Renewable Energy 261 (2026) 125267

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

New wood chips type for residential use: a pellet substitute for the European market

Claudio Fagarazzi *, Andrea Miceli

Department of Agriculture, Food, Environment and Forestry, University of Florence, P.le delle Cascine 18, 5, 50144, Florence, Italy

ARTICLE INFO

Keywords:
Wood chips
Wood pellet
Renewable energy
Mini wood chips
Pellet stove
Biofuel
Heating systems

ABSTRACT

The European energy market in rural areas has been characterized by steady growth in wood pellet consumption; recent supply chain disruptions and geopolitical tensions have exposed market vulnerabilities. This study investigates new biofuel, mini wood chips (MWC) and calibrated mini wood chips (CMWC), as substitutes for imported pellets in residential heating in Europe. Tests were conducted on a conventional pellet stove adapted to use the new biofuels. Although MWC faced operational issues due to oversized chips that obstructed the auger, CMWC exhibited reliable performance during extended trials.

A statistical evaluation was performed using two-way analysis of variance (ANOVA), and compromise programming to assess a setup with respect to key parameters such as the efficiency; global power output; flue gas temperature; and carbon monoxide, particulate matter, and oxygen emissions. The analysis revealed that optimizing stove settings is essential to ensure functionality, maximize power, and minimize emissions when using CMWC. These findings suggest that CMWC is an alternative to conventional wood pellets, reducing import, enhancing supply chains, and fostering local economic and environmental benefits.

Overall, the integration of CMWC emerges as both a viable technological pathway for household heating and a strategic contribution to energy policy, reinforcing the goals of ecological transition and sustainable territorial development.

1. Introduction

According to the International Energy Agency, power consumption in buildings worldwide accounts for 32 % of total final energy use, highlighting the construction sector as the largest energy consumer [1,2]. This trend has been confirmed by Eurostat 2023 [3], according to which the household sector in the EU-27 accounted for 26.9 % (i.e., 243 Mtoe) of the final energy consumption in 2022, which is more than that of industries (25.1 %) and closer to that of the transport sector (31.0 %). In particular, the consumption of residential energy in EU-27 in 2022 was 30.9 % natural gas, 25.3 % electricity, and 18.6 % renewable energy and biofuels [4]. In the last decade, global bioenergy from wood pellets has accounted for a significant portion of the domestic heating market, with an increase in production from 18 million tons in 2012 to 47 million tons in 2022 [5]. In 2023, the demand in the EU decreased slightly to 24.5 million metric tons (MMT) due to a milder winter and reduced demand from the commercial power sector [6]. However, EU-28 was the world's largest consumer of wood pellets in 2023, with over 72 % of total consumption [5], although it accounts for only 52.7 % of the world's pellet production [5]. The 2024 report of the USDA confirms that the demand for pellets in the EU has significantly exceeded domestic production over the past decade, with consequent increase in imports from Russia, the United States, Belarus, and Ukraine. In April 2022 the EU banned the import of Russian wood pellets in response to Russia's invasion of Ukraine, excluding two of the world's leading fuel producers and causing a fuel shortage with a consequent increase in prices.

In this context, Italy is the largest European pellet consumer with 3.4 MMT (approximately 24 % of total consumption in EU), and the country is characterised by the widespread presence of domestic pellet-based heating technologies, with approximately 2.4 million stoves [7,8].

Consequently, Italy has been strongly affected by the current socio-political tensions in the wood pellet market. Thus, alignment between supply and demand is essential at the national level for this biofuel. However, it is not possible to significantly increase the local production of pellets. Although Italy has an abundance of forests, the high production costs render any future growth in pellet production unlikely.

This study aims to investigate the possibility of exploiting other types

* Corresponding author.
E-mail addresses: claudio.fagarazzi@unifi.it (C. Fagarazzi), andrea.miceli@unifi.it (A. Miceli).

https://doi.org/10.1016/j.renene.2026.125267
Received 19 May 2025; Received in revised form 17 December 2025; Accepted 10 January 2026
Available online 12 January 2026

of woody biomasses of local origin as a substitute for pellets imported from non-EU countries. To achieve this goal, two pellet substitute fuels were studied, specifically, *A1+Cippatino* [9], hereafter referred to as mini wood chips (MWC), and calibrated mini wood chips (CMWC). In particular, it has been verified the functionality and compatibility of MWC and CMWC with existing heating technologies in Italian and European households to define the optimal settings of traditional pellet stoves that ensure proper functioning of the heat generator when using these new fuels [10–13]. In consideration of the presence of technical problems, MWC was ruled out, since it was unsuitable for conventional pellet stoves. The presence of wood chips longer than 31.50 mm caused frequent stove blockages and makes the fuel unreliable [10].

The study on CMWC as a pellet-compatible wood fuel, showing how a calibrated particle-size specification enables reliable feeding in legacy pellet stoves. An appliance level integration scarcely covered by prior peer-reviewed work, which has mostly examined chips in small boilers or discussed micro/mini chips as pellet surrogates at the supply chain level [11,12].

Growing reliance on pellets for residential heating has exposed households to price and supply volatility, motivating interest in locally sourced, pellet-like fuels and in test methods that explicitly allow "other fuels (e.g., wood chips)" when declared by manufacturers [13].

The development of a pellet surrogate based on a simplified and environmentally friendly production process could therefore contribute to a significant reduction in the carbon footprint of the manufacturing process [14]. Studies confirm that the ecological footprint (Carbon Footprint, CF) of the wood chips production process is about one-third of the CF generated by the pellet production process, as highlighted by the EU Commission, Joint Research Centre report [15] and further supported by peer-reviewed assessments on the environmental performance of forest residues for domestic heating [16]. This type of conversion would be in accordance with the objectives of EU energy policies [17].

2. Material and methods

2.1. Methods for characterization of biomass fuel samples

The biofuels used for the tests were derived from the processing of virgin wood from forests. Three different types of biofuels were analysed and characterized according to the guidelines of European certification systems (ENplus) and National Certification System (Biomassplus): pellets, mini wood chips MWC, and calibrated mini wood chips CMWC, as shown in Supplementary Fig. S1.

The fuel characterization was performed in accordance with ISO 17225-2 for wood pellets, while ISO 17225-4 was applied for MWC and CMWC. Wood pellet fuel characterization was carried out according to the international ENplus certification scheme, considering the following parameters: origin and sources (ISO 17225-1), diameter (mm) (ISO 17829), moisture content (w-%) (ISO 18134), ash content (w-% dry) (ISO 18122), fine particle content (w-% ≤3.15 mm) (ISO 18846), net calorific value (kWh/kg) (ISO 18125), and bulk density (kg/m^3) (ISO 17828).The classification of the two types of wood chips was conducted in accordance with the Italian national standard *Biomass Plus* [9], based on the following parameters: origin and sources (ISO 17225-1), particle size (mm) (ISO 17827-1), moisture content (w-%) (ISO 18134-1; ISO 18134-2), bulk density (kg/m^3) (ISO 17828), net calorific value kWh/kg (ISO 18125), and ash content (w-% dry) (ISO 18122).

The pellets were purchased from a large-scale retail store, while the MWC was supplied by a forestry company located in Tuscany.

The third type of wood chips tested was CMWC, obtained through a selective screening of MWC performed using a prototype screening system (EU Patent No. 102022000022869).

2.2. Combustion tests

Combustion tests were conducted on an outdated model pellet stove with technical characteristics that are extremely common in European domestic heating systems [18].

Thus, if the feasibility of using the new biofuels (MWC and CMWC) in stoves with aging technology is confirmed, it can reasonably be assumed that they will also perform well in stoves equipped with new technologies such as high-performance burners and automatic systems for unlocking the feed auger.

Thus, pellets, MWC, and CMWC were tested in the Adele 7 pellet stove (produced by Ravelli Group Industry in 2015). The Adele 7 pellet stove is a top-feed burner [19]; this feed system represented 70 % of the pellet stoves in European households in 2012 [18,20].

The stove has a combustion bed without holes and forced ventilation directs air flow straight to the fuel pile (as shown in technical diagram in Supplementary Fig. S2) [21]. The nominal power of the stove is 6.6 kW, with an automatic combustion control system based on a lambda sensor and tilting grate for ash removal. This pellet stove features a widely used technology with an internal tank and an auger that transports the fuel to the top of a chute, from where it drops onto the combustion bed (Supplementary Fig. S2) [8,18].

The initial combustion tests with mini wood chips (MWC) and calibrated mini wood chips (CMWC) revealed three operational constraints. First, fuel bridging occurred in the hopper above the auger, attributable to poor flowability that promotes arching in bulk solids [22]; such bridging of wood chips is experimentally documented and quantified with standardized arching tests [23]. To mitigate this, a 20-cm cylindrical vibration device was installed inside the hopper, restoring continuous feeding. Second, with MWC only, particles >31.5 mm jammed the auger and prevented completion of the runs; no practical retrofit was identified, indicating that this fuel is unsuitable for legacy pellet stoves [10]. Third, the low energy density of CMWC (≈ one third that of pellets) caused flameouts under default settings. Stable operation was achieved by adjusting the auger loading time and the stove draught, while holding fuel moisture constant by using anhydrous CMWC to isolate the effect of appliance settings.

After a technical check, MWC was ruled out, since as it was unsuitable for conventional pellet stoves. The presence of wood chips longer than 31.50 mm caused frequent stove blockages and makes the fuel unreliable [10]. Therefore, the combustion tests focused on identifying the optimal stove settings to ensure operational reliability, high power, and performance with CMWC. One combustion test with pellets (replicated twice according to UNI EN 14785:2006) and fifteen tests with CMWC (each replicated twice according to UNI EN 14785:2006) were conducted. The pellet combustion test duration was on average 9 h and the CMWC test duration was over 155 h without lockouts. During the tests, 170 kg of CMWC was consumed.

Pellet combustion tests were conducted under standard conditions: auger load time = 1.9 s; stove draught = 12.2 Pa. Therefore, to identify the optimal settings of pellet stoves using CMWC, different auger loading times (s) and stove draught (Pa) were tested. For the auger load time, five settings were selected, each differing by 0.7 s. A minimum value of 3.0 s has been selected to keep the stove running, while the maximum value (i.e. 5.8 s) represented the technical limit setting for the stove model used. For the stove draught, three values were selected, minimum (9.6 Pa), maximum (15.0 Pa), and average (12.2 Pa).

For each setting configuration, analyses were conducted to monitor the key dependent variables considered in the study: the efficiency (η), global power (P), flue gas temperature (°T), emission of particulate matter (PM) and carbon monoxide (CO) (g/m^3), and oxygen concentration O_2 (%).

Each experiment began from cold stove conditions and proceeded through three stages. First, the ignition stage (approximately 13–14 min) ended when the stove entered modulation mode and the flue gas temperature reached 150 °C; at that point, the auger load time and stove draught were set. Second, a pre-conditioning period (approximately 60 min) was used to attain steady operation; stability was verified by monitoring the flue gas temperature for 30 min and confirming a variation within ±5 °C. Third, the measurement stage (3 h) was carried out, during which all data required to evaluate the variables of interest were collected.

The efficiency (η) and global power (P) were calculated according to the UNI EN 14785:2006. For CO, PM, and O_2 the amount of emissions and their flue gas temperatures were detected during the test using a system equipped with a particulate measurement probe and combustion gas analyser (Testo 350-S analyser in a two-component configuration: controller and analyser and Testo 380 particle analyser coupled with a Testo 330-2 LL exhaust gas analyser). The two independent variables in the combustion tests were the auger load time and stove draught.

2.3. Data analysis

In literature several studies have employed methodologies such as the Taguchi method and analysis of variance (ANOVA) to ascertain the optimal combinations of parameters that influence the system [24,25].

The literature also shows that, although diverse optimization methodologies are well established across other energy domains, studies specifically targeting heating-system optimization remain scarce [24,25].

This study employed two-way ANOVA to identify the optimal operating parameters of pellet stoves fuelled with novel biofuels [26,27]. All data were normalized to the 13 % O_2 reference in accordance with UNI EN 14785:2006. Several tests were conducted to assess system performance, including emission levels [1]. Stove draught and auger load time configurations were evaluated in relation to efficiency, power level, flue gas temperature, and emissions of CO, PM, and O_2. Statistical significance was assessed through separation of means using Fisher's least significant difference test at $P \leq 0.05$. Analyses were performed with the open-source software R (version 3.6.2).

The optimal settings for stove draught and auger load time were determined through a multi-criteria decision-making (MCDM) framework based on compromise programming, in line with recent applications of CP to energy system optimization [28,29].

CP is a multi-objective optimization technique used to determine optima by minimising the distance from an ideal point [30]. In CP, a hypothetical ideal solution to the problem under consideration is defined. This solution, designated the ideal alternative, corresponds to the highest value of the individual objectives evaluated. Consequently, the ideal alternative is defined by the maximum value of the factors in the effect matrix. The levels achieved by the six factors (efficiency; power; flue gas temperature; CO, PM, and O_2 emissions) are presented under varying parameter combinations such as the stove draught and auger load time.

The ideal value in this case is represented by the two maximum values of the efficiency and power, and the four minimum values of CO, PM, O_2 and flue gas temperature. The goal is to determine the configuration that best approximates the ideal values of the six factors examined. To this end, the CP was formulated on the concept of distance to the ideal point.

The CP distance is based on the family of *Lp*-metrics (called Minkovsky metrics), represented by the following general form [31,32]:

$$L_j = \left[\sum_{i=1}^{n} w_{ji} \cdot \left(\left(y_i^* - y_{ji} \right) \Big/ \left(y_i^* - y_{*i} \right) \right)^p \right]^{1/p} \quad (1)$$

where L_j is the normalized distance from all ideal points for the alternative j; y^*_i and $y_{j,i}$ are the ideal point for factor i and point value for alternative j and factor i, respectively; p is the value governing the geometrical distance; and w_j is the weight factor [33].

In this study, CP was effective in identifying the optimal settings for auger load time and stove draught in pellet stoves fuelled with CMWC. The value of p was set to 1 (Manhattan distance) to linearly aggregate deviations, ensuring that all differences contribute proportionally to the overall distance. In this manner, the approach treats each deviation equally without disproportionately penalizing larger differences.

Optimal decision making in heating technology optimization (pellet stove) requires structuring the model into the structure of MCDM. The model applied in this study is based on the CP method characterized by the following elements: (a) goal, (b) decision criteria (factor), (c) alternatives, (d) ideal point of each factor, and (e) factor weight (degree of importance of each factor) [33].

The CP model developed in this study aimed to identify the optimal settings of mature heating technologies to guarantee operation with CMWC. Six decision criteria were considered: efficiency and power, to be maximized, and CO, PM, O_2 emissions and flue gas temperature, to be minimized. Fifteen stove setup combinations were tested to evaluate management alternatives. For each criterion, ideal and anti-ideal points were defined and the data were normalized according to Eq. (1). Criterion weights were then assigned based on their statistical significance, determined by ANOVA analysis of the effects of auger load time and stove draught, and subsequently compared through a hierarchical analysis [32,34] using Expert Choice software (version 11).

3. Results and discussion

3.1. Characteristics of the biomass fuel samples

The first type of biofuel was pellets produced by a German wood factory from silver fir woods (*Abies alba* Mill.), while the wood chips fuel tested are made from chestnut coppice (*Castanea sativa* Mill.) produced by a Tuscany-based harvesting enterprise.

The main characteristics of the tested biofuels are shown in Table 1. The MWC, pellets, and CMWC had moisture contents of 8.89 %, 0.60 %, and 0 %, respectively. The bulk density ranged from 700.00 kg/m^3 for the pellets to 265.00 kg/m^3 for the MWC, with the CMWC having a density of 268.50 kg/m^3. The ash content was 0.46 % for CMWC, 0.42 % for MWC, and approximately 0.60 % for the pellets. The net calorific value remained constant at 4.45 kWh/kg for both types of wood chips, and it was 5.00 kWh/kg for the pellets. The energy density increased from 1179.25 kWh/m^3 for the MWC to 1194.83 kWh/m^3 for the CMWC, with the pellet reaching 3500 kWh/m^3.

The particle distribution is shown in Fig. 1; the ash content (% of dry weight) was 0.60 %; moisture (W) was 0.6 %; net calorific value (Q) was 5.0 kWh/kg, and the bulk density (BD) was 700 kg/m^3 (Table 1). These values classify it as ENplus A1.

The MWC particle distribution is shown in Fig. 2. It is interesting to note that the particle size distributions obtained using a round-hole sieve with sizes specified in ISO 17827-1 do not indicate the presence of chips longer than 31.50 mm in MWC. However, laboratory sample analysis showed that this class represents 15 % by weight.

The ash content (as a percentage of dry weight) was 0.46 %; moisture content (W) was 8.89 %; net calorific value (Q) was 4.45 kWh/kg, and BD was 265 kg/m^3 (Table 1).

This CMWC had the following characteristics: particle distribution as shown in Fig. 3; the average value of ash content (as a percentage of dry weight) was 0.42 %; moisture (W) was 0.0 % (after drying the MWC); net calorific value (Q) was 4.45 kWh/kg, and BD was 268.5 kg/m^3 (Table 1).

Table 1
Characteristics of the biofuel used for the combustion tests.

Parameters (average value)	Pellet	MWC	CMWC
Moisture (%)	0.60	8.89	0.00
Bulk density (kg/m^3)	700.00	265.00	268.50
Ash Content (%)	0.60	0.46	0.42
Net calorific value (kWh/kg)	5.00	4.45	4.45
Energy density (kWh/m^3)	3500	1179.25	1194.83

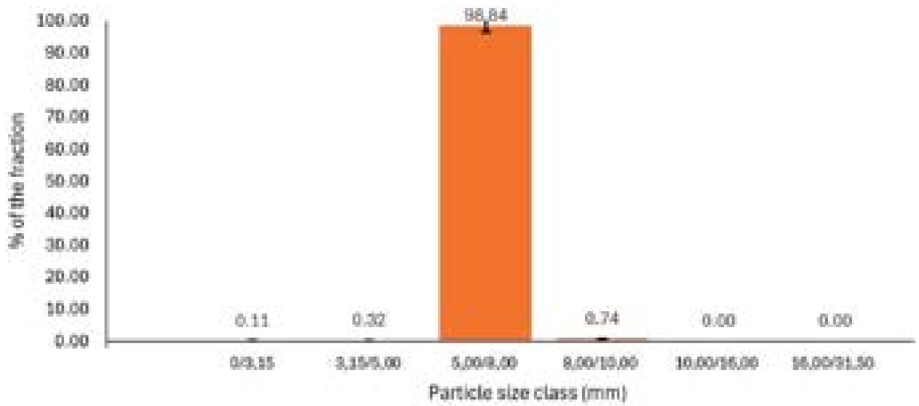

Fig. 1. Distribution of the fraction in percentage by particle size class of the pellet sample used for the combustion tests.

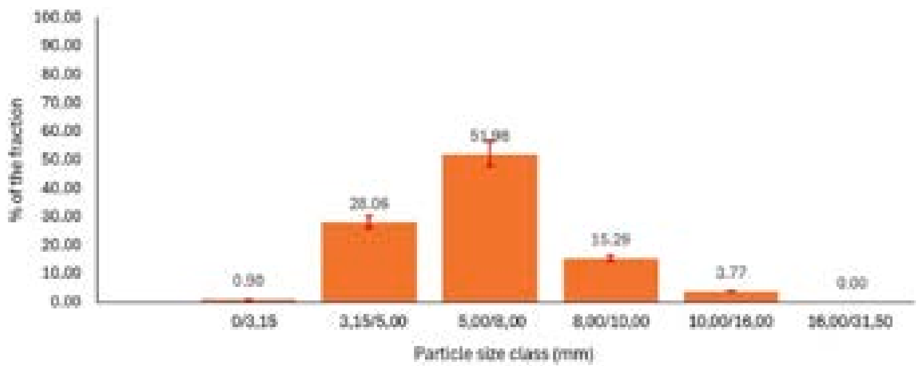

Fig. 2. Distribution of the fraction in percentage by particle size class of the A1+ MWC sample.

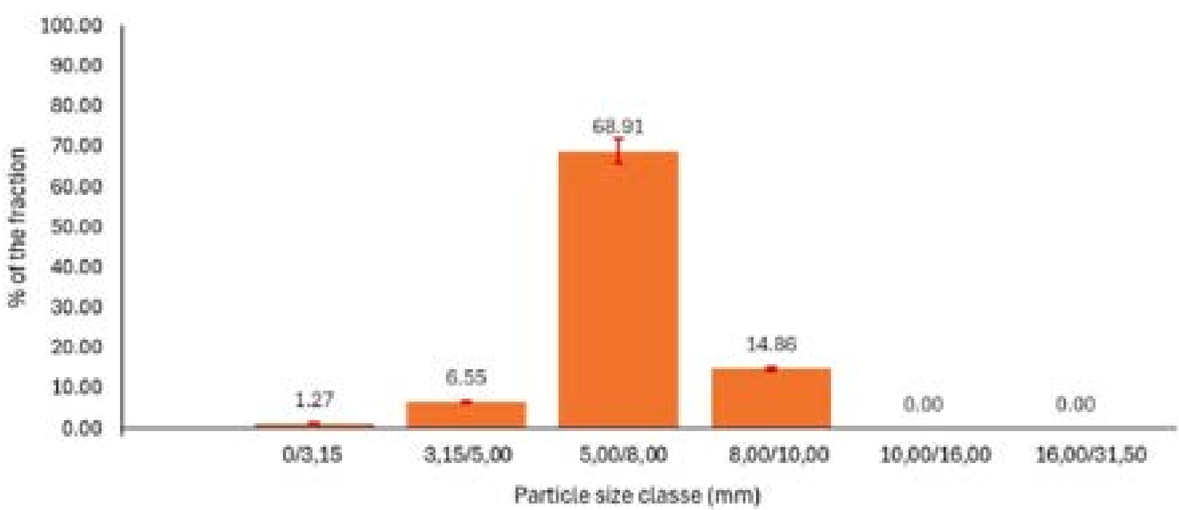

Fig. 3. Distribution of the fraction in percentage by particle size class of the CMWC sample used for the combustion tests.

Table 2
Pellet effect: results obtained by setting the stove with average parameters for the pellets.

Alternatives setup for CMWC	Independent variables		Dependent variables					
	Auger load time (s)	Stove draught (Pa)	Efficiency (%)	Global power (kW)	CO avg (mg/m^3)	PM (mg/m^3)	O_2 (%)	Flue gas temperature (°C)
Pellet	1.9	12.2	90.56	4.58	783	13.09	15.5	119.2

3.2. Data from combustion test

A total of 16 tests (two replicates and 32 total tests in accordance with UNI EN 14785:2006), comprising fifteen tests on CMWC and one test on pellets, were conducted. Table 2 shows the values of dependent variable from the test with pellet. Table 3 summarize the effects matrices with the 15 combustion tests with CMWC and the results under varying auger load time and stove draught settings, respectively.

3.3. Statistical analysis

A two-way ANOVA test was conducted on the CMWC effect matrix, and the results are shown in Table 4. It can be seen that the two parameters have different influences on the factors of interest. Regarding efficiency, neither auger load time nor stove draught was significant ($P > 0.05$). By contrast, for the global power, the auger load time was significant ($0.01 < P < 0.05$) and stove draught had a moderate significance ($0.001 < P < 0.01$). For the flue gas temperature, only the auger load time was found to be significant ($0.001 < P < 0.01$). For flue gas emission, auger load time was found to be significant in terms of CO and PM emissions ($P \leq 0.0010$), while stove draught had a moderate significance ($0.001 < P < 0.01$). Considering O_2 emission, both the stove draught and auger load time were moderate significance ($0.001 < P < 0.01$).

From these results, it was considered useful to further investigate the relationship between the two parameters and the six factors analysed. The following sections describe these analyses in detail.

3.3.1. Effect of auger load time and stove draught on thermal efficiency, η (%)

The efficiency exhibited a direct relationship with the auger load time and an inverse relationship with the stove draught (Fig. 4). The efficiency varied between a minimum of 83.58 %, obtained at the second auger loading level (3.0 s) and at highest draught level (15.0 Pa), to a maximum of 96.98 %, recorded at the highest auger loading level (5.8 s) and highest draught level (15.0 Pa).

As confirmed by the ANOVA analysis (Table 4), variations in the auger load time and stove draught did not affect the efficiency.

3.3.2. Effect of auger load time and stove draught on global power, P (kW)

It was observed that as the auger load time increased (Fig. 5) from a minimum of 3.0 s to a maximum of 5.8 s (i.e., the maximum allowed by the appliance), the global power tended to increase significantly. In contrast, the global power exhibited an inverse relationship with the stove draught (Fig. 5). As the draught increased from a minimum of 9.6 Pa to a maximum of 15.0 Pa, the global power tended to decrease. The global power varied between a minimum of 3.10 kW, obtained at the first auger loading level (3.0 s) and the lowest draught level (9.6 Pa), to a maximum of 6.73 kW, recorded at the fourth auger loading level (5.1 s) and the lowest draught level (9.6 Pa).

As observed previously, the variation of the two parameters influenced the changes in the global power values.

Table 4
Results of the two-way ANOVA evaluating the effects of stove draught, auger load time, and their interaction on efficiency, global power, flue gas temperature, and flue gas emissions (CO, PM, and O_2). The table reports the p-values of the F-ratio test for each factor. Levels of statistical significance are indicated as follows: *P ≤ 0.05; **P ≤ 0.01; **P ≤ 0.001.

Factors	Stove draught	Auger load time	Interaction
Efficiency	0.107	0.122	0.585
Global power	0.0096**	0.00103**	0.038*
Flue gas temperature	0.826	0.0070**	0.918
Flue gas Emission: CO	0.0013**	<0.0010***	0.498
Flue gas Emission: PM	0.0076**	<0.0010***	0.207
Flue gas Emission: O_2	0.0054**	0.0136*	0.256

3.3.3. Effect of auger load time and stove draught on flue-gas temperature, °T (°c)

Only the auger loading parameter was found to influence the flue gas temperature, and the stove draught did not affect it (Fig. 6). The temperature varied between a minimum of 100.6 °C, obtained at the lower auger loading level (3.0 s), to a maximum of 132.9 °C, obtained at the highest auger loading level (5.8 s).

An increase in the auger load time significantly affected the increase in the combustion gas temperature. This effect is due to the increase fuel supply to the burner, which enhances combustion and leads to an increase in the temperature. Conversely, variations in stove draught had no effect on this parameter. This outcome indicates that, within the tested range, the thermal behaviour of the system is primarily governed by the fuel feeding rate rather than by variations in stove draught.

3.3.4. Effect of auger load time and stove draught on flue-gas O_2 concentration, O_2 (%) (normalized to 13 % O_2)

Throughout all combustion tests, the O_2 levels were consistently exceeded the ideal threshold of 13 % (UNI EN 14785:2006) [35] regardless of the auger and draught settings.

However, it was observed that O_2 levels increased with higher stove draught due to excess intake air. This excess air cools the combustion process, reducing its efficiency and leading to lower oxygen consumption.

Conversely, O_2 levels increased significantly as auger load time

Table 3
Effect matrix CMWC: results obtained by setting the stove with 5 auger configurations and 3 stove draught pellet configurations.

Alternatives setup for CMWC	Independent variables		Dependent variables					
	Auger load time (s)	Stove draught (Pa)	Efficiency (%)	Global power (kW)	CO avg (mg/m^3)	PM (mg/m^3)	O_2 (%)	Flue gas temperature (°C)
1	3.0	9.6	87.32	3.10	4794	215.38	17.1	100.9
2	3.0	12.2	87.36	3.61	4891	228.57	16.8	109.6
3	3.0	15.0	83.58	3.13	6849	362.35	17.6	101.4
4	3.7	9.6	91.14	4.26	2944	172.86	15.4	116.1
5	3.7	12.2	94.07	3.74	3753	224.35	16.4	112.9
6	3.7	15.0	84.98	2.99	4365	234.78	16.4	117.9
7	4.4	9.6	93.41	5.13	1290	46.20	13.9	123.3
8	4.4	12.2	92.05	4.33	2303	72.16	15.9	123.1
9	4.4	15.0	85.48	3.61	3627	111.22	16.9	118.9
10	5.1	9.6	93.38	6.73	1165	58.75	14.6	124.3
11	5.1	12.2	91.56	6.30	1773	70.18	15.3	132.6
12	5.1	15.0	90.68	4.42	2305	83.08	15.8	128.6
13	5.8	9.6	95.09	5.25	853	47.27	14.4	125.4
14	5.8	12.2	91.44	5.24	891	48.24	14.2	132.9
15	5.8	15.0	96.98	5.88	1979	73.60	16	126.7

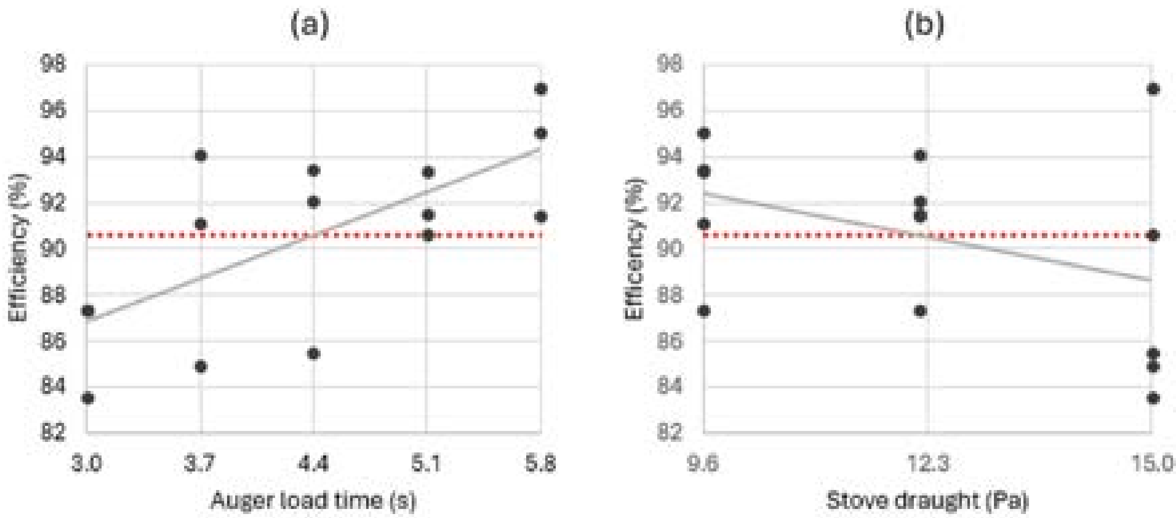

Fig. 4. Effect of the auger load time (a) and the stove draught (b) on the efficiency of the pellet stove filled by CMWC. The dotted grey lines represent the average values obtained from the sample of the tests carried out.

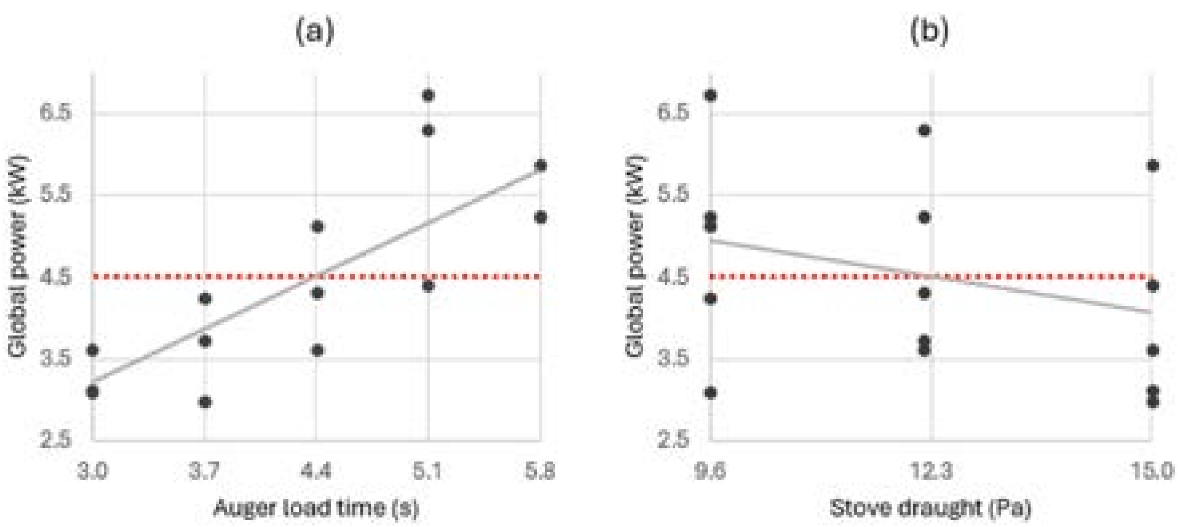

Fig. 5. Effect of the auger load time (a) and the stove draught (b) on the global power of the pellet stove filled by CMWC. The dotted red lines represent the average values obtained from the sample of the tests carried out. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

decreased. This is due to a lack fuel in the burner, preventing the combustion agent (O_2) from being consumed.

O_2 measurements revealed that the lowest level (13.9 %) was recorded at an auger load time of 4.4 s and stove draught of 9.6 Pa, and the highest O_2 emission (17,6 %) was recorded at the lowest auger load time level (3.0 s) and highest stove draught level (15.0 Pa) (Fig. 7).

3.3.5. *Effect of auger load time and stove draught on CO and PM emissions (normalized to 13 % O_2)*

The gas emission evaluation followed the "*less is more*" principle. The tests demonstrated that the reduction target for CO and PM emissions was achieved through a combination of a high auger load time and low stove draught. Specifically, the lowest CO (853 mg/m^3) and PM (47.27 mg/m^3) emissions were recorded at the highest auger load time level (5.8 s) and lowest stove draught level (9.6 Pa), while the highest CO (6849 mg/m^3) and PM (362.35 mg/m^3) emissions were recorded at the lowest auger load time level (3.0 s) and highest stove draught level (15.0 Pa).

CO emissions consistently exceeded the Italian national legal limit (250 mg/m^3), whereas PM emissions occasionally fell below the threshold of 50 mg/m^3.

Despite being widely used in European households, this obsolete technology delivered promising results. Even tests with high quality pellets under "average" conditions (12.2 Pa draught and 1.9 s auger load time) yielded CO emissions of 783 mg/m^3, exceeding the current legal limits (Fig. 8).

3.3.6. *Compromise programming (CP): best-compromise operating settings*

As discussed previously, a hypothetical ideal solution is defined by taking, for each objective, its best attainable value, while the anti-ideal (Nadir) point collects the worst values; in the present study, these reference points were used to compute the compromise (optimal) settings of stove draught and auger load time (Table 5). [29].

In Table 6, the significance level of the effects of the auger load time and stove draught from the ANOVA results and corresponding weights are illustrated. The auger load time and stove draught had no significant impact ($P > 0.05$) on the efficiency.

The ANOVA results demonstrate that variations in stove settings had

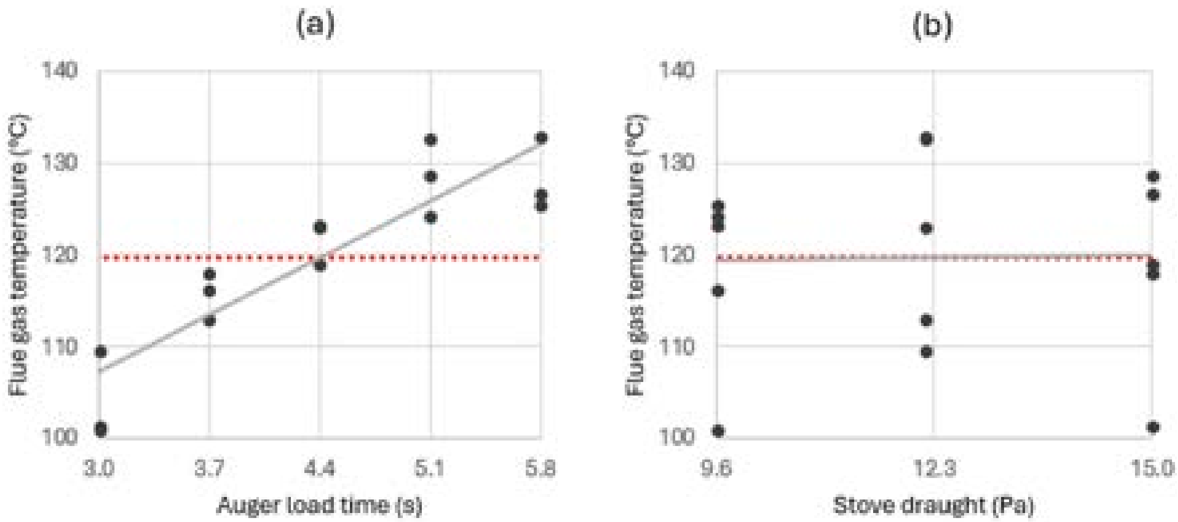

Fig. 6. Effect of the auger load time (a) and the stove draught (b) on the flue gas temperature of the pellet stove filled by CMWC. The dotted red lines represent the average values obtained from the sample of the tests carried out. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

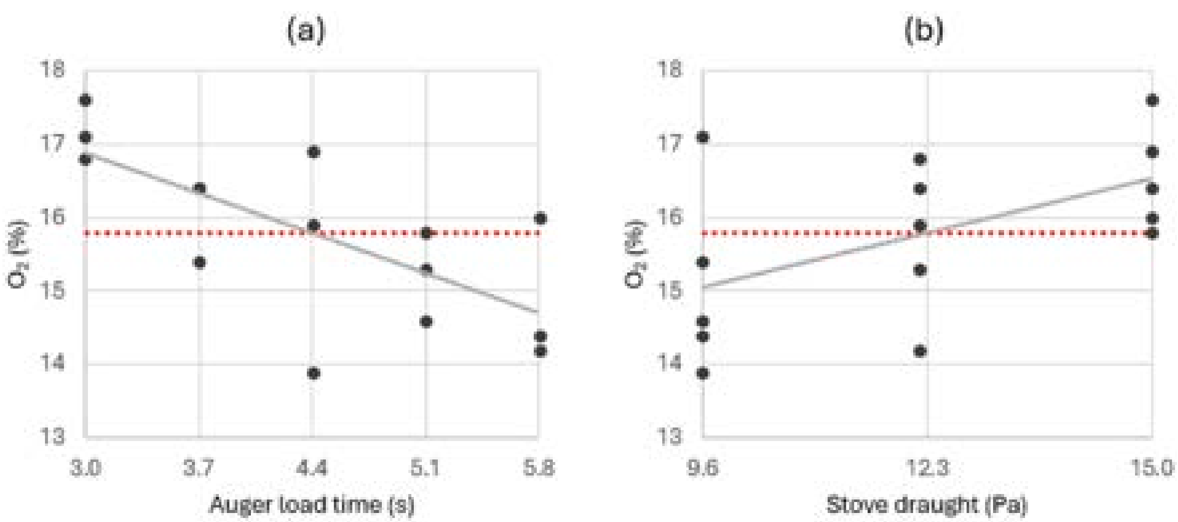

Fig. 7. Effect of the auger load time (a) and the stove draught (b) on flue gas emission for O_2 of the pellet stove filled by CMWC. The dotted red lines represent the average values obtained from the sample of the tests carried out. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

no statistically significant effect on the efficiency. Therefore, the efficiency factor was excluded from the CP model when defining the optimal settings and from the pairwise comparison matrix used to define the weights (w_j *efficiency* = 0).

In Table 7, the normalized distance for each factor and corresponding weight (*wj*) are shown. The data for the four alternatives with the most promising results are highlighted in bold. Specifically, alternatives 10 and 13 both exhibit the lowest L_j distance values of 0.08 and 0.09, respectively, and alternatives 7 and 14 demonstrates a marginally higher distance of 0.10, indicating its viability.

According to the evaluation model, the optimal settings for the implementation of CMWC in pellet stoves necessitate the auger level to be set to its value of 5.1 s, while the draught should be configured at minimum value of 9.6 Pa. Alternative 13 shows consistent values under an auger loading time of 5.8 s.

3.4. Discussion

The combustion tests indicated that MWC is not operational, and therefore, cannot be used with existing pellet stoves. Its use is limited to new technologies designed as bi-fuel systems, intended for both pellets and MWC. In contrast, CMWC was operated for 155 h without malfunction and demonstrated suitable physical characteristics for use in conventional pellet stoves. Consequently, CMWC emerges as a potential substitute for pellets. The quality standards of the CMWC analysed in this study are shown in Table 8, alongside a comparison with those already available on the market. The high quality pellet, En Plus A1 (according to ENplus certification based on ISO 17225-2), and the MWC (according to the Italian National Standard Biomass Plus and ISO 17225-4) were used for this purpose [9].

An examination of Table 8 highlights some significant differences between CMWC and pellets: firstly, the bulk density, which is approximately one-third of that of pellets, and secondly, the length of the chips, which for CMWC must be less than 25 mm. In addition, there is a higher

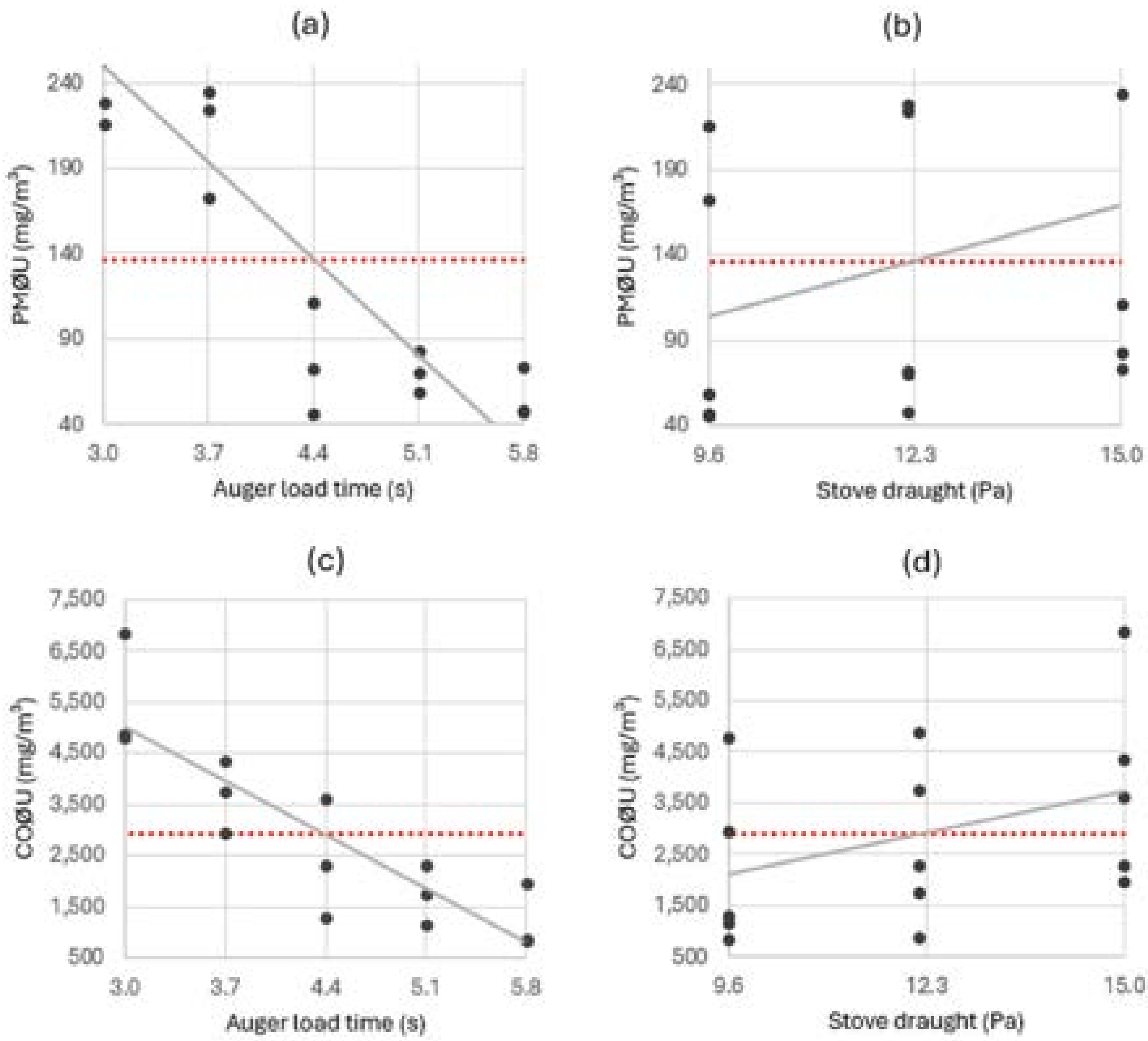

Fig. 8. Effect of the auger load time (a, c) and the stove draught (b, d) on flue gas emission for PM (a, b), CO (c, d) of the pellet stove filled by CMWC. The dotted red lines represent the average values obtained from the sample of the tests carried out. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 5
Ideal and anti-ideal values of each variable are illustrated.

	Efficiency (%)	Global power (kW)	CO avg (mg/m³)	PM (mg/m³)	O_2 (%)	Flue gas temperature (°C)
Ideal Point (max)	96.98	6.73	853	46.20	13.9	100.9
Non ideal point (min)	83.58	2.99	6849	362.35	17.6	132.9

presence of fine material (up to 5 %), and the particle size distribution of CMWC ranged 3.15–10 mm, significantly lower than the 16 mm limit for pellets.

The difference in the size classification of MWC and CMWC can also be observed. In the latter, there were no chips elements longer than 25 mm. This study also shows that the classification of small-sized wood chips on the basis of particle size distribution conducted using horizontal sieves (provided by the ISO 17225-4 and Biomass Plus standard) present critical limitations, because these sieves cannot assess the shape of the wood particles [36]. This is a qualitative aspect that can be further analysed through image classification [36].

These physical differences in the biofuels require the introduction of certain technical adjustments to the stoves to ensure proper operation with pellet substitutes.

Examining the CMWC pellet-stove tests, a two-way ANOVA indicated that auger load time and stove draught affect different response variables. For global power, both factors were significant ($0.001 < P < 0.01$), in line with studies showing that air-supply configuration/draught settings modulate performance and efficiency in pellet stoves [37]. For CO and PM, auger load time was highly significant ($P \leq 0.001$), while stove draught showed moderate significance ($0.001 < P < 0.01$), consistent with evidence that stabilising/-regularising the fuel feed markedly reduces CO and PM emissions [20]. Considering O_2, both draught and auger load time had moderate significance ($0.001 < P < 0.01$), coherently with Ostwald-diagram analyses that link excess-air/O_2 levels to the combustion regime in domestic pellet stoves [38]. Finally, for flue gas temperature only auger load time was significant ($0.001 < P < 0.01$); accordingly, Fig. 8c shows essentially no correlation with stove draught—an observation compatible with biomass-appliance literature where temperature/in-flue responses

Table 6
Significance level of the effects generated by auger load time and stove draught in relation to ANOVA analysis of variance. Significance level: (n.c.) Not classifiable, (*) Very low, (**) Low; (***) Medium, (****) High, (*****) Very high. Factors weight (w_j) defined with pairwise comparison technique and Consistent Index (C.I.) = 0.05

Factors	Level of significance of the effects generated by auger load time and stove draught	Factors weight (*wj*)
Efficiency	n.c.	n.c
Global power	***	0.12
Flue gas temperature	*	0.04
Flue gas emission CO	****	0.27
Flue gas emission PM	*****	0.50
Flue gas emission O_2	***	0.07
		C.I. = 0.05

are dominated by combustion condition and fuel-feed state rather than small draught variations [39]. The absence of correlation between flue gas temperature and stove draught differs from what has been reported in the literature [21,40]. Sungur and Basar (2023) [21] have shown that at fixed thermal input, increasing the combustion air supply (stronger draught) in a forced draft pellet stove to raise the flue gas temperature and lower efficiency, as the larger gas flow carries more sensible heat to the stack (λ from 1.7 to 3 across multiple burner-pot geometries). Zadravec et al. (2021) [40] instead analysed the stack sensible heat losses and verify that reducing excess air (lower O_2 in flue gas) decreases flue gas sensible losses (because total flue mass flow drops) even when the burner configuration (primary air-secondary air ratio) is varied only modestly. A different experimental control leads to a third trend: with combustion air held approximately constant while fuel feed/thermal input is increased, the flue gas temperature rises and the measured O_2 falls, reflecting a load-driven increase in heat release. While Rebaque et al. (2020) [41] emphasizes the importance that regime and boundary conditions matter in smouldering regimes (non-flaming beds), introducing a bottom air draft can accelerate heating and drive higher gas temperatures above the bed, up to transient flaming. Regarding the literature, the results are not contradictory but complementary; the flue gas temperature is essentially not correlated to the tested stove draught but related to auger load time. The tests were conducted at high O_2 and increasing stove draught can raise the flue gas mass flow and the convective heat transfer while reducing the useful heat release and the flame temperature, producing offsetting effects at the stack outlet and a nearly constant flue gas temperature. The dominant driver is the auger load time, which directly sets the thermal duty and thus the flue gas temperature. Unlike Sungur and Başar (2023) [21] this study did not vary the position or distribution of the air, and unlike Zadravec et al. (2021) [40] the collected data focused on flue gas temperature rather than heat lost in flue gas; different metrics and constraints yield trends that differ but are reconcilable. Extending the draught variation range may reveal a significant relationship with flue gas temperature.

The compromise programming (CP) analysis was used to identify the best-compromise operating settings in terms of performance, emissions, and flue gas temperature. Alternatives 10 and 13 (Tables 3 and 7) showed the lowest distances from the ideal point, corresponding to an auger load time of 5.1 s and 5.8 s, respectively, with a stove draught of 9.6 Pa. For pellet operation, the 'average' settings were auger load time 1.9 s and stove draught 12.2 Pa (Table 2).

The results indicate that, to ensure the operation of legacy pellet heating technologies with the new CMWC fuel, it is necessary to adjust the auger load time. These changes should include setting of the auger load time at least three times longer than the pellet auger load time and always keep the stove draught at the lowest setting. This will aid in reducing fuel leakage from the grate and loss of power.

Moreover, high-quality CMWC should be used, produced from wood free of branches and bark and dried to pellet-like moisture levels [42], preferably via natural (solar) drying. The material should be screened to remove all particles longer than 25 mm.

However, using CMWC entails critical issues related to its lower bulk density compared with pellets, which affects storage and logistics [43, 44]. Storage requires large, enclosed, dry spaces to accommodate CMWC bags. For example, a consumer needing 3 t of pellets per year requires about 4 m^3 of storage space, whereas approximately 11 m^3 are needed to store the same mass of CMWC. This constraint also impacts transport, as larger volumes must be handled for the same biomass tonnage.

However, the potential economic effects induced by the activation of these short supply chains can be significant, both in terms of the added value generated in disadvantaged mountainous areas and reducing the ecological footprint of the supply chain. According to the United States Department of Agriculture [6], in 2023, the EU consumed 24.5 MMT fuel, of which approximately 24 % was imported from North and South America and Asia, with a total value of $1.32 billion. Furthermore, it has

Table 7
Compromise programming (CP) results showing normalized distances (Lj) from the ideal solution and factor weights (wj) for each stove setup. Independent variables are auger load time and stove draught; dependent variables are efficiency, global power, CO, PM, O_2, and flue gas temperature. Alternatives 10 (Lj = 0.08) and 13 (Lj = 0.09) perform best, with alternatives 7 and 14 also viables (both Lj = 0.10). Optimal settings correspond to 5.1 s auger load time and 9.6 Pa stove draught.

Alternatives setup for CMWC	Independent variables		Dependent variables						Normalized distance from ideal points for each alternative (*Lj*)
	Auger load time (s)	Stove draught (Pa)	Efficiency (%)	Global power (kW)	CO avg (mg/m^3)	PM (mg/m^3)	O_2 (%)	Flue gas temperature (°C)	
1	3	9.6	0.72	0.97	0.66	0.54	0.86	–	0.62
2	3	12.2	0.72	0.83	0.67	0.58	0.78	0.27	0.64
3	3	15.0	1.00	0.96	1.00	1.00	1.00	0.02	0.96
4	3.7	9.6	0.44	0.66	0.35	0.40	0.41	0.48	0.42
5	3.7	12.2	0.22	0.80	0.48	0.56	0.68	0.38	0.57
6	3.7	15.0	0.90	1.00	0.59	0.60	0.68	0.53	0.64
7	**4.4**	**9.6**	**0.27**	**0.43**	**0.07**	**-**	**-**	**0.70**	**0.10**
8	4.4	12.2	0.37	0.64	0.24	0.08	0.54	0.69	0.25
9	4.4	15.0	0.86	0.83	0.46	0.21	0.81	0.56	0.41
10	**5.1**	**9.6**	**0.27**	**-**	**0.05**	**0.04**	**0.19**	**0.73**	**0.08**
11	5.1	12.2	0.40	0.11	0.15	0.08	0.38	0.99	0.16
12	5.1	15.0	0.47	0.62	0.24	0.12	0.51	0.87	0.27
13	**5.8**	**9.6**	**0.14**	**0.40**	**-**	**-**	**0.14**	**0.77**	**0.09**
14	**5.8**	**12.2**	**0.41**	**0.40**	**0.01**	**0.01**	**0.08**	**1.00**	**0.10**
15	5.8	15.0	–	0.23	0.19	0.09	0.57	0.81	0.19
	Factor weight (w_j)		-	*0.12*	*0.27*	*0.50*	*0.07*	*0.04*	

Table 8
Characteristics of biofuels used for the combustion tests.

Quality standards		Pellet En Plus A1	MWC	CMWC
Origin and source (ISO 17225)		1.1.3 Steamwood 1.2.1 Chemically untreated wood by-products and residues	1.1.1 Whole trees without roots 1.1.3 Steamwood 1.1.4 Logging residues 1.2.1 Chemically untreated wood by-products and residues	1.1.1 Whole trees without roots 1.1.3 Steamwood 1.2.1 Chemically untreated wood by-products and residues
Particle size (P)	*Min. 60 % by weight of the main fraction*	3.15 mm ≤ P ≤ 16 mm	3.15 mm ≤ P ≤ 16 mm	3.15 mm ≤ P ≤ 10 mm
	% by weight of fine fraction (<3.15 mm)	≤1 %	≤1 %	≤5 %
	% by weight of coarse fraction	–	≤5 % > 16 mm	≤10 % > 10 mm and 0 % > 16 mm
	Max. length of particles	3.15<L ≤ 40	≤31.5 mm	≤25 mm
	Thickness	–	–	≤5 mm
Ash content (% of dry weight)		≤0.7 %	≤1.0 %	≤1.0 %
Moisture, M [w]		M10 ≤ 10 %	M10 ≤ 10 %	M10 ≤ 10 %
Net calorific value Q		Q ≥ 16.3 MJ/kg Q ≥ 4.6 kWh/kg	Q ≥ 16 MJ/kg Q ≥ 4.5 kWh/kg	Q ≥ 16 MJ/kg Q ≥ 4.5 kWh/kg
Bulk density, BD		600 kg/mc ≤ BD ≤ 750 kg/mc	BD150 ≥ 150 kg/mc BD200 ≥ 200 kg/mc BD250 ≥ 250 kg/mc	BD ≥ 250 kg/mc

been estimated that over 9,000,000 tons of pellets are consumed in 5.3 million European household pellet plants with a capacity of less than 50 kW [5]. For instance, converting approximately 30 % of European households to utilize this new biofuel would involve approximately 1.6 million users that can help reduce pellet imports by approximately 2.3 million tons, amounting to $720 million. Forestry restoration induced by this transition in the market would facilitate the management of 350, 000 to 400,000 ha of presently unmanaged forests, in accordance with the principles of sustainable forest management [45,46]. Furthermore, the employment rate in the forestry sector [47] indicates that the reactivation of this "sustainable" supply chain could create between 2300 and 2700 employment opportunities in the forestry sector alone, with positive social impacts in economically disadvantaged rural area. In Italy, this new fuel could enable the productive use of approximately 800,000 ha of chestnut forests [48], which are currently underutilized due to the progressive decline of markets for chestnut poles and beams [48,49].

4. Conclusion

The results demonstrate that calibrated mini wood chips (CMWC) can represent a viable and sustainable alternative to conventional pellets for residential heating. Tests conducted on legacy pellet stoves highlighted the possibility of maintaining stable and reliable operation, provided that specific combustion settings are adjusted. Particle-size calibration of the fuel, combined with proper adjustments of auger load time and stove draught, enabled satisfactory efficiency and global power. The operational issues observed with uncalibrated mini wood chips confirm the crucial role of particle-size control, which is essential to ensure compatibility with existing technologies and to prevent mechanical blockages. Nevertheless, emission levels—particularly carbon monoxide—remained higher than current regulatory thresholds, indicating the need for further optimization of combustion parameters or appliance design.

From both an energy and environmental perspective, the adoption of CMWC can strengthen local supply chains, reduce dependence on pellet imports, and enhance the resilience of domestic markets. Despite the lower energy density and the higher storage and transport requirements, the advantages associated with the valorization of regional forest resources and the reduced carbon footprint of the production process are significant. Moreover, the potential to generate new economic and employment opportunities in marginal rural areas, coupled with the contribution to sustainable forest management, reinforces the strategic relevance of this new biofuel. Therefore, the integration of CMWC should be regarded not only as a technical solution for household heating appliances but also as a broader opportunity for energy and environmental policy, fully aligned with the objectives of ecological transition and sustainable territorial development.

CRediT authorship contribution statement

Claudio Fagarazzi: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Andrea Miceli:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Funding received from research project Fondation of Cassa di Risparmio di Firenze Bank 2020.1437 is gratefully acknowledged. The authors also wish to thank the agro-forestry company Fratelli Travaglini from Greve in Chianti – Florence, for supplying the wood chips used in the combustion tests.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2026.125267.

References

[1] G. Martinopoulos, K.T. Papakostas, A.M. Papadopoulos, A comparative review of heating systems in EU countries, based on efficiency and fuel cost, Renew. Sustain. Energy Rev. 90 (2018) 687–699, https://doi.org/10.1016/j.rser.2018.03.060.
[2] E. Heiskanen, K. Matschoss, Understanding the uneven diffusion of building-scale renewable energy systems: a review of household, local and country level factors in diverse European countries, Renew. Sustain. Energy Rev. 75 (2017) 580–591, https://doi.org/10.1016/J.RSER.2016.11.027.
[3] EUROSTAT, Final energy consumption by sector (Residential). https://doi.org/10.2908/TEN00124, 2024.
[4] EUROSTAT, Final energy consumption in households by type of fuel. https://doi.org/10.2908/TEN00125, 2024.
[5] Bioenergy Europe, Statistical report: pellet report 2023. www.bioenergyeurope.org, 2023. (Accessed 20 October 2024).
[6] USDA, Wood pellets annual. https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=WoodPelletsAnnual_TheHague_European Union_E42024-0018.pdf, 2024.
[7] N. Scarlat, J. Dallemand, N. Taylor, M. Banja, Brief on Biomass for Energy in the European Union, 2019, https://doi.org/10.2760/546943. Luxembourg.
[8] Bioenergy Europe, Statistical report: pellet report 2019. www.bioenergyeurope.org, 2019. (Accessed 20 May 2024).

[9] AIEL, Manuale per la certificazione di qualità dei biocombustibili legnosi Parte speciale per la certificazione del cippato. Legnaro (PD) - Italy, 2015. www.aiel.cia.it.
[10] M. Wöhler, D. Jaeger, G. Reichert, C. Schmidl, S.K. Pelz, Influence of pellet length on performance of pellet room heaters under real life operation conditions, Renew. Energy 105 (2017) 66–75, https://doi.org/10.1016/j.renene.2016.12.047.
[11] R. Spinelli, L. Pari, N. Magagnotti, New biomass products, small-scale plants and vertical integration as opportunities for rural development, Biomass Bioenergy 115 (2018) 244–252, https://doi.org/10.1016/j.biombioe.2018.05.004.
[12] T. Persson, M. Rönnbäck, J. Erik Mattsson, B.O. Danielsson, D. Ryde, Chunkwood fuel feeding and combustion experiments in small-scale boilers to provide design suggestions for chunkwood friendly boiler construction, Sustain. Energy Technol. Assessments 71 (2024), https://doi.org/10.1016/j.seta.2024.103986.
[13] G. Reichert, C. Schmidl, M.T. Hansen, Advanced Test Methods for Pellet Stoves, 2022.
[14] M.F. Pereira, V.P. Nicolau, E. Bazzo, Exergoenvironmental analysis concerning the wood chips and wood pellets production chains, Biomass Bioenergy 119 (2018) 253–262, https://doi.org/10.1016/j.biombioe.2018.09.022.
[15] J. Giuntoli, A. Agostini, R. Edwards, L. Marelli, Calculated according to the methodology set in COM(2010) 11 and SWD 259 (2014), https://doi.org/10.2790/25820.
[16] J. Giuntoli, S. Caserini, L. Marelli, D. Baxter, A. Agostini, Domestic heating from forest logging residues: environmental risks and benefits, J. Clean. Prod. 99 (2015) 206–216, https://doi.org/10.1016/j.jclepro.2015.03.025.
[17] Directive (EU) 2023/2413 of the European parliament and of the council. http://data.europa.eu/eli/dir/2023/2413/oj, 2023. (Accessed 20 August 2025).
[18] J.L. Míguez, J.C. Morán, E. Granada, J. Porteiro, Review of technology in small-scale biomass combustion systems in the European market, Renew. Sustain. Energy Rev. 16 (2012) 3867–3875, https://doi.org/10.1016/j.rser.2012.03.044.
[19] A. Anca-Couce, C. Hochenauer, R. Scharler, Bioenergy technologies, uses, market and future trends with Austria as a case study, Renew. Sustain. Energy Rev. 135 (2021) 1–22, https://doi.org/10.1016/j.rser.2020.110237.
[20] L. Da Lio, M. Bortolus, P. Canu, Emissions reduction from wood pellet stoves by uniform feeding, Renew. Energy 242 (2025) 122273, https://doi.org/10.1016/J.RENENE.2024.122273.
[21] B. Sungur, C. Basar, Experimental investigation of the effect of supply airflow position, excess air ratio and thermal power input at burner pot on the thermal and emission performances in a pellet stove, Renew. Energy 202 (2023) 1248–1258, https://doi.org/10.1016/j.renene.2022.12.042.
[22] Z. Cheng, J.H. Leal, C.E. Hartford, J.W. Carson, B.S. Donohoe, D.A. Craig, Y. Xia, R. C. Daniel, O.O. Ajayi, T.A. Semelsberger, Flow behavior characterization of biomass Feedstocks, Powder Technol. 387 (2021) 156–180, https://doi.org/10.1016/j.powtec.2021.04.004.
[23] S. Hinterreiter, H. Hartmann, P. Turowski, Method for determining bridging properties of biomass fuels-experimental and model approach, Biomass Convers. Biorefinery 2 (2012) 109–121, https://doi.org/10.1007/s13399-012-0033-7.
[24] A.H. Bademlioglu, A.S. Canbolat, O. Kaynakli, Multi-objective optimization of parameters affecting Organic Rankine Cycle performance characteristics with Taguchi-Grey Relational Analysis, Renew. Sustain. Energy Rev. 117 (2020), https://doi.org/10.1016/j.rser.2019.109483.
[25] W.H. Chen, M. Carrera Uribe, E.E. Kwon, K.Y.A. Lin, Y.K. Park, L. Ding, L.H. Saw, A comprehensive review of thermoelectric generation optimization by statistical approach: taguchi method, analysis of variance (ANOVA), and response surface methodology (RSM), Renew. Sustain. Energy Rev. 169 (2022) 112917, https://doi.org/10.1016/j.rser.2022.112917.
[26] L. St»hle, S. Wold, Analysis of variance (ANOVA), Chemometr. Intell. Lab. Syst. 6 (1989) 259–272, https://doi.org/10.1016/0169-7439(89)80095-4.
[27] H.J. Keselman, C.J. Huberty, L.M. Lix, S. Olejnik, R.A. Cribbie, B. Donahue, R. K. Kowalchuk, L.L. Lowman, M.D. Petoskey, J.C. Keselman, J.R. Levin, Statistical practices of educational researchers: an Analysis of their ANOVA, MANOVA, and ANCOVA analyses, Rev. Educ. Res. 68 (1998) 350–386, https://doi.org/10.3102/00346543068003350.
[28] R. Kumar, S. Kumar, An extended combined compromise solution framework based on novel intuitionistic fuzzy distance measure and score function with applications in sustainable biomass crop selection, Expert Syst. Appl. 239 (2024), https://doi.org/10.1016/j.eswa.2023.122345.
[29] R. Mena, M. Godoy, C. Catalán, P. Viveros, E. Zio, Multi-objective two-stage stochastic unit commitment model for wind-integrated power systems: a compromise programming approach, Int. J. Electr. Power Energy Syst. 152 (2023), https://doi.org/10.1016/j.ijepes.2023.109214.
[30] L.L. Li, Y. Miao, M.K. Lim, K. Sethanan, M.L. Tseng, Integrated energy system for low-carbon economic operation optimization: pareto compromise programming and master-slave game, Renew. Energy 222 (2024), https://doi.org/10.1016/j.renene.2024.119946.
[31] M. Zeleny, Multiple criteria decision making: eight concepts of optimality, Hum. Syst. Manag. 17 (1998) 97–107, https://doi.org/10.3233/HSM-1998-17203.
[32] I. Bernetti, C. Fagarazzi, L'IMPIEGO DEI MODELLI MULTICRITERIALI GEOGRAFICI NELLA PIANIFICAZIONE TERRITORIALE, AESTIMUM, 2002, pp. 1–26. https://www.sba.unifi.it/upload/policy-oa-2016-1.pdf.
[33] S. Baja, D.M. Chapman, D. Dragovich, Spatial based compromise programming for multiple criteria decision making in land use planning, Environ. Model. Assess. 12 (2007) 171–184, https://doi.org/10.1007/s10666-006-9059-1.
[34] R.W. Saaty, The analytic hierarchy process—what it is and how it is used, Math. Model. 9 (1987) 161–176, https://doi.org/10.1016/0270-0255(87)90473-8.
[35] C. Schön, D. Kuptz, R. Mack, V. Zelinski, A. Loewen, H. Hartmann, Influence of wood chip quality on emission behaviour in small-scale wood chip boilers, Biomass Convers. Biorefinery 9 (2019) 71–82, https://doi.org/10.1007/s13399-017-0249-7.
[36] H. Hartmann, T. Böhm, P. Daugbjerg Jensen, M. Temmerman, F. Rabier, M. Golser, Methods for size classification of wood chips, Biomass Bioenergy 30 (2006) 944–953, https://doi.org/10.1016/J.BIOMBIOE.2006.06.010.
[37] B. Sungur, C. Basar, A. Kaleli, Multi-objective optimization of the emission parameters and efficiency of pellet stove at different supply airflow positions based on machine learning approach, Energy 278 (2023), https://doi.org/10.1016/j.energy.2023.127896.
[38] J.F. González, A. Álvarez Murillo, D. Díaz García, S. Nogales-Delgado, The determination of combustion for different pellets based on ostwald diagrams in a domestic stove under experimental conditions, Appl. Sci. 13 (2023), https://doi.org/10.3390/app132112007.
[39] J. Leskinen, J. Tissari, O. Uski, A. Virén, T. Torvela, T. Kaivosoja, H. Lamberg, I. Nuutinen, T. Kettunen, J. Joutsensaari, P.I. Jalava, O. Sippula, M.R. Hirvonen, J. Jokiniemi, Fine particle emissions in three different combustion conditions of a wood chip-fired appliance - particulate physico-chemical properties and induced cell death, Atmos. Environ. 86 (2014) 129–139, https://doi.org/10.1016/j.atmosenv.2013.12.012.
[40] T. Zadravec, B. Rajh, F. Kokalj, N. Samec, Influence of air staging strategies on flue gas sensible heat losses and gaseous emissions of a wood pellet boiler: an experimental study, Renew. Energy 178 (2021) 532–548, https://doi.org/10.1016/j.renene.2021.05.150.
[41] V. Rebaque, I.S. Ertesvåg, R.F. Mikalsen, A. Steen-Hansen, Experimental study of smouldering in wood pellets with and without air draft, Fuel 264 (2020), https://doi.org/10.1016/j.fuel.2019.116806.
[42] L. Guerrini, A. Tirinnanzi, F. Guasconi, C. Fagarazzi, F. Baldi, P. Masella, A. Parenti, A plackett-burman design to optimize wood chipper settings, Croat. J. For. Eng. 40 (2019) 81–87, https://doi.org/20193278560.
[43] K. Sahoo, E.M. (Ted) Bilek, S. Mani, Techno-economic and environmental assessments of storing woodchips and pellets for bioenergy applications, Renew. Sustain. Energy Rev. 98 (2018) 27–39, https://doi.org/10.1016/j.rser.2018.08.055.
[44] C. Whittaker, I. Shield, Factors affecting wood, energy grass and straw pellet durability – a review, Renew. Sustain. Energy Rev. 71 (2017) 1–11, https://doi.org/10.1016/j.rser.2016.12.119.
[45] M. Lier, M. Köhl, K.T. Korhonen, S. Linser, K. Prins, A. Talarczyk, The new EU forest strategy for 2030: a new understanding of sustainable forest management? Forests 13 (2022) https://doi.org/10.3390/f13020245.
[46] E.Z. Baskent, A thorough assessment of various forest management planning initiatives and development of improvement strategies towards an ecosystem-based planning, Environ. Dev. 50 (2024) 101006, https://doi.org/10.1016/J.ENVDEV.2024.101006.
[47] ISTAT, Rapporto sul Territorio 2020: Capitolo 2 La struttura del territorio. https://doi.org/10.1481/Istat.RapportoTerritorio.2020.2.1.1, 2020.
[48] M.C. Manetti, M. Conedera, F. Pelleri, P. Montini, A. Maltoni, B. Mariotti, M. Pividori, E. Marcolin, Optimizing quality wood production in chestnut (Castanea sativa Mill.) coppices, For. Ecol. Manag. 523 (2022), https://doi.org/10.1016/j.foreco.2022.120490.
[49] F. Carbone, S. Moroni, W. Mattioli, F. Mazzocchi, M. Romagnoli, L. Portoghesi, Competitiveness and competitive advantages of chestnut timber laminated products, Ann. For. Sci. 77 (2020) 1–19, https://doi.org/10.1007/s13595-020-00950-4.