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RESEARCH ARTICLE

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Combustion performance and emission characteristics of agricultural residue pellets as alternatives to wood pellets

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ABSTRACT

The increasing demand for sustainable heating has increased interest in biomass pellets from agricultural residues. This study examines the combustion performance, emissions, and thermal degradation of various agricultural residue pellets compared to wood pellets. Combustion tests in a pellet stove revealed that woody residues, such as pine needle and olive pruning pellets, had higher efficiency, lower CO and NO_x emissions, and more stable combustion than herbaceous residues such as grass and pepper stalk pellets. Olive pruning pellets reached the highest flue gas temperature (274 °C), while pepper stalk pellets recorded the lowest temperature (154 °C). CO emissions from herbaceous pellets (up to 6,318 mg Nm^{-3}) were significantly higher than wood pellets (576 mg Nm^{-3}). NO_x emissions correlated with nitrogen content, peaking at 904 mg Nm^{-3} for grass pellets. Some agricultural pellets, such as pomegranate pruning pellets (15.13 GJ m^{-3}), had energy densities surpassing wood pellets (13.60 GJ m^{-3}). However, optimizing stove design is necessary for efficient agricultural pellet combustion.

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Alternative energy; biomass; burning; flue gas emission

Introduction

The utilization of wood pellets for residential and industrial heating has gained prominence in recent years, with forest product residues being recognized as a primary source for their production (Kamperidou 2022). Wood pellets are known for their low ash content and high calorific value, as well as the advantage of an already established feedstock supply management system (Vuong et al. 2023). Their standardized fuel quality and optimized pelletization parameters contribute significantly to the sustainability of the pellet industry. Moreover, wood pellets are the most extensively used biomass fuel because they offer high energy density, consistent quality, and comparatively low emissions when combusted in modern pellet stoves (Dula, Kraszkiewicz, and Parafiniuk 2024; Picchio et al. 2023). Pellet stoves are heating appliances designed to automatically feed pellets from the storage hopper into the combustion chamber. The widespread adoption of residential pellet stoves has further accelerated wood pellet consumption in both urban and rural regions (Priestley et al. 2023). Although this represents a favorable trend, the need to meet current and anticipated demand places considerable pressure on the forest products sector (Visser et al. 2022). To address this challenge, the utilization of sustainably sourced agricultural residues, supported by established collection and supply management systems, has been suggested by researchers as a promising alternative feedstock for pellet production. For instance, cacao pod husk (Meza-Sepúlveda et al. 2021), corn straw and cashew nut shell (Moreira et al. 2023), as well as agroforestry pruning residues, such as grapevine, citrus, olive, and kiwi, have been reported as sustainable feedstocks for pellet production (Papandrea et al. 2024). Moreover, expanding regional agropellet production may reduce supply-chain costs (Ebadian et al. 2021).

Economically viable agropellet production requires optimized logistics, including collection and processing. It also requires suitable pellet quality and combustion performance to meet user expectations. In particular, the use of regionally available agricultural residues as pellet feedstock provides a dual solution

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for waste management and renewable fuel production (Ribeiro and Braghini 2023). Where sustainable, residue management is implemented (Golub et al. 2025), pellets produced from agricultural residues (Palma et al. 2023) and secondary biomass sources (Rashedi et al. 2022) have been proposed as viable alternatives to wood pellets.

In pellet stoves, stable combustion depends on controlled feeding and waiting cycles (Da Lio, Bortolus, and Canu 2025). It also requires properly adjusted primary and secondary airflows matched to the stove capacity and combustion chamber design (Champion et al. 2025). These operational parameters ensure an optimal air–fuel ratio (Da Lio, Bortolus, and Canu 2025), maintaining flame stability (Deng et al. 2020) and minimizing incomplete combustion (Sungur, Basar, and Kaleli 2023). Additionally, ash discharge systems and collection chambers are specifically engineered for wood pellets, which typically exhibit low ash contents in the range of 0.5–1%. This design consideration enables efficient ash removal and reduces the risk of slagging formation or airflow obstruction during long-term operation. Consequently, most manufacturers recommend the use of only high-grade wood pellets. They discourage alternative fuels, such as agricultural residues, because these fuels may reduce combustion efficiency, worsen emissions, and damage the appliance. In relation to this limitation, Table S3 presents a comprehensive compilation of manufacturers' documents that explicitly warn users to operate pellet stoves exclusively with wood pellets. These documents emphasize that alternative feedstocks, such as agricultural residues or nonstandard biomass pellets, should not be combusted because of their potential to impair combustion stability, increase emissions, and cause mechanical or operational failures in the stove system. In addition, several manufacturing standards and institutional reports emphasize that commercially marketed pellet stoves are operationally optimized for woody pellets. They also state that performance testing and certification procedures should be conducted exclusively using wood pellets (Caubel et al. 2023; Reichert and Schmidl 2022). Nevertheless, agricultural residues are increasingly being pelletized because they are abundant and locally available. As a result, users are becoming more interested in burning regionally produced agropellets in existing combustion systems (Liu et al. 2023).

The growing availability of agropellets and the increasing tendency to use them in pellet stoves have attracted research interest in their combustion characteristics. Most studies have examined these characteristics under stable combustion regimes using laboratory-scale systems, such as tube furnaces (Zhai et al. 2022), single-pellet combustion setups (Hedayati et al. 2021), fluidized beds (Guo et al. 2024), fixed-bed reactors (Cheng et al. 2024), and electric furnace reactors (Moreira et al. 2023). In addition, pellet stove experiments were typically performed under conditions where agropellets can burn without operational issues. Previous studies showed that stable and efficient combustion can be achieved through fuel-specific adjustments. Lustenberger et al. (2022) modified the feeding and pause periods, Álvarez-Murillo et al. (2024) optimized the air-supply intensity and cycling, and Matijašević et al. (2025) adjusted the stove power settings through the electronic control panel.

However, agropellets differ considerably from wood pellets in key fuel properties, such as ash and nitrogen content, as well as in combustion behavior. Their performance under the default operating conditions of wood pellet stoves has not been sufficiently quantified. Previous studies have mainly examined agropellet combustion in laboratory systems or under fuel-specific optimized conditions. Therefore, this study evaluates the combustion performance, emission behavior, and thermogravimetric characteristics of a broad range of agropellets and secondary biomass pellets in a residential pellet stove operated under unmodified conditions originally optimized for wood pellets. To reinforce the experimental findings, thermogravimetric analysis (TGA) was employed to derive characteristic combustion indices and thermal reactivity parameters. This approach linked the thermal degradation behavior of the fuels to their actual combustion performance.

Materials and methods

Feedstock collection and preparation for pelletization

The wood pellets used in the experiments were purchased from a local pellet factory (Natura Pellet, Antalya). The company utilizes sawdust from yellow pine obtained from regional pine plantations as

its primary raw material. The raw materials for the agropellets were selected based on sustainable agricultural activities across Türkiye and the regional availability of biomass residues. Hazelnut husks were collected from a processing facility in Samsun, located in the Black Sea region, which is one of the main centers of hazelnut cultivation (Tufan and Ayrılmış 2016). Grass mowing residues were collected from regularly maintained lawns on the Akdeniz University campus in Antalya, representing typical urban landscape waste (Yılmaz et al. 2023). Pepper and eggplant stems were collected at the end of the cultivation season from greenhouse farms in Antalya, where greenhouse cultivation is extensively practiced (Bilgin, Yılmaz, and Koçer 2015). Vineyard, pomegranate, and olive prunings were collected during routine orchard management practices in Antalya, which is a key center of fruit production in the Mediterranean region of Türkiye (Yılmaz et al. 2019). The pine needles were collected from the forest floor of pine stands located within the university campus and botanical garden. Olive cake, a solid byproduct of olive oil extraction, was collected from a local processing facility in Antalya. The sustainable availability of these residues, along with the presence of established collection systems, has confirmed their potential to be further evaluated as pellet feedstocks by other researchers (Collado et al. 2025; Paris et al. 2024).

The process flow for preparing agricultural residues for pelletization was presented in Figure 1.

As described in Figure 1, collected residues were classified into three groups: herbaceous, woody, and fine-particulate materials. At the time of collection, the herbaceous residues had a moisture content of 80–85% (wb), woody prunings 55–60% (wb), and particulate materials (olive cake and pine needles) 15–20% (wb). Since pelletization requires ground material, chopping and milling processes were applied sequentially. Herbaceous residues, including hazelnut husks, grass mowing, pepper stalks, and eggplant stalks, were first size-reduced using a drum-type chopper (Batmaz Agricultural Machinery, Burdur, Türkiye). Woody pruning residues were shredded with a disc chipper (Soydanlar Machinery, Mersin, Türkiye). Before milling, the shredded residues were dried under sun for 3 days to reduce the moisture content to 6–8%. Due to their naturally small particle size at collection, pine needles and olive cakes were directly grounded with a hammer mill equipped with a 4 mm screen (Batmaz Agricultural Machinery, Burdur, Türkiye). Each dried and grounded raw material was pelletized under controlled conditions using an automatic pelletizing system with steam conditioning, at a moisture content of 13–15%.

Pellet ultimate and proximate analyses

The elemental contents of the pellets were determined using the Thermo Scientific Flash 2000 elemental analyzer. The moisture content (MC), ash content (AC), and volatile matter (VM) were determined according to the procedures outlined in ASTM D7582, ASTM D1102-84, and ASTM E872-82 methods, respectively (ASTM D1102-84, 2021; ASTM D7582, 2023; ASTM E872-82, 2019). The higher heating values (HHV) of the pellets were calculated using (1), which has been widely developed for agricultural residues (Ozyuguran, Akturk, and Yaman 2018).

$$HHV = -4.9140 + 0.2611\mathrm{N} + 0.4114\mathrm{C} + 0.6114\mathrm{H} + 0.3888\mathrm{S} + 0.02097\mathrm{O}. \quad (1)$$

Combustion experiments at pellet stove

A Smartpel model Kozlusan brand pellet stove (Manisa, Türkiye) with a power range of 3–11 kW and automatic feeding was used for the combustion of the pellets. The schematic diagram of the pellet stove, along with the experimental combustion setup, is presented in Figure 2.

The stove manufacturer's optimized feeding period for wood pellets was fixed in the digital interface. The manufacturer reported that the feeding capacity in case of continuous feeding is 1.5–2 kg h^{-1}. Preliminary tests have shown that the optimal cycle is 3 s feeding followed by 10 s of waiting. Based on this cycle, the feeding capacity of the wood pellets and agropellets used in the experiments was calculated as 1.45–2.27 kg h^{-1} under the recommended feeding interval. Method details for pellet feed calibration are included in the supplementary material (Figure S2). On the other hand, to ensure continuous combustion

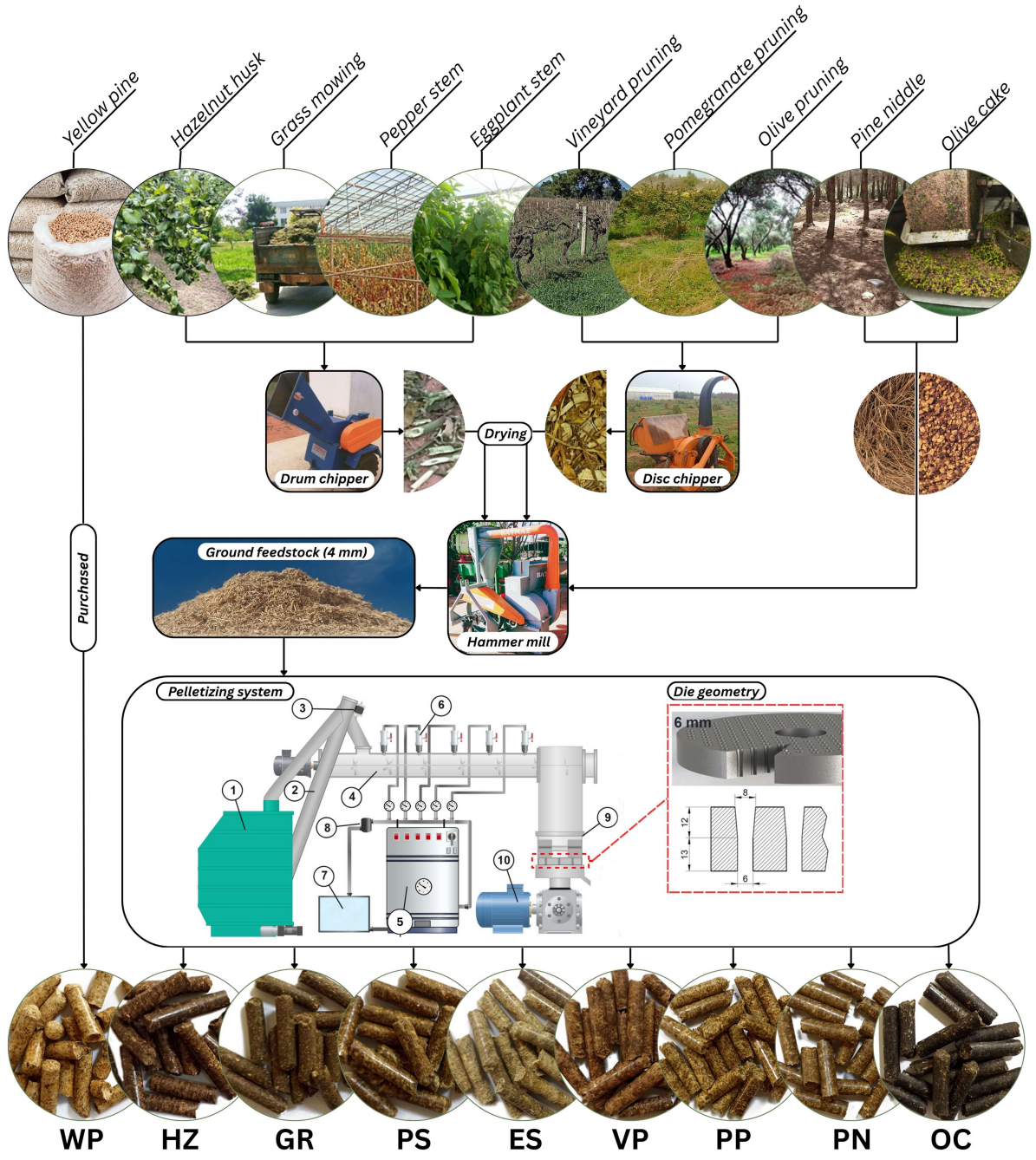


Figure 1. Feedstock sources and process flow for pellet production.

in the stable flame phase, an appropriate airflow must be provided. For this, an anemometer (Kestrel-4000, USA) was placed in the pellet combustion chamber, and the stove cover was closed. By increasing the scale values on the stove's digital panel, the airflow velocity at the relevant point was measured, and the air flow rate was calculated. The airflow value on the digital control panel of the pellet stove was set to 130 (109 m^3/h; 2.70 m/s) on the 0–255 scale (0–111 m^3/h; 0–3.08 m/s) (Figure S2).

After each combustion trial, the combustion chamber, air intake and exhaust channels, ash tray, and pellet storage were thoroughly cleaned using both pressurized and vacuumed air to ensure optimal performance and accuracy in subsequent trials. At the beginning of each trial, the pellet storage was filled, and approximately 20–30 g of pellets were poured into the combustion chamber to initiate ignition. Once a stable flame height was reached, the transition to the stable combustion period was made, and the periodic pellet feeding process was initiated.

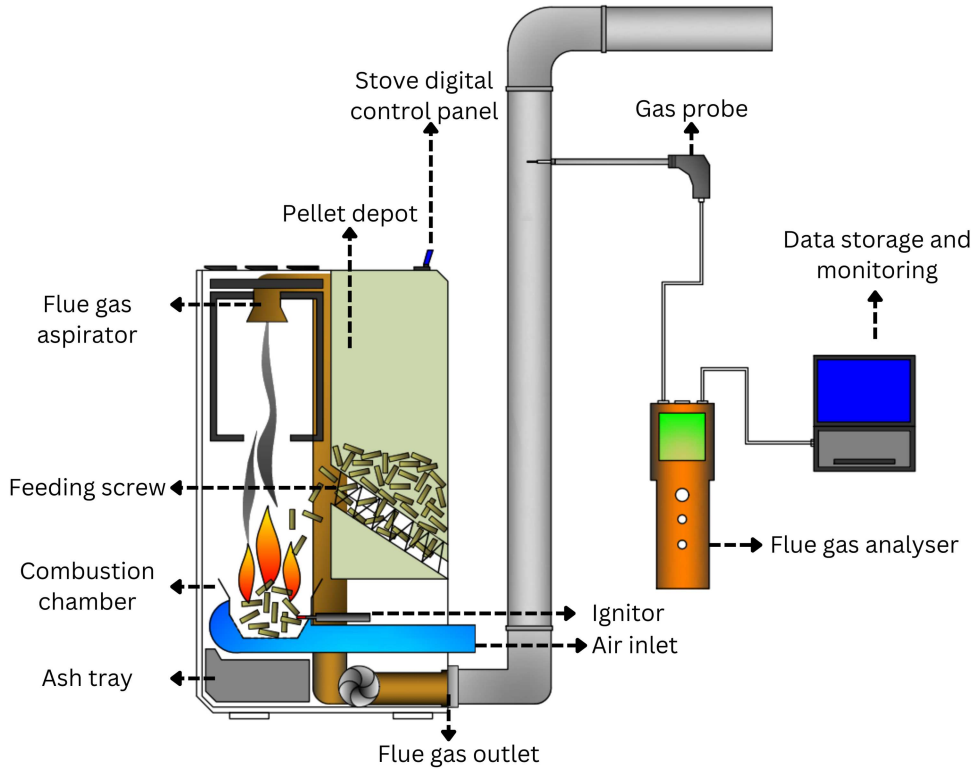


Figure 2. The schematic diagram of the pellet stove and the measurement system.

The emission probe was securely fixed to the aluminum alloy chimney by creating a precise hole, ensuring no external air intake. The flue gas emissions were measured using a Testo 340 (Germany) device, equipped with electrochemical measurement cells (Table S1). During the combustion process, the emissions of O_2 (%), CO_2 (%), NO_x (ppm), CO (ppm), and the flue gas temperature were measured. Emission measurements were initiated through a computer while the pellets were burning stably, and data were recorded at 1-s intervals for 120 s.

To enable a comparative evaluation of the NO_x and CO values under identical conditions, they were converted to mg Nm^{-3} values at 10% and 13% O_2 equivalents with Equation(2) (Hrdlička et al. 2016).

$$C_m^X = C_V^X \cdot [(M_X \cdot p_{ref})/(R \cdot T_{ref})] \cdot [(21 - O_{2ref})/(21 - O_{2meas})]. \quad (2)$$

In the equation, C_m^X: mass concentration of the component "X" (mg Nm^{-3}), C_m^X: volumetric concentration of the component "X" (ppm), M_X: molecular weight of the component "X" (g mol^{-1}), p_{ref}: reference (normal) pressure (kPa), R: universal gas constant (J $(mol\ K)^{-1}$), T_{ref}: reference (normal) temperature (K), O_{2ref}: oxygen reference concentration (% vol.), and O_{2meas}: measured oxygen concentration (% vol.).

The excess air ratio (λ) was calculated using Equation(3), considering the O_2 emissions measured in the flue gas.

$$\lambda = 21/(21 - O_{2meas}). \quad (3)$$

During combustion, the TI (toxicity index) value was calculated based on the CO (%) and CO_2 (%) emissions detected in the flue gas using Equation (4) (Dula, Kraszkiewicz, and Parafiniuk 2024).

$$TI = (CO/CO_2) \times 100. \quad (4)$$

In evaluating combustion efficiency, the modified combustion efficiency (MCE) Eq. (5) was utilized (Shrestha et al. 2021).

$$MCE = CO_2(ppm)/(CO_2(ppm) + CO(ppm)). \quad (5)$$

Combustion characteristics via TGA analysis

The TGA analysis was conducted under atmospheric air conditions, with a controlled heating rate of 30 °C min^{-1}. The combustion process was performed with a heating rate of 30 °C min^{-1} and under temperature conditions ranging from room temperature to 1,000 °C using the HITACHI STA 3700 thermal analyzer (Japan). Based on the TG and DTG curves obtained from the analysis, the following critical points were determined DTG_{max}: maximum weight loss rate (% min^{-1}), T_{in}: initial combustion temperature (°C), T_{ig}: ignition temperature, T_{brn}: burnout temperature (°C) and T_{max}: temperature at maximum combustion rate (°C), t_{max}: time at maximum combustion rate (min), and t_{ig}: time at ignition temperature (min). The combustion characterization of the pellets was evaluated by calculating the comprehensive combustion characteristic index (S_n), ignition index (D_i, % min^{-3}), and reactivity index (R_f) according to Equations 6–8 (Aniza et al. 2024; Fraga et al. 2020).

$$S_n = \frac{DTG_{max} \times DTG_{avg}}{T_{ig}^2 \times T_{brn}}, \tag{6}$$

$$D_i = (dm/dt)_{max}\, t_{max} \times t_{ig}, \tag{7}$$

$$R_f = (dm/dt)_{max}\, T_{max} \times 100. \tag{8}$$

Statistical analysis

All the statistical analyses were performed using OriginLab 2025b (OriginLab Corp., USA). Prior to correlation analyses, the normality of the datasets was assessed using the Shapiro–Wilk test at a 5% significance level. All variables exhibited p values greater than 0.05, indicating that the null hypothesis of normal distribution could not be rejected (Supplementary Material). Accordingly, Pearson's correlation analysis was applied to examine the relationships among the TGA-derived indices, combustion performance parameters, fuel parameters, and emission indicators.

For smaller datasets where the sample size ($n = 10$ and $n = 19$) limited statistical power, correlations were interpreted as indicative rather than absolute trends, emphasizing physical consistency rather than inferential generalization. Only statistically significant correlations with $|r| \geq 0.70$ were considered meaningful and further discussed in the context of thermal decomposition behavior and emission performance.

Results and discussion

Pellet fuel characterization

The ultimate and proximate analysis values of the pellets are provided in Table 1. Since all the pellets were produced under identical conditions, their moisture contents were about 7–8%. Herbaceous pellets exhibit

Table 1. Elemental composition, proximate analysis, and key fuel properties of the pellets.

Pellet	MC (%)	AC (%, db)	VM (%, db)	FC (%, db)	C (%)	H (%)	N (%)	S (%)	O (%)	HHV (MJ kg^{-1})	BD (kg m^{-3})	ED (GJ m^{-3})
WP	6.48	1.11	84.85	14.04	49.23	5.96	0.21	0.00	43.49	19.95	681.86	13.60
HZ	8.47	11.76	68.44	19.79	41.45	5.34	0.55	0.08	40.82	16.43	724.33	11.90
GR	8.02	13.72	74.46	11.82	43.38	5.40	2.53	0.16	36.93	17.69	617.33	10.92
PS	7.12	14.60	68.08	17.32	41.25	4.87	1.83	0.42	35.80	16.45	615.21	10.12
ES	8.14	8.36	73.73	17.91	40.08	4.98	2.01	0.00	24.73	16.08	696.53	11.20
VP	6.65	4.60	76.69	18.71	49.89	5.92	0.78	0.09	38.72	20.28	693.89	14.07
PN	8.15	7.75	70.18	22.07	47.12	5.99	0.39	0.00	38.75	19.05	669.56	12.75
PP	6.41	2.48	77.25	20.27	48.31	5.70	0.87	0.10	42.54	19.60	771.70	15.13
OC	6.55	9.34	80.11	10.55	50.58	6.26	1.01	0.06	32.75	20.70	540.36	11.18
OP	6.84	3.39	78.28	18.33	49.99	5.72	0.55	0.10	40.25	20.18	628.12	12.67

a relatively high ash content, whereas woody pellets have a significantly lower ash content and among all tested samples, the lowest ash content was observed in wood pellets, with a value of 1.11%.

The HHV of the pellets mostly range between 19 and 20 MJ kg^{-1}, with hazelnut husk, pepper stalk, and eggplant stalk exhibiting lower calorific values of approximately 16 MJ kg^{-1}. Individually, the calorific values of pellets vary depending on the ash content and elemental composition, whereas in bulk form, the energy densities of the pellets are related to their bulk density. In this context, the highest energy density was obtained from pomegranate pruning residues (15.13 GJ m^{-3}), while the lowest energy density was found in pepper stalk pellets (10.12 GJ m^{-3}). Agricultural residue pellets show notably high nitrogen and sulfur contents. The highest nitrogen content was found in grass pellets (2.53%), while the lowest nitrogen content in agricultural residues was observed in hazelnut husk and olive pruning (0.55%) pellets. On the other hand, the highest sulfur content was found in pepper stalk (0.42%), while no sulfur content was detected in pine needle, eggplant stalk, and wood pellets. Since biomass containing sulfur can lead to harmful SO_2 emissions during combustion, raw materials with high sulfur content are generally avoided (Bianchini et al. 2021). On the other hand, the nitrogen content in biomass is directly related to the emission of NO_x (Dula, Kraszkiewicz, and Parafiniuk 2024). In this regard, it can be stated that the primary factors limiting the use of agricultural residues as biomass pellets are their sulfur (S) and nitrogen (N) content.

Combustion experiments at residential pellet stove

The combustion performance values recorded while the pellets were burning in a stable regime, along with the calculated averages, were presented in Table 2.

The highest flue gas temperature was recorded at 274 ± 6 °C for OP and 268 ± 3 °C for PN, indicating that these pellets achieved high combustion temperatures and provided more efficient combustion. In contrast, PS showed the lowest flue gas temperature at 154 ± 16 °C. This result is consistent with its low volatile matter content (68.08%), low HHV (16.45 MJ kg^{-1}), and high ash content (14.60%). The moisture and ash content of biomass are among the primary factors influencing flue gas temperature (Dula, Kraszkiewicz, and Parafiniuk 2024; Palma et al. 2023). Since the pellets in this study have a narrow moisture content range (6–8%), their ash content varying between 1.11% and 14.60% suggests that the primary factors influencing flue gas temperature differences are ash content and calorific value. Flue gas temperature can be considered an indicator of combustion efficiency (Shen et al. 2015). Thus, it is observed that wood pellets and woody agricultural residues exhibit high combustion efficiency due to their favorable fuel properties, while herbaceous agricultural residues characterized by higher ash content and lower energy density, tend to demonstrate lower combustion efficiency.

Oxygen emissions during combustion are a direct indicator of combustion efficiency. High levels of unreacted oxygen in the flue gas often indicate incomplete combustion, which can lead to increased emissions of harmful pollutants, such as CO and unburned hydrocarbons (Mack et al. 2024; Polonini, Petrocelli, and Lezzi 2023). Conversely, low oxygen emissions suggest more complete combustion, which is desirable for both efficiency and environmental performance. During the combustion process, O_2 emissions were measured within a range of 13.29% for the PN pellets to 17.76% for the PS pellets. Under similar conditions, the amount of oxygen reacting with the fuel depends on the air–fuel mixture. This mixture is

Table 2. The average emission values and combustion parameters recorded during the combustion tests.

Pellet	Flue gas temp. (°C)	O_2 (%)	Excess air ratio (%)	%10 O_2		%13 O_2		Toxicity index
				CO (mg Nm^{-3})	NO_x (mg Nm^{-3})	CO (mg Nm^{-3})	NO_x (mg Nm^{-3})	
WP	245 ± 0.18	14.73 ± 0.05	3.37 ± 0.03	576 ± 13.99	165 ± 0.80	1102 ± 26.70	314 ± 1.52	0.48
HZ	195 ± 0.43	16.94 ± 0.02	5.19 ± 0.02	5373 ± 49.67	778 ± 3.25	10245 ± 95.00	1486 ± 6.20	4.71
GR	235 ± 0.47	14.30 ± 0.04	3.15 ± 0.02	2821 ± 52.79	904 ± 5.20	5381 ± 100.79	1725 ± 9.94	2.41
PS	154 ± 1.94	17.76 ± 0.10	5.97 ± 0.10	6318 ± 217.77	882 ± 24.87	10690 ± 415.74	1509 ± 47.48	5.85
ES	214 ± 0.62	16.50 ± 0.15	6.41 ± 0.44	5351 ± 294.24	1066 ± 52.62	10058 ± 561.73	2026 ± 100.45	4.37
VP	255 ± 0.30	15.57 ± 0.04	3.90 ± 0.03	3479 ± 116.62	668 ± 3.39	6681 ± 222.64	1274 ± 6.47	3.00
PN	268 ± 0.31	13.29 ± 0.04	2.73 ± 0.01	289 ± 2.06	485 ± 1.30	552 ± 3.94	925 ± 2.48	0.25
PP	218 ± 0.35	15.00 ± 0.07	3.55 ± 0.04	3369 ± 137.27	610 ± 3.21	6470 ± 262.06	1164 ± 6.13	2.78
OC	236 ± 0.45	16.07 ± 0.02	4.27 ± 0.02	4416 ± 81.66	543 ± 1.45	8436 ± 155.89	1036 ± 2.77	3.87
OP	274 ± 0.58	13.93 ± 0.10	3.03 ± 0.04	2881 ± 79.59	426 ± 1.77	5502 ± 151.94	813 ± 3.39	2.41

influenced by ash content, volatile matter, and pellet geometry (Moya et al. 2015; Tanaka et al. 2012). During the combustion process, our observations in the combustion chamber reveal that the pellets falling from the feeding auger have a significant impact on the air circulation and flame stability. In this context, O_2 emissions tend to rise during the initial combustion phase of the falling pellets but gradually decrease once combustion becomes fully established. In well-optimized combustion systems, the oxygen levels are generally lower, signifying more efficient and complete combustion. Maintaining stable airflow and optimizing pellet feeding can further increase the combustion efficiency and reduce excess oxygen emissions. However, in combustion processes where the fuel type, combustion chamber, and operating conditions do not match, oxygen emissions tend to be significantly high (Dula, Kraszkiewicz, and Parafiniuk 2024; Sippula et al. 2017).

According to the Ecodesign Directive (EU 2015/1185), the emission thresholds for residential pellet stoves are $CO \leq 500\ mg\ Nm^{-3}$ and $NO_x \leq 200\ mg\ Nm^{-3}$, both normalized to 10% O_2 (European Parliament and of the Council, 2015; Obidziński et al. 2025). The results in Table 2 show that wood pellets and pine pellets (WP, PN) clearly satisfy these limits, with CO and NO_x emissions well below the threshold values, confirming efficient oxidation and stable combustion under the tested conditions. In contrast, agropellets significantly exceed the Ecodesign limits for both CO and NO_x. Their CO emissions range from roughly 2800 to 6300 $mg\ Nm^{-3}$, and NO_x emissions from 900 to 2000 $mg\ Nm^{-3}$, indicating incomplete oxidation and enhanced thermal-NO formation. These deviations are mainly attributed to higher ash and mineral contents, which alter devolatilization kinetics and hinder complete char burnout.

The excess air ratio directly affects the combustion efficiency of pellet stoves (Kaleli, Sungur, and Basar 2023). An optimal excess air ratio typically ranges from 1.1 to 1.5, meaning that 10% to 50% more air is supplied than is theoretically required for complete combustion (Venturini et al. 2015; Wang et al. 2017). The excess air ratio values measured during the experiment ranged from 2.73 (PN) to 6.41 (ES). A lower excess air ratio indicates more efficient combustion and better fuel oxidation, whereas a very high excess air ratio can lead to increased heat losses in the combustion chamber, ultimately reducing overall efficiency. The high excess air ratio observed for the ES pellet suggests that the surplus air during combustion may hinder the complete oxidation of the fuel. In contrast, WP and PN pellets demonstrated more efficient combustion performance because of their lower excess air ratios. Additionally, significant correlations were identified between the excess air ratio and other key combustion parameters, highlighting its crucial role in optimizing combustion efficiency (Figure 3). The corresponding descriptive statistical table and full correlation matrix related to this correlation analysis were provided in Table S4 and Table S5, respectively.

According to Figure 3, a strong positive correlation was found between the excess air ratio and the toxicity index. The excess air ratio is directly related to O_2 emissions and is proportional to O_2 emissions Equation (3). Therefore, in an inefficient combustion process, an increase in O_2 levels will increase the toxicity index. Similarly, a high-level (−0.92) negative correlation was found between CO_2 emissions and the excess air ratio. On the other hand, significant increases in CO emissions were observed with an increase in the excess air ratio. Therefore, to minimize CO emissions, it is essential to keep the excess air ratio and consequently O_2 emissions as low as possible (Yildizay and Esiyok 2021). Modified combustion efficiency (MCE) is a key indicator of how effectively a pellet stove converts the energy content of the fuel into heat. Higher MCE values signify better energy utilization, which is essential for cost-effective heating solutions (Dula, Kraszkiewicz, and Parafiniuk 2024). When examining the MCE data, a strong (−0.85) negative relationship with the excess air ratio is observed. As a result, it can be concluded that a lower excess air ratio is a critical parameter that will increase combustion efficiency.

NO_x emissions during biomass combustion are primarily influenced by the nitrogen content of the fuel, with higher *N* levels typically resulting in increased fuel NO_x formation (Fachinger et al. 2017; Polonini, Petrocelli, and Lezzi 2023). In this study, WP had the lowest nitrogen content (0.21%), while GR exhibited the highest (2.53%). A strong (0.82) positive correlation was found between the nitrogen content of the pellets and NO_x emissions (Figure 3), confirming that *N*-rich agricultural residues produce significantly higher NO_x levels. Among the tested fuels, woody pellets such as PN, OP, and PP resulted in lower NO_x emissions, whereas herbaceous pellets such as PS, ES, and GR produced considerably higher values. This aligns with previous findings, highlighting a key limitation of agricultural residues in biomass combustion: their tendency to emit elevated NO_x due to intrinsic nitrogen levels (Schmidt et al. 2018). As such,

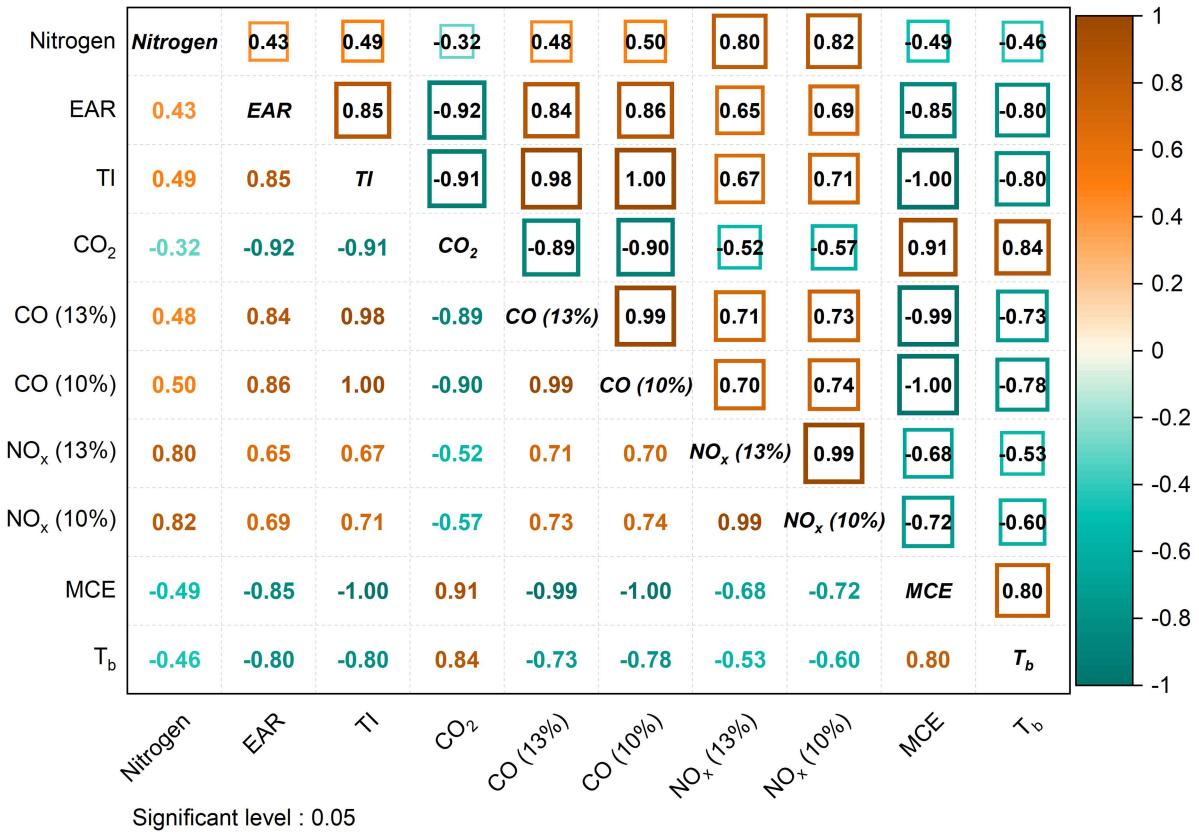


Figure 3. Spearman correlation matrix among nitrogen content, excess air ratio, and key combustion/emission parameters (EAR = excess air ratio, TI = toxicity index, MCE = modified combustion efficiency, T_b = flue gas temperature).

Table 3. The TGA combustion behavior parameters of the pellets.

Combustion parameter	WP	HZ	GR	PS	ES	VP	PN	PP	OC	PP
WL_1 (%)	6.01	8.54	8.94	6.36	7.63	7.13	8.78	6.67	6.92	7.01
WL_2 (%)	93.48	79.24	80.68	80.59	84.85	88.17	85.79	90.65	91.09	90.99
m_R (%)	0.51	12.22	10.38	13.05	7.52	4.70	5.43	2.68	1.99	2.00
T_{in} (°C)	157	177	194	155	167	156	167	161	158	166
T_{ig} (°C)	295	259	249	257	252	262	267	272	262	263
T_{brn} (°C)	401	413	439	401	411	428	478	429	395	407
T_{max} (°C)	362	304	305	302	308	319	335	340	296	295
t_{ig} (min)	10.7	9.07	8.78	9.04	8.90	9.13	9.30	9.44	9.16	9.18
t_{tmax} (min)	11.92	10.21	10.24	10.16	10.33	10.61	11.03	11.20	10.00	10.01
DTG_{avg} (% min^{-1})	9.04	7.67	7.59	7.29	7.75	8.62	8.24	8.01	8.81	8.94
DTG_{max} (% min^{-1})	37.63	20.37	18.57	35.81	29.46	25.08	22.70	28.92	27.32	27.31
S_n (%^{2} min^2 C^2 10^{-6})	9.70	5.64	5.17	9.85	8.74	7.35	5.49	8.21	8.88	8.68
D_i (% min^{-3})	0.31	0.22	0.21	0.39	0.32	0.26	0.22	0.27	0.30	0.30
R_f (% min^{-1} °C)	13.85	9.80	9.39	14.00	12.29	10.95	10.17	11.78	11.71	11.71

WL_1= weight loss at 1st stage, WL_2= weight loss at 2nd stage, m_R= residual mass, T_{in}= initial decomposition temperature, T_{ig}= ignition temperature, T_{brn}= burnout temperature, T_{max} = temperature at maximum combustion rate, t_{ig}= time at ignition temperature, t_{tmax}= time at maximum combustion rate, DTG_{avg}= average weight loss rate, DTG_{max} = maximum weight loss rate, S_n= comprehensive combustion characteristic index, D_i =ignition index, R_f= reactivity index.

agricultural residue pellets despite their sustainability pose a challenge in meeting strict emission standards unless further refined or blended with low-*N* fuels.

TGA combustion analyses of pellets

The thermal degradation behavior parameters of the pellets in the atmospheric environment and combustion performance parameters are presented in Table 3. Additionally, the TGA curves of the pellets are shown in Figure 4, and a detailed evaluation of the TGA curves can be found in the supplementary file.

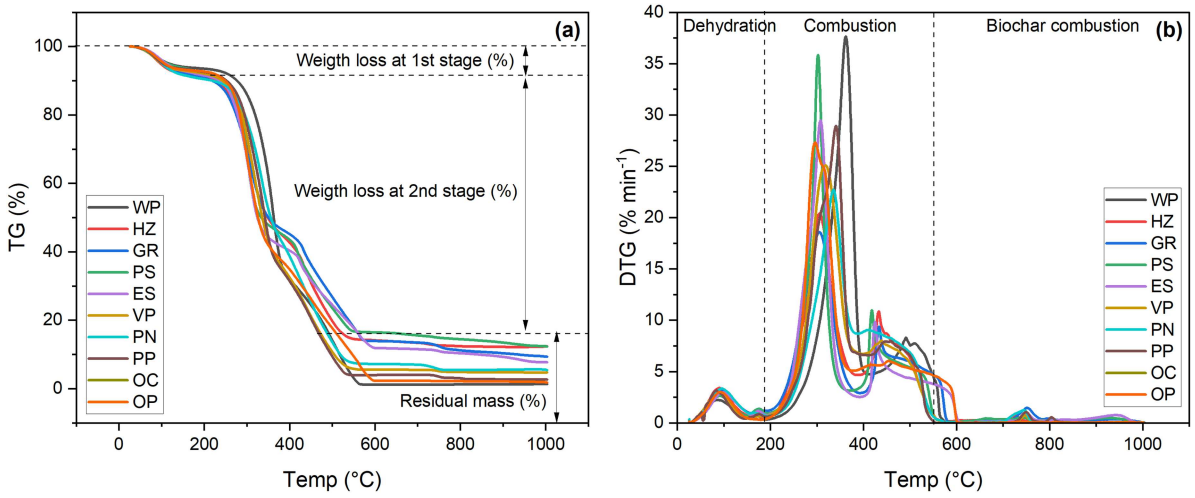


Figure 4. Mass loss (a) and thermal decomposition curves (b) obtained from the pellets in the TGA analysis.

The moisture content and initial mass losses (WL_1) of the pellets are within the range of 6.01–8.94%, with the highest mass loss occurring in the combustion zone (WL_2). The mass loss in the combustion zone is parallel to the amount of volatile matter. WP pellets, which have the highest volatile matter content (84.85%), exhibited the greatest mass loss in this zone. On the other hand, the high ash content and low volatile matter in GRS pellets resulted in relatively low mass loss.

The residual mass (m_R) is primarily composed of ash, which is the inorganic residue left after the complete combustion of organic materials. The m_R content is consistent with the ash content of the pellets. In this study, WP exhibited the lowest residual mass, whereas PS, HZ, and GR stood out with notably higher residual mass and ash content, indicating a greater presence of inorganic components in these biomass types. The finding of this study align with previously reported data, and Moreira et al. (2023) indicated that the combustion of biomass with high volatile content tends to produce less residual mass, as more of the material is converted into gaseous products during combustion. Furthermore, the atmospheric conditions during combustion can influence the residual mass. Wang et al. (2017) emphasized that an optimal air-to-fuel ratio is crucial for achieving high combustion efficiency and minimizing unburned residues. This residual mass is critical for understanding the environmental impact of biomass combustion, as higher ash content can lead to increased emissions of particulate matter and other pollutants (Vicente et al. 2020).

In TGA analysis, the ignition temperature can be influenced by various factors, such as the composition of biomass, its moisture content, and the presence of volatile matter. Moreira et al. (2023) noted that there is a direct relationship between the percentage of volatile matter in biomass pellets and their ignition temperature; higher volatile content typically results in lower ignition temperatures. Contrary to the general approach reported in literature, no significant relationship was observed between the ignition temperatures determined through TGA analysis and the volatile matter content. A likely reason is the mineral-rich ash present in many agricultural residues. These minerals may originate from both the biomass itself and field inputs such as fertilizer and pesticides. The biomass's varying levels of lignin, cellulose, hemicellulose, and also its elemental composition, especially nitrogen content, can affect fundamental thermal behaviors such as ignition temperature (Acampora et al. 2021; Bi et al. 2020). Moreover, according to our observations during the combustion trials in the pellet stove, the ignition process generally takes 6–7 min under identical conditions. However, ignition occurred in as little as 3 min for wood pellets (WPs), pine needles (PNs), and olive cake (OC) pellets. This is believed to be due to multiple factors, such as volatile matter, mineral contents, and the contact of the pellets with air. In this regard, Polonini, Petrocelli, and Lezzi (2023) reported that smaller particles in biomass have a greater surface area, which facilitates heat transfer and occurs more efficiently, thereby enhancing the ignition capability. However, the ignition behavior observed in the TGA analysis under micro conditions does not align with the behavior in the pellet stove. This is because the pellet mass, the geometric structure of the

pellets, and their position in the combustion chamber are the key factors that determine the ignition ability in the stove.

According to the TGA results, the burnout temperature (T_{brn}) varies between 401–478°C depending on the type of raw material used. The lowest T_{brn} value was measured at 401 °C (WP), while the highest was 478 °C (PN). In general, pellets with lower Tb values, such as WP, HZ, GR, and OC, have a high volatile matter content and complete combustion occur at lower temperatures. On the other hand, pellets with higher T_{brn} values, such as PN, PP, and VP, have higher carbon content and fixed carbon content, resulting in complete combustion at higher temperatures. This indicates that the composition of the pellets, particularly their volatile and carbon content, plays a significant role in determining the temperature at which complete combustion occurs.

A high comprehensive combustion characteristic index (S_n) value indicates better ignition and efficient complete combustion of the biomass (Aniza et al. 2024). A low ignition temperature and low burnout temperature lead to an increase in the S_n value. Based on the analyses, PS, PP, and OC were found to have the highest S_n values, indicating that they are the most reactive and efficient biomasses in terms of combustion characteristics. WP, ES, and PN exhibited moderate S_n values, and their combustion processes were evaluated as balanced. HZ, GR, and VP had relatively low S_n values, exhibiting lower reactivity and longer combustion processes. As emphasized in extensive studies, lignin, cellulose, hemicellulose, ash, volatile matter, and fixed carbon contents are the components that collectively influence combustion characteristics (Barmina et al. 2024; Vieira et al. 2023). On the other hand, alkali metals, which are estimated to be quite abundant in agricultural residues, can catalyze combustion reactions (Li, Song, and Zhan 2012). This situation may lead to misleading predictions regarding efficiency when TGA analysis of agricultural residue pellets, which exhibit high emission gas release and low combustion efficiency in practice, is evaluated. This suggests that other factors, beyond just the chemical composition, influence the combustion performance. To clarify this situation, it is important to analyze the ash minerals in agricultural residue pellets and assess their potential impact on combustion behavior and emission release.

Correlation between thermogravimetric indices and combustion/emission performance

To better interpret the link between the fundamental thermogravimetric behavior and the practical combustion performance of agropellets, a correlation analysis was performed between the TGA-derived indices and experimentally measured fuel and emission parameters. Only statistically significant correlations ($|r| \geq 0.70$) were considered to emphasize strong relationships between thermal degradation characteristics and combustion efficiency or emission trends under stove scale conditions (Table 4). Beyond these relationships, the full correlation matrix encompassing all the parameters and descriptive statistical data were presented in Supplementary Material for comprehensive reference (**Tables S6 and S7**).

The results revealed that several TGA parameters, particularly WL_2, DTG_{avg}, and m_R, exhibited strong correlations with key combustion and emission indicators such as ash content, volatile matter, CO, NO_x, and modified combustion efficiency. These relationships demonstrate that the devolatilization behavior and residual fraction determined during TGA closely reflect the oxidation completeness and emission performance observed in pellet stove tests. Fuels exhibiting higher mass loss rates and lower residual fractions in TGA tend to achieve higher MCE values and lower CO emissions, indicating efficient oxidation and stable flame propagation. Conversely, higher ignition temperatures or slower decomposition rates correspond to elevated NO_x levels, which is consistent with longer high-temperature residence times favoring thermal NO formation (Polonini, Petrocelli, and Lezzi 2023).

Notably, agropellets and wood pellets displayed distinct thermal degradation patterns in TGA, which align with their practical combustion efficiencies. Agropellets showed delayed ignition and higher residual mass, reflecting inhibited oxidation, and lower stove scale combustion efficiency. This is mainly due to the inorganic constituents in agropellet ash, which strongly affect both combustion performance and TGA behavior (Zhai et al. 2020). In contrast, wood pellets with higher devolatilization rates and lower char residues exhibited superior thermal reactivity in TGA, consistent with their higher flame stability, faster burnout, and reduced CO emissions during practical operation (Moreira et al. 2023). Thus, integrating

Table 4. Correlation of TGA indices with combustion and emission parameters (highlighting significant correlations with $|r| \geq 0.70$).

TGA parameter	Fuel/emission parameter	Correlation coefficient (r)	p value	Thermochemical implication
WL_2	AC	−0.88	<0.01	Higher ash content reduced mass loss in the main combustion stage. Ash is the noncombustible fraction and lowers the amount of degradable organic matter.
	VM	+0.88	<0.01	Higher volatile matter increased mass loss in the main combustion stage. This is consistent with stronger devolatilization during heating.
	HHV	+0.85	<0.01	Higher HHV/LHV corresponded to greater mass loss in the main
	LHV	+0.84	<0.01	combustion stage. Fuels with more combustible fractions released more mass during thermal degradation.
m_R	AC	+0.88	<0.01	Residual mass increased with ash content. The inorganic fraction remains as solid residue after combustion.
	VM	−0.86	<0.01	Residual mass decreased as volatile matter increased. Fuels richer in volatiles left less solid material after thermal degradation.
	HHV	−0.88	<0.01	Higher residual mass was linked to lower HHV/LHV. Fuels leaving more
	LHV	−0.86	<0.01	residue generally contained a lower proportion of combustible material.
	Tb	−0.72	0.02	Higher residual mass corresponded to lower flue gas temperature. Lower heat release during combustion may explain this trend.
	MCE	−0.72	0.02	Higher residual mass was associated with lower modified combustion efficiency. Less effective fuel conversion is consistent with this relationship.
T_{ig}	AC	−0.74	0.01	Ignition temperature decreased as ash content increased. Ash-forming minerals may affect the early thermal behavior of the fuel.
	NOx	−0.86	<0.01	Lower ignition temperature corresponded to higher NOx emission. The relationship was clear, although the underlying mechanism may involve multiple fuel and combustion factors.
	MCE	+0.71	0.02	Higher ignition temperature corresponded to higher modified combustion efficiency. This relationship suggests consistency between the TGA ignition behavior and stove-scale combustion performance.
DTG_{avg}	AC	−0.77	0.01	Average mass loss rate decreased as ash content increased. More inorganic material generally slows thermal degradation.
	VM	+0.82	<0.01	Average mass loss rate increased with volatile matter content. Volatile-rich fuels generally devolatilized faster.
	HHV	+0.88	<0.01	Higher HHV/LHV corresponded to higher average mass loss rate. Fuels
	LHV	+0.87	<0.01	with greater energy content also showed stronger thermal reactivity.
	MCE	+0.74	0.02	Higher average mass loss rate was associated with higher modified combustion efficiency. Better stove-scale performance was generally observed in more reactive fuels.
	T_b	+0.77	0.01	Higher average mass loss rate corresponded to higher flue gas temperature. Stronger heat release during combustion is consistent with this trend.

WL_2 = second-stage weight loss, m_R = residual mass loss, T_{ig} = Ignition temperature, DTG_{avg} = average mass loss rate, AC = ash content, VM = volatile matter, HHV = higher heating value, LHV = lower heating value, MCE = modified combustion efficiency, Tb = flue gas temperature.

TGA characterization with combustion experiments offers an efficient framework for assessing agropellets in stoves designed for wood pellets, where their distinct devolatilization and ash behavior can influence efficiency and emissions.

Conclusions

Users increasingly attempt to burn agropellets and other secondary biomass pellets in conventional pellet stoves; however, these appliances are originally designed and optimized for wood pellets. In this study, a practical and application-oriented approach was adopted by combusting agropellets in a residential pellet stove under the manufacturer-defined operating conditions originally optimized for wood pellets. First, our observations indicated that pellets with high ash content and low volatile matter exhibited weaker ignition stability and less stable combustion compared to wood pellets.

In terms of combustion performance, clear differences were observed between wood pellets and the other pellets under the same stove settings. Flue gas temperature (T_b) ranged from 154 °C for pepper stalk pellets to 274 °C for olive pruning pellets, while the excess air ratio (EAR) varied from 2.73 for pine needle pellets to 6.41 for eggplant stalk pellets. These results indicate that woody pellets maintained more stable

and efficient combustion, whereas several agropellets required higher excess air and produced lower combustion temperatures. The correlation analysis also supported this trend. EAR showed a strong negative correlation with Tb ($r = -0.80$) and MCE ($r = -0.85$), while MCE was positively correlated with T_b ($r = 0.80$). These relationships indicate that increasing excess air reduced both flue gas temperature and combustion efficiency under the fixed operating conditions optimized for wood pellets.

Emission results also revealed clear differences between wood pellets and the other pellets. At 10% O_2, CO emissions ranged from 289 mg Nm^{-3} for pine needle pellets to 6,318 mg Nm^{-3} for pepper stalk pellets, while wood pellets produced 576 mg Nm^{-3}. In the same range, NOx emissions varied from 165 mg Nm^{-3} for wood pellets to 1,066 mg Nm^{-3} for eggplant stalk pellets. The toxicity index also changed markedly among fuels, with the lowest value recorded for pine needle pellets (0.25) and the highest for pepper stalk pellets (5.85). The correlation analysis supported these trends. The toxicity index showed a strong positive correlation with EAR ($r = 0.85$), CO ($r = 1.00$ for CO at 10% O_2), and NOx ($r = 0.71$), while it showed a strong negative correlation with MCE ($r = -1.00$) and CO_2 ($r = -0.91$).

The TGA results were generally consistent with the combustion behavior observed in the pellet stove. Ignition temperatures ranged from 249 to 295 °C, while burnout temperatures varied between 401 and 478 °C, indicating clear differences in the thermal reactivity of the pellets. Wood pellets and some woody residues showed stronger devolatilization and lower residual mass, whereas several agropellets exhibited higher residual fractions and weaker thermal degradation behavior. Strong correlations were found between the TGA parameters and the combustion performance parameters. The second-stage mass loss showed strong positive correlations with volatile matter ($r = 0.88$) and HHV ($r = 0.85$), while residual mass was positively correlated with ash content ($r = 0.88$) and negatively correlated with both Tb ($r = -0.72$) and MCE ($r = -0.72$). In addition, the average mass loss rate was positively correlated with MCE ($r = 0.74$) and Tb ($r = 0.77$). These correlations demonstrate that the thermogravimetric indices can serve as predictive indicators of how pellets behave during real stove combustion, offering early guidance on their efficiency and emission tendencies.

One limitation of this study is the difference in pellet sources. Wood pellets were obtained from a regional commercial producer, whereas agricultural and secondary biomass feedstocks were pelletized under optimized laboratory conditions. Moreover, the experiments were carried out using a residential pellet stove specifically designed for wood pellets, with the manufacturer's recommended operating parameters followed throughout the tests. It should also be noted that pellets produced from the same type of agricultural residue may exhibit different chemical characteristics depending on the cultivation region and growing conditions. Similarly, the optimized operating parameters of pellet stoves can vary among manufacturers, which may influence combustion performance and emission outcomes.

From a future perspective, reducing the negative effects of high ash and nitrogen content in agropellets requires improvements on both the pellet and stove sides. On the pellet side, future studies should first identify and quantify the mineral species inherently present in agropellets, as these minerals strongly affect ash behavior and emission characteristics. Accordingly, co-pelletization or additive-based approaches using kaolin, dolomite, or limestone can help capture alkali elements and mitigate ash-related problems. Water washing or leaching can also lower the ash content, and blending with woody biomass can balance mineral and nitrogen levels. On the stove side, several improvements may enhance the use of agricultural pellets. These include ash-tolerant combustion chambers, automatic ash cleaning systems, sensor-based feed control, and optimized secondary air supply.

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Author contributions

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Disclosure statement

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article, its supplementary materials and at 10.17632/rhh7gxm6p5.1.

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