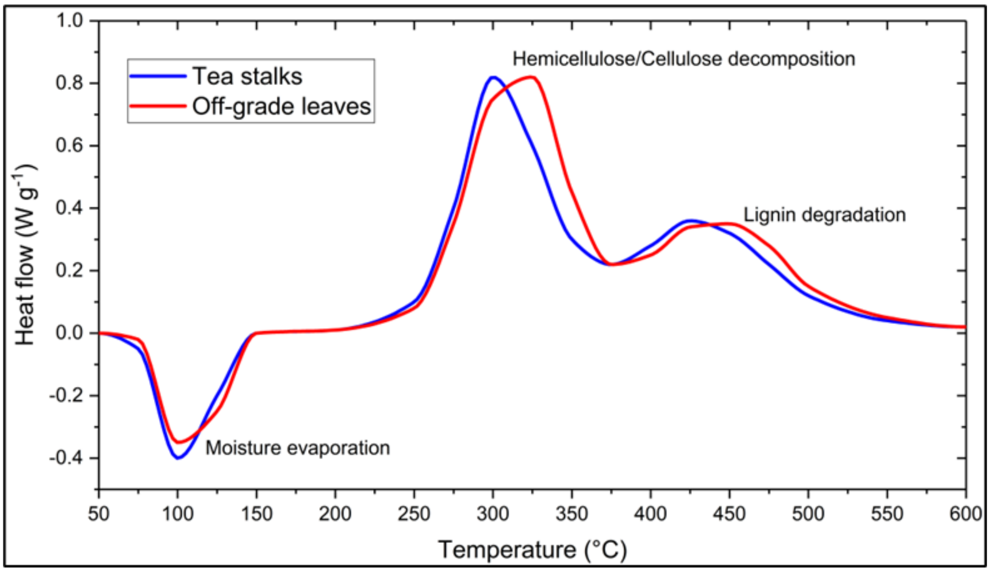

Fig 4. Differential scanning calorimetry (DSC) curves of tea processing residues (stalks and off-grade leaves) obtained at a heating rate of 10 °C·min⁻¹. The curves show thermal events associated with moisture evaporation, hemicellulose and cellulose decomposition, and lignin degradation.

combustion, thereby minimizing environmental impacts associated with flue gas emissions (Kosowska-Golachowska *et al.*, 2022; Proto *et al.*, 2021).

Calorific value measurements confirmed that tea residues exhibit energy densities comparable to other widely used agricultural biomass fuels. The measured higher heating values ranged from approximately 17.9 to 18.7 MJ·kg^{-1}, while net calorific values ranged from 16.6 to 17.3 MJ·kg^{-1}. These values are similar to those reported for coffee husks, corn stover, and sugarcane bagasse, which are commonly utilized in decentralized biomass energy systems (Mendoza Martinez et al., 2021; Shah et al., 2023).

Thermal analysis results obtained through thermogravimetric and calorimetric techniques further confirmed the suitability of tea residues for thermochemical energy conversion. The TGA and DSC profiles exhibited the characteristic decomposition behavior of lignocellulosic biomass, including sequential degradation of hemicellulose, cellulose, and lignin components. The presence of well-defined exothermic reactions during thermal degradation indicates that these materials possess favorable combustion characteristics and stable energy release profiles (Güleç *et al.*, 2024).

Although combustion, pyrolysis, and gasification are all technically possible pathways for tea processing residues, their practical suitability differs according to process complexity and energy objective. Based on the NCV values, high volatile matter content, and moderate ash levels obtained in this study, controlled combustion appears to be the most immediate option for decentralized heat generation in tea processing facilities. Gasification could provide greater flexibility through producer gas generation, but it would require stricter control of temperature, air supply, and tar formation. Pyrolysis may be attractive when biochar or liquid products are targeted, although its feasibility depends on product recovery and market demand. Therefore, controlled combustion is likely the most practical initial route for energy recovery from these residues, while gasification and pyrolysis should be further evaluated through pilot scale studies.

The measured NCV values of tea stalks and off-grade leaves fall within the range commonly reported for lignocellulosic solid biofuels and suggest preliminary suitability for thermal applications. However, formal classification according to ISO 17225 was not performed because this standard requires additional fuel quality parameters, including particle size, bulk density, mechanical durability, ash composition, chlorine content, and moisture specifications depending on the fuel category. Therefore, the present results should be interpreted as an initial fuel quality assessment rather than a formal solid biofuel classification.

To provide a first order estimate of the practical energy potential of tea processing residues, a theoretical recovery calculation was performed using the average NCV obtained in this study, 16.95 MJ·kg^{-1}, derived from stalks and off grade leaves. Assuming a conservative residue generation factor of 3% of made tea during sorting and grading, Indonesian tea production of approximately 122,700 t year^{-1} would generate about 3,680 t year^{-1} of residues. This amount could provide approximately 62 TJ year^{-1} of theoretical thermal energy, equivalent to about 17 GWh year^{-1}. In terms of fossil fuel substitution, this energy corresponds to approximately 1.7 million L of diesel or 2,600 t of coal per year, before accounting for conversion losses. Assuming a typical biomass combustion efficiency of 70%, the useful thermal energy would be approximately 43 TJ year^{-1}, indicating potential for integration into decentralized heat generation systems for tea drying or process heat applications.

In addition to direct combustion, tea processing residues could also be considered for co-firing with coal or other agricultural residues in existing biomass combustion systems. Their NCV values and high volatile matter content suggest that they may contribute to ignition and thermal energy release when blended with more carbon-rich fuels. However, co-firing feasibility would depend on the blending ratio, ash composition, slagging and fouling behavior, chlorine and alkali content, and emission formation. Therefore, pilot-scale combustion tests are required before recommending industrial implementation.

A realistic decentralized energy scenario for tea factories would involve using dried stalks and off-grade leaves as a supplementary solid fuel for process heat generation. These residues could be combusted in controlled biomass furnaces or boilers to provide hot air for tea drying or steam for factory operations. Based on the useful thermal energy estimated in this study, tea residues would be more suitable as a complementary fuel rather than as the sole energy source. Their integration could reduce fossil fuel consumption and improve residue management, provided that combustion efficiency, ash behavior, feeding systems, and emission control are properly managed.

Considering the large quantities of residues generated during tea processing, the utilization of these materials as solid biofuels could contribute to improved resource efficiency and waste management in tea-producing regions. Integrating tea residues into local energy systems could reduce reliance on fossil fuels, provide renewable heat for processing operations, and support circular economy strategies within the tea sector (Duarah *et al.*, 2024; Z. Wang *et al.*, 2024). Such approaches may be particularly beneficial in rural areas where biomass resources are readily available and decentralized energy solutions are needed to enhance energy security and sustainability.

4. Conclusions

This study provided a comprehensive thermochemical characterization of residues from tea processing with particular emphasis on stalks and off-grade leaves generated during tea manufacture. Proximate and ultimate analysis revealed that these residues have physicochemical properties typical for lignocellulosic biomass, such as high volatile matter content, moderate fixed carbon content and carbon concentrations indicating potential energy applications.

The calorific value measurements showed that the residues examined have higher heating values in the range of about 17.9–18.7 MJ·kg^{-1} and net calorific values between 16.6 and 17.3 MJ·kg^{-1}, indicating that they are energy dense like other agricultural biomass fuels. The results indicate promising characteristics of tea processing residues as potential solid biofuels, but further validation is required before any practical implementation can be proposed.

Thermogravimetric and calorimetric analysis showed thermal degradation behavior characteristic of lignocellulosic biomass materials. The decomposition stages observed were related to the elimination of moisture, degradation of hemicellulose and cellulose and decomposition of lignin. The results indicate that the residues could be used in thermochemical conversion processes such as controlled combustion, pyrolysis or gasification, depending on the technology and operating conditions.

This study was limited to lab scale characterization of stalks and off-grade leaves from one particular tea processing facility. Therefore, the results represent a preliminary evaluation of the potential of fuels and not a comprehensive industrial validation. Overall, the results show that tea processing residues are an unexploited biomass resource with a preliminary potential for renewable energy production. Valorization of these wastes may help improve waste management, energy efficiency and circular economy strategies in tea-producing regions. However, practical application will depend on operational factors not considered in this study, such as bulk density, particle size distribution, storage behavior, moisture reabsorption, biological stability, densification performance, ash behavior, emissions, and combustion performance under real operating conditions.

Therefore, future research should focus on pilot scale validation, controlled combustion tests, storage stability, densified behavior, pretreatment technologies and techno-economic feasibility of incorporating tea residues into decentralized bioenergy systems. Torrefaction, briquetting, pelletization or hydrothermal carbonization are also possible strategies to improve the fuel quality, handling, storage stability and energy density.

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