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Characterization of Beech Wood Pellets as Low-Emission Solid Biofuel for Residential Heating in Serbia

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Abstract: This study evaluated the suitability of two types of beech wood pellets as renewable, low-emission biofuel sources in order to combat the energy mix and poor air quality in Serbia. Key solid biofuel characteristics, including the heating values (18.5–18.7 MJ/kg), moisture content (5.54–7.16%), and volatile matter (82.4–84.4%) were assessed according to established standards. The elemental composition (mass fractions of 48.26–48.53% carbon, 6% hydrogen, 0.12–0.2% nitrogen, 0.02% sulfur, non-detected chlorine) and ash content (0.46–1.2%) demonstrated that the analyzed beech pellets met the criteria for high-quality classification, aligning with the ENplus A1 and ENplus A2 standards. The emissions of O_2, CO_2, CO, NO_x, SO_2, and TOC were quantified in the flue gas of an automatic residential pellet stove and compared with the existing literature. While combustion of the beech pellets yielded low emissions of SO_2 (6 mg/m^3) and NO_x (188 mg/m^3), the fluctuating CO (1456–2064 mg/m^3) and TOC (26.75–61.46 mg/m^3) levels were influenced by the appliance performance. These findings underscore the potential of beech wood pellets as a premium solid biofuel option for Serbian households, offering implications for both end-users and policymakers.

Keywords: solid biofuel; beech wood pellets; small-scale heating; emissions; gaseous pollutant

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Citation: Matijašević, V.; Beňo, Z.; Tekáč, V.; Duong, V.M. Characterization of Beech Wood Pellets as Low-Emission Solid Biofuel for Residential Heating in Serbia. *Resources* **2024**, *13*, 104. https://doi.org/10.3390/resources13080104

Academic Editors: Kittisak Jermsittiparsert and Thanaporn Sriyakul

Received: 20 June 2024
Revised: 17 July 2024
Accepted: 23 July 2024
Published: 25 July 2024

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1. Introduction

In response to the global energy crisis and escalating climate change concerns, there has been a notable shift toward renewable energy sources [1–3]. Biomass energy, characterized by its low greenhouse gas emissions, abundance, and versatility, has emerged as a promising alternative to traditional fossil fuels, contributing significantly to energy diversification [4–6]. Currently, bioenergy constitutes approximately 10–14% of the global energy supply, making it the second-largest energy source worldwide, following non-renewable fossil fuels [7]. Solid biofuels, derived from various biomass sources, such as plants, animals, and municipal waste, play a crucial role in electricity generation, heating, and cooking applications. [8,9].

Wood pellets, derived from wood scraps or unprocessed wood, undergo a pelletization process involving cutting, grinding, and compression to yield pellets typically sized between 6 mm and 8 mm in diameter and ranging from 5 mm to 30 mm in length [10,11]. Known for their homogenous structure, high packing density, and concentrated energy content, rendering them superior to traditional solid biofuels such as firewood [12–14], wood pellets are standardized according to the ISO 17225-2 scope [15], which classifies them into quality categories A1, A2, and B based on various properties [16,17]. In Serbia, pellet production primarily utilizes firewood, long-length roundwood, and slabs [18]. Between 2012 and 2015, pellet consumption surged by an average of 20.4% annually, reaching 89,000 tons in 2015, with notable growth in household and commercial usage in the country. However, despite this increase, nearly 40% of the total production is exported, highlighting potential for greater domestic utilization [18]. Pellet production and consumption continued to

grow until 2021, reaching 470,500 tons and 489,500 tons, respectively. However, between 2021 and 2023, pellet production and consumption fell by 17% and 26%, respectively. This decline can be attributed to challenges in securing a steady supply of wood raw materials and warmer winters in Serbia in the past two years [19].

Thermochemical conversion routes for wood pellets primarily involve direct combustion or co-combustion with fossil fuels like coal [19–21]. Larger combustion facilities, exceeding 100 MW, exhibit higher energy efficiency and lower pollutant emissions compared to small-scale domestic appliances [22–24]. In Serbian households, small-scale pellet combustion appliances, including pellet stoves, boilers, and ovens, are used for heat and steam production, with pellet heating accounting for 5.1% of household usage, where pellet stoves represent 0.9% and pellet boilers 6% [25]. Small-scale heating appliances emit pollutants that pose significant health risks, including cardiovascular, respiratory, and nervous system issues, leading to short-term effects and premature death [26]. Emissions vary depending on the appliance type, age, operating conditions, and fuel characteristics [27]. Understanding detailed emission factors for different wood pellets is crucial to prevent and mitigate the adverse effects of biofuel combustion on local air quality.

The majority of wood pellets in Serbia are sourced from beech wood [28], a deciduous species belonging to the genus *Fagus*, comprising approximately 10 timber and ornamental trees endemic to subtropical and temperate regions of the Northern Hemisphere [29]. European beech (*Fagus sylvatica*) is particularly prevalent and significant in Europe [30,31], growing up to 30–50 m and thriving in humid climates with well-drained soil [32,33]. Known for its hardness, wear resistance, and strength, beech finds diverse applications, including furniture building, boat construction, instruments, pulp, and firewood [30,34]. In Serbia, beech constitutes the most common tree type, accounting for 63% of the total tree volume, which amounts to 82,074,497.5 m^3 [35].

This study aims to analyze the fuel characteristics of commercially available wood pellets and the gaseous emissions during the combustion process to supplement the existing database on air quality in Serbia. Two types of beech wood pellets, classified as A1 and A2 according to the producer and devoid of additives or bonding agents, are examined. The analysis includes proximate analysis (moisture, volatile matter, ash, and fixed carbon content), specific energy testing, ultimate analysis of six elements (carbon, hydrogen, nitrogen, oxygen, sulfur, and chlorine), and assessment of the ash melting temperature. The emission measurements encompass oxygen, carbon dioxide, carbon monoxide, sulfur dioxide, nitrogen oxides, and organic gaseous pollutants from combustion within small-scale heating appliances. This research adds valuable data to the existing knowledge on low-emission biofuels and offers practical insights for improving air quality and promoting sustainable energy practices in Serbia and similar regions.

2. Materials and Methods

2.1. Solid Biofuel Characterization

The pellet sampling adhered to ISO 21945:2020 for small-scale applications [36], while the sample preparation followed the ISO 14780:2017 guidelines [37]. The proximate analysis utilized samples with a 2 mm diameter, while the elemental analysis employed samples with a 0.25 mm diameter. The specific energy analysis samples were prepared by compressing previously milled pellets (2 mm diameter) into cylinders measuring 12 mm in diameter and 4 mm in height using a Silfradent 660 hydraulic press.

The proximate analysis of the beech pellets included moisture content measurement (wet basis), volatile matter, ash, and fixed carbon content (dry basis), with three measurements per sample averaged. The moisture content was determined per ISO 18134–3:2015 [38] by drying samples in a 105 °C furnace until constant mass. The volatile matter analysis followed ISO 18123:2015 [39], with the samples dried overnight at 105 °C then heated to 900 °C for 7 min. The ash content, analyzed as per ISO 18122:2015 [40], involved gradually raising the sample temperature to 550 °C overnight. The fixed carbon content was calculated by subtracting the sum of the ash and volatile matter mass fractions from 1.

The specific energy analysis was conducted following the ISO 18125:2017 guidelines [41] using an IKA C 200 bomb calorimeter. The calibration tests were performed with certified benzoic acid. The bomb calorimeter measured the gross calorific value (HHV) [MJ/kg] after 14 min, with benzoic acid as the weight standard. This process was repeated twice for each sample type. The net calorific value (LHV) [MJ/kg] was then calculated from the obtained gross calorific value.

2.2. Emissions Testing

The elemental analysis was conducted in accordance with the ISO 16948:2015 [42] and ISO 16994:2016 [43] guidelines using a Thermo Scientific Flash EA 1112 CHNS analyzer. The carbon, hydrogen, nitrogen, and sulfur contents were determined. The chlorine content was determined following ISO 16995:2015 [44] using a titration method with 0.01 M silver nitrate ($AgNO_3$) and 5% potassium chromate (K_2CrO_4) as an indicator. A calibration curve was established using a sodium chloride (NaCl) standard solution. The oxygen content was calculated by subtracting the combined mass fractions of ash and carbon, hydrogen, nitrogen, sulfur, and chlorine from 1.

The determination of the ash melting temperature was performed following the ISO 21404:2020 guidelines [45]. The samples were prepared and subjected to controlled temperature increases from room temperature to 250 °C (5 °C per min) for 180 min, followed by a ramp to 550 °C (10 °C per min) for 120 min. After cooling, the ash samples were moistened with ethanol, compressed into cylindrical molds using a spring press, and heated incrementally. Changes in the ash shape were recorded, including the deformation temperature (DT), shrinkage starting temperature (SST), hemisphere temperature (HT), and flow temperature (FT). Temperature recordings were taken at 5 °C intervals from 550 °C onward to accurately determine the ash melting characteristics.

The emissions from the pellet combustion were measured by determining the mass concentration and flow of pollutants generated during residential heating appliance operation. Due to the limitations of the prevailing methods, the pollutant mass flow was derived from the concentration and waste gas flow rate. In small-capacity appliances (<200 kW), the fuel gas flow rate measurement uncertainty led to computation using the fuel consumption, composition, flue gas composition, and combustion stoichiometry. Continuous analysis of the O_2, CO, CO_2, SO_2, NO, and NO_2 utilized a PG 350 gas analyzer (HORIBA) with ±2% relative uncertainty. The gas composition analysis employed paramagnetic, chemiluminescence, and non-dispersive infrared spectroscopy methods. The organic compounds were measured as the total organic carbon (TOC) using a THERMO FID analyzer (SK-Elektronik GmbH). The pollutant volume fractions were measured directly, and the TOC volume fraction in wet flue gas was recalculated into the dry flue gas volume fraction. The mass concentration was calculated using established equations. The flue gas flow was assumed to contain only CO_2, water vapor, excess oxygen, and nitrogen for the flow calculation. The pollutant emission factor, both mass-based and energy-based, was calculated accordingly.

The combustion experiment utilized the Toledo IV 32 automatic residential space heater produced by Haas + Sohn, operating within the framework of European standard EN 16510-1:2018 [46]. Developed by the UCT Prague Emission and Immissions Measurement Laboratory, the apparatus features core components in line with standard specifications. The pellets were conveyed to the burner pot via a rotating auger conveyor, initiating combustion through an electric spark ignition system. The primary combustion air entered through the bottom and side openings, while the unburned material descended to the ash pan. Cleaning cycles, occurring every 30 min, increased the air volume to remove ash and residue. The actual operation of the test appliance was monitored on a touch screen panel. The technical parameters, dimensions, and performance characteristics are detailed in Table 1.

Table 1. Specifications of the residential space heater model Toledo IV 32.

Parameter	Value	Unit
Nominal heat output	8	[kW]
Range of heat output	2.4–8.3	[kW]
Type of fuel	Wood pellets	
Start-up method	Electric ignition	
Capacity of pellet hopper	32	[kg]
Combustion time per hopper (min./max.)	20/60	[h]
Thermal efficiency	90/95	[%]
Temperature of flue gas	206	[°C]
Chimney draught at nominal heat output	11	[Pa]
Chimney draught at minimal heat output	5	[Pa]
Flue gases mass flow rate	5.6	[g/s]
Dimensions		
Height	1201	[mm]
Width	544	[mm]
Depth	499	[mm]
Flue gas outlet diameter	80	[mm]
Weight	110	[kg]

Figure 1 illustrates the layout of the test bench, including the construction arrangement and measurement devices. The test setup involved connecting the measurement section of the appliance to the flue socket using an uninsulated flue connector and flue adapter, with the steel flue connector measuring 2 m in length, 1 mm in thickness, and Ø 80 mm in diameter. Integration with the downstream measuring section, as shown in Figure 1, was facilitated through the flue adapter. This downstream measuring section encompassed the temperature, pressure, and gaseous inorganic pollutants and TOC measurements, featuring a diameter matching that of the flue socket. The temperature readings were captured using GMH 3200 series thermoelements, while the chimney draught was monitored with GMH 3100 series differential manometers by Greisinger GmbH, with the manufacturer's recommended optimal pressure ranging between 5 and 15 Pa. Two exhaust gas samples were collected for quantitative analysis, with solid particles removed using PSP 4000-H gas sample probes by Testo AG equipped with sintered ceramics filters, heated to 200 °C for effective particle elimination. The conditioned gas sample was transported via heated pipes operating at 200 °C, with a THERMO FID analyzer by SK-Elektronik GmbH installed directly on the heated line for determining the gaseous organic compounds. The moisture content in the gas sample was eliminated using a PSS 5 cooling and drying unit from M&C Tech Group installed on a separate pipeline. Following gas conditioning, the PG 350 analyzer by HORIBA was employed for the determination of the O_2, CO, CO_2, SO_2, NO, and NO_2 in the exhaust gas. The analyte values were recorded at 30 s intervals within the internal memory of the measuring apparatus and later manually transferred to a computer via USB.

The test procedure encompassed two distinct phases: the pre-test and the main test phase. During the pre-test, a sufficient quantity of pellets was loaded into the pellet hopper through the top stove hatch to establish stable combustion conditions. This phase commenced from a cold start and lasted approximately 30 min to ensure optimal conditions before initiating the measurement test phase. Each test measurement for the different pellet types was preceded by this pre-test period.

For the A1 and A2 class beech pellets, the main test phase involved adding 5 kg of pellets to the appliance hopper at the beginning of the test. After the combustion of the first batch, an additional 5 kg of pellets was added. The pellet consumption was determined based on the remaining pellets in the hopper at the end of the test. The air to fuel ratio (λ) was maintained at approximately 1.5, ensuring optimal combustion conditions. The temperature in the furnace, where the pellets were combusted, was consistently monitored and maintained within the range of 800–900 °C throughout the test runs. The test duration was 6.25 h (375 min), as detailed in Table 2.

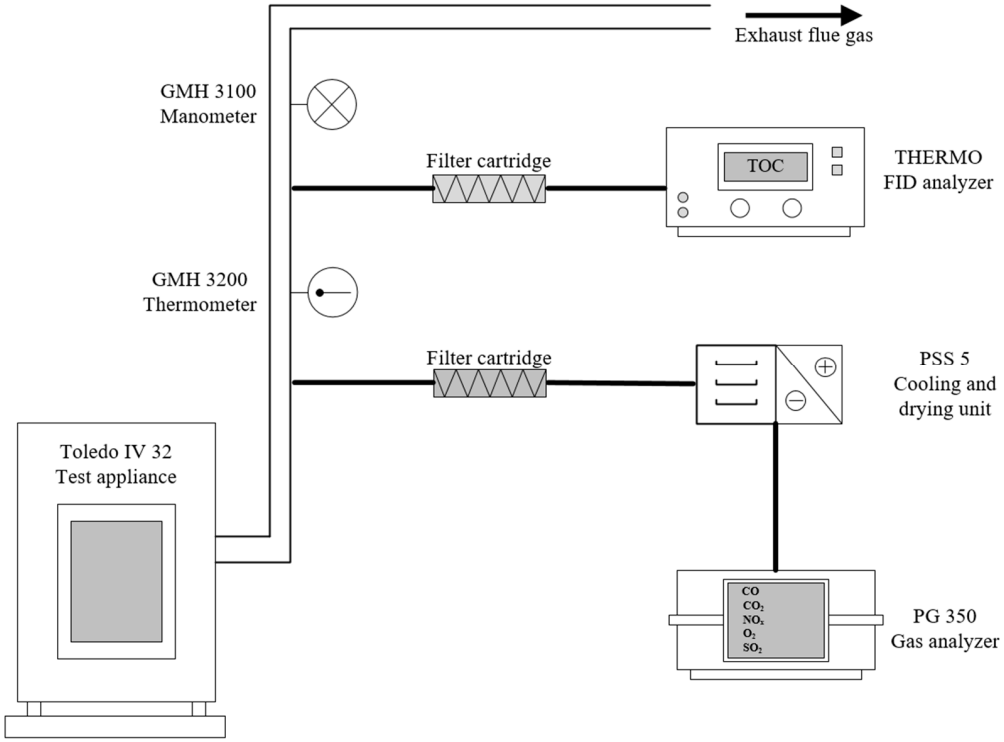


Figure 1. Schematic layout of the test bench equipment arrangement.

Table 2. Parameters recorded during the test run of the investigated beech pellets.

Parameter	Value		Unit
	A1	A2	
Start time	08:45	16:45	[hh:mm]
End time	15:00	23:00	[hh:mm]
Actual measurement duration	6.25	6.25	[h]
Solid biofuel mass	9.92	11.25	[kg]
Solid biofuel mass flow	1.587	1.800	[kg/h]
Ambient temperature	9.3	7.0	[°C]
Atmospheric pressure	1024	1023	[hPa]
Atmospheric relative humidity	59	69	[%]
Average room temperature	20.1	19.5	[°C]
Average exhaust gas temperature	193.5	211.3	[°C]
Average negative pressure in the exhaust gas draught	34.2	35.3	[Pa]
Average exhaust gas flow rate at standard conditions	17.11	19.6	[m^3/h]
Air to fuel ratio (λ)	1.5	1.5	[-]
Power consumption	27.30	31.71	[MJ/h]

Throughout the test run with the A1 class beech pellets, the average pellet consumption rate was calculated to be 1.587 kg/h, resulting in a total consumption of 9.92 kg over the 6.25 h period. The average room temperature during this test was recorded at 20.1 °C, with the average flue gas temperature measured at 193 °C, the exhaust gas draught pressure averaging 35.3 Pa, and the flow rate at 17.11 m^3/h. The combustion of the A1 class beech pellets yielded ash characterized by a fine particle size and homogeneous distribution.

During the 6.25 h test run with the A2 class beech pellets, a total of 11.25 kg of pellets was combusted, corresponding to an average consumption rate of 1.80 kg/h. The ambient temperature in the test room was recorded at 19.5 °C, with an average exhaust gas temperature of 211.3 °C and an exhaust gas draught pressure averaging 35.3 Pa. The average flue gas flow rate was measured at 19.6 m^3/h. The combustion of the A2 class beech pellets also resulted in the production of ash characterized by a fine particle size.

3. Results and Discussion

The fuel characterization analysis results for the beech wood pellets of quality classes A1 and A2 are summarized in Table 3, depicting the mean values of the proximate analysis and specific energy. These results provide insights into the composition and properties of the pellets, including the major elements, moisture content, volatile matter, ash content, and fixed carbon across different bases: raw, dry, and dry ash-free (daf).

Table 3. Characteristics of the analyzed pellets as the test solid biofuel.

Parameter	Value						Unit
	A1			A2			
	Raw	Dry	Daf	Raw	Dry	Daf	
Proximate analysis							
Moisture content	7.16	0.00	0.00	5.54	0.00	0.00	[%]
Volatile matter	78.35	84.40	84.79	77.88	82.45	83.45	[%]
Ash content	0.43	0.46	0.00	1.13	1.20	0.00	[%]
Fixed carbon	14.06	15.15	15.21	15.45	16.35	16.55	[%]
Specific energy							
HHV	17,205	18,532	18,617	17,620	18,653	18,879	[kJ/kg]
LHV	15,804	17,211	17,290	16,253	17,349	17,559	[kJ/kg]
Ultimate analysis							
C	45.06	48.53	48.75	45.59	48.26	48.84	[%]
H	5.62	6.06	6.09	5.65	5.98	6.05	[%]
N	0.11	0.12	0.12	0.19	0.20	0.20	[%]
S	0.04	0.04	0.04	0.00	0.00	0.00	[%]
Cl	0.00	0.00	0.00	0.00	0.00	0.00	[%]
O	41.58	44.79	44.99	41.91	44.37	44.90	[%]
Ash melting temperature							
DT		890			980		[°C]
SST		900			1000		[°C]
HT		1450			1430		[°C]
FT		1460			1440		[°C]

3.1. Fuel Characterization

For the A1 type pellets, the dry basis analysis reveals a carbon mass fraction of 48.53% and hydrogen at 6.06%, contributing to a higher heating value of 18.5 MJ/kg, which indicates a high potential heat release [47]. The moisture content of 7.16% falls within the normative range of 5–10% for wood pellets, with minimal influence on the combustion behavior and gross calorific value. The high volatile matter mass fraction of 84.4% on the dry basis indicates significant vaporization before the gas phase homogeneous combustion reaction occurs, influencing the thermal decomposition [48]. The nitrogen content of 0.12%, sulfur content of 0.04% and chlorine content under the level of detection on the dry basis meet the specifications for ENplusA1 class pellets, being $\leq$0.3%, $\leq$0.04% and $\leq$0.02% respectively, as specified by the ISO 17225-2 scope [15]. Additionally, the ash content of 0.46% is within the range requirements of class A1 and the statement of the producer, being a mass fraction of $\leq$0.7% on the dry basis. The low ash level suggests adequate pre-treatment of the pellets and minimal influence on the combustion conditions, the process of the de-ashing, and ash disposal [49]. Furthermore, the ash melting temperatures were observed, showing signs of deformation and starting to shrink at 890 °C and 900 °C, forming a hemisphere shape at 1450 °C, and finally, spreading out in a thin layer at 1460 °C.

On the other hand, the A2 class beech pellets exhibit slightly lower carbon and hydrogen mass fractions of 48.26% and 5.98% on a dry basis, indicating a high potential heat release, which resulted in a higher heating value of 18.7 MJ/kg [47]. Furthermore, a moisture content of 5.54% is at the low end of the normative range of 5–10%, presenting a negligible effect on the higher heating value and the combustion behavior. The volatile matter mass fraction of 82.4% on the dry basis implies that the largest fraction of the beech pellets was vaporized before gas phase combustion occurred [48], similarly to the A1 pellets.

The mass fractions of nitrogen of 0.2% and sulfur and chlorine, which were under the limit of detection, on the dry basis were within the scope of the ISO 17225-2 specifications of ≤0.5% for nitrogen, ≤0.05% for sulfur and ≤0.02%, the specified limits for the ENplus A2 class of wooden pellets [15]. Additionally, the ash content of 1.2% meeting the ENplus A2 class requirements of ≤1.2% further confirms the manufacturer's diligent pellet pre-treatment, as well as its minimal impact on the combustion conditions, the de-ashing process, and ash disposal procedures [49]. The ash melting temperatures were relatively elevated, as evidenced by the observation of the edge rounding of the ash test piece at 980 °C, shrinking occurring at 1000 °C, and the formation of a hemispherical shape and thin layer at 1430 °C and 1440 °C, respectively. The elevated ash melting temperatures indicate a tendency for volatile inorganic compounds to decrease, with partial decomposition observed in key ash-forming elements [25].

A comparison between the A1 and A2 beech wood pellets reveals a notable difference in the ash content, with the A1 pellets having a significant 2.6 times lower mass fraction. This suggests potential differences in the quality of the pre-treatment process, such as the cleaning, barking, or sieving of wood feedstock for the pelletization of the A1 and A2 class pellets. The gross calorific values of 18.5 MJ/kg and 18.7 MJ/kg on the dry basis for the A1 and A2 classes, respectively, exhibit a minimal disparity, which is unsurprising given the closely comparable mass fractions of carbon, hydrogen, and volatile matter in these pellet types. Nonetheless, the A2 beech pellets exhibit a moisture content 1.29 times lower than that of the A1 variant, resulting in a higher gross calorific value on the raw basis. Specifically, the raw basis values of both variants are 17.6 MJ/kg and 17.2 MJ/kg, respectively. Additionally, the nitrogen content of the A1 class pellet is 1.67 times lower, whereas the sulfur content is slightly higher compared to the A2 pellets.

Several studies have assessed the fuel properties of beech wood pellets in recent years [50–53]. A study in 2019 reported a gross calorific value of 19,113 ± 102 kJ/kg and an ash content of 3.09%, both higher than our measured values [51]. The study by B. Ciupek and K. Gołoś indicated carbon and hydrogen contents of 41.5% and 4.77%, respectively, with ash and moisture values of 2.1% and 18%, and a gross calorific value of 16.1 MJ/kg [52]. In comparison, the Serbian beech pellets exhibit superior fuel characteristics, with higher calorific values due to the greater carbon and hydrogen content, and a significantly lower ash and moisture content. M. Masche et al. reported a moisture content of 8.4% and a high calorific value of 18.4 MJ/kg for beech pellets, closely aligning with our findings for Serbian A1 pellets [53]. Additionally, a study in 2023 on the ash melting temperatures of various wood pellets found similar values for beech sawdust pellets, with hemisphere and flow temperatures of around 1500 °C [54]. Several studies have also analyzed the fuel characteristics of wood pellets made from oak and pine trees [52,55–58]. Oak wood pellets generally exhibit moisture and ash content similar to our examined beech pellets and have a gross calorific value that is comparable or slightly higher [55–57]. Pine pellets show similar ash and moisture content, but their gross calorific value is slightly lower than that of beech pellets [52,58]. According to J. I. Arranz et al., pine wood pellets have ash melting temperatures of around 1200–1300 °C, lower than those of beech pellets, while oak pellets exhibit slightly better ash melting temperatures, with HT and FT over 1500 °C [59].

3.2. Emission Profile Analysis

The combustion of beech pellets primarily emits oxygen, carbon dioxide, carbon monoxide, nitrogen oxides, sulfur dioxide, and organic compounds, consistent with the expected chemical reactions during solid wood biofuel combustion. Table 4 provides comprehensive data on the measurement readings, mass concentration, average mass flow, and emission factor of these six main gas components in the exhaust gas stream from the combustion of A1 and A2 class beech pellets.

Table 4. Emissions of gaseous compounds from the test runs of the examined beech pellets.

Air Pollutant	Value		Unit
	A1	A2	
Measurement readings			
Oxygen	15.42	14.36	[%]
Carbon dioxide	5.30	6.35	[%]
Carbon monoxide	1149	815	[ml/m^3]
Nitrogen oxides as NO_2	63.9	93.7	[ml/m^3]
Sulfur dioxide	1.5	1.6	[ml/m^3]
Total organic carbon as C_3H_8	26.4	11.5	[ml/m^3]
Mass concentration at standard conditions			
Carbon monoxide	2064	1465	[mg/m^3]
Nitrogen oxides as NO_2	188	276	[mg/m^3]
Sulfur dioxide	6.08	6.47	[mg/m^3]
Total organic carbon as C_3H_8	61.46	26.75	[mg/m^3]
Average mass flow			
Carbon monoxide	35.31	28.72	[g/h]
Nitrogen oxides as NO_2	3.22	5.41	[g/h]
Sulfur dioxide	0.10	0.13	[g/h]
Total organic carbon as C_3H_8	1.05	0.52	[g/h]
Average emission factor referring to the fuel quantity			
Carbon monoxide	22.25	15.96	[g/kg]
Nitrogen oxides as NO_2	2.03	3.01	[g/kg]
Sulfur dioxide	0.07	0.07	[g/kg]
Total organic carbon as C_3H_8	0.66	0.29	[g/kg]
Average emission factor referring to the fuel energy content			
Carbon monoxide	1293	906	[mg/MJ]
Nitrogen oxides as NO_2	118	171	[mg/MJ]
Sulfur dioxide	4.1	4.0	[mg/MJ]
Total organic carbon as C_3H_8	39	17	[mg/MJ]

Throughout the test runs for both the A1 and A2 class beech pellets, the volume fractions of oxygen, carbon dioxide, carbon monoxide, sulfur dioxide, nitrogen oxides (expressed as NO_2), and gaseous organic compounds (expressed as the total organic carbon) were monitored in the exhaust gas and reported as percentages for O_2 and CO_2 or in ml/m^3 for NO_2, SO_2, CO and total organic carbon. Subsequently, the volume fractions were converted into mass concentrations under standard conditions [mg/m^3] and then further transformed into the average mass flow of the analytes [g/h], average emission factor [g of analyte per kg of burnt fuel], and emission factor based on the energy content of the fuel [mg/MJ]. The emission factor based on the fuel energy content is particularly noteworthy as it quantifies the pollutants emitted per unit of energy generated during fuel combustion. This parameter enables a comparison of the emission levels and environmental impacts among different solid biofuels.

Figure 2 complements the data presented in Table 4 by illustrating the emission profiles of the main gaseous components in the exhaust gas stream during the 6.25 h test runs for both the A1 and A2 class beech pellets, demonstrating how the volume fractions of these gases change over time. The fluctuation of the oxygen levels, a critical factor influencing emissions, was observed in 30 min intervals, with average volume fraction values of 15.42% (beech A1) and 14.36% (beech A2). Figure 2 illustrates that variations in the O_2 fraction correlated with changes in the volume fractions of CO_2, CO, SO_2, NO_2, and TOC. These fluctuations coincided with the burn test conducted by the heating appliance software every 30 min, during which an increased volume of air was blown into the burner.

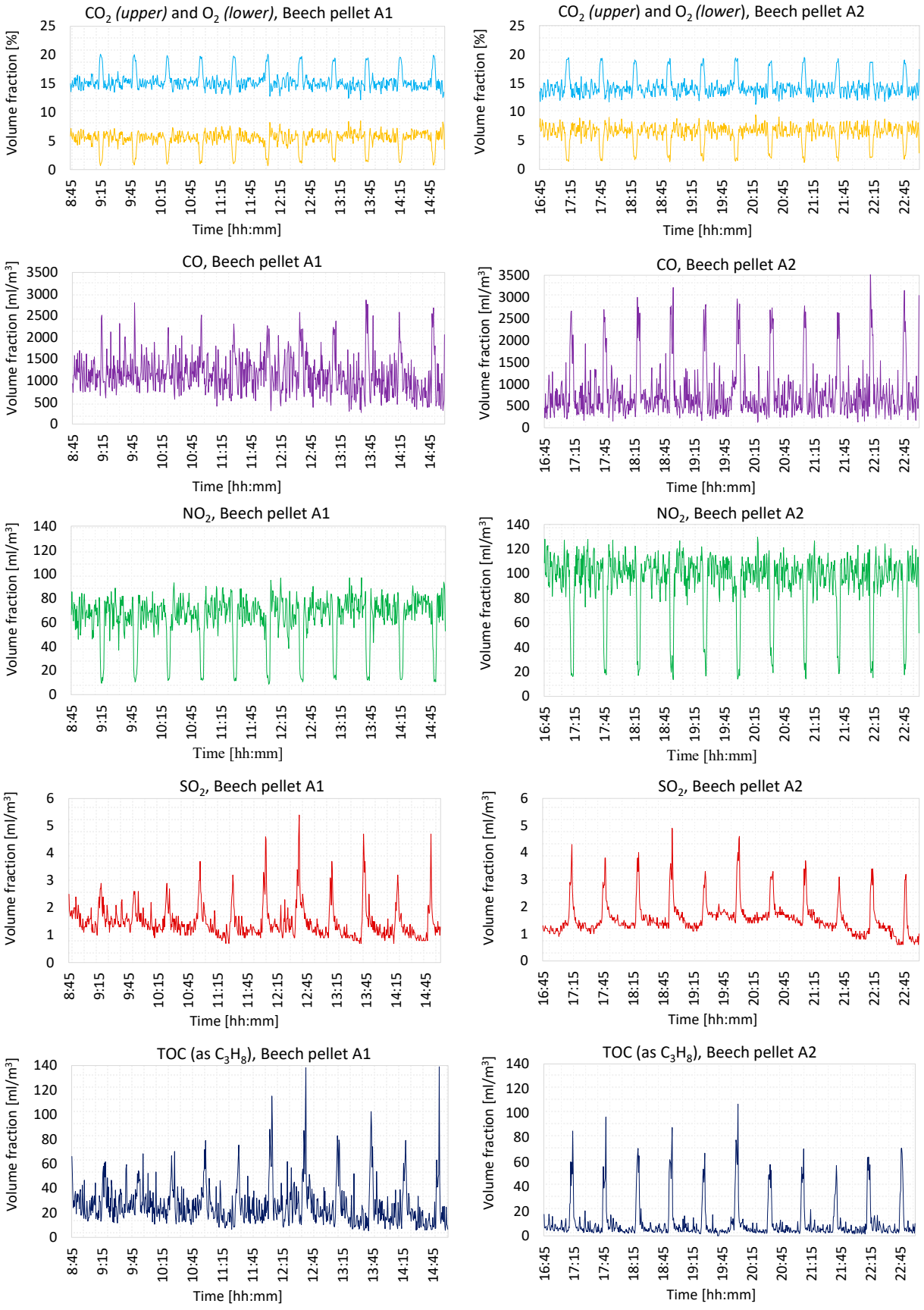


Figure 2. Emission profiles from the test runs of the investigated beech pellets.

During these fluctuations, the CO, SO_2, and TOC values increased due to suboptimal combustion conditions resulting from the low flame temperatures. Conversely, the NO_2 emissions decreased due to the reduced production of NO_x from atmospheric nitrogen in the lower temperature flame. The average volume fraction of the CO emissions was 1149 mL/m^3, corresponding to a mass concentration of 2064 mg/m^3 under standard conditions, resulting in an emission factor of 1293 mg/MJ for the beech A1 pellets. For the beech A2 pellets, the average volume fraction of the CO emissions was 815 mL/m^3, with a corresponding mass concentration of 1456 mg/m^3 and an emission factor of 906 mg/MJ, as summarized in Table 4. These elevated CO levels, accompanied by fluctuating patterns, indicate incomplete combustion, which is a significant concern in non-industrial practice, suggesting that the current combustion process needs improvement. The variability in the CO emissions can be attributed to several factors inherent to small-scale residential combustion settings, including the operational load, mechanical feeding, turbulence within the combustion chamber, and ash deposits in the fire bed. Additionally, the reduction of the flame affects both the temperature level and oxidation efficiency, crucial factor impacting the CO emission levels. Optimizing the combustion parameters, enhancing the air distribution, and ensuring proper ventilation could potentially mitigate incomplete combustion with elevated CO levels [60].

The nitrogen oxide (NO and NO_2) emissions were aggregated as NO_2. For beech pellet class A1, the nitrogen dioxide volume fraction ranged from 8.7 to 97.2 mL/m^3, with an average of 63.9 mL/m^3 and a mass concentration under normal conditions of 188 mg/m^3. The energy-based NO_2 emission factor was 118 mg/MJ, consistent with values reported in previous studies [61,62]. Studies by J. A. Perez [60], O. Sippula [61], and G. Shmidt [62] indicated lower NO_2 emissions for spruce stem pellets (95 $\pm$ 28 mg/MJ), willow stem pellets (103 $\pm$ 28 mg/MJ) and pine stem pellets (82 $\pm$ 16 mg/MJ) compared to the beech class A1 pellets analyzed here. Conversely, higher NO_2 emissions were observed for pine bark (131 $\pm$ 28 mg/MJ), willow bark (282 $\pm$ 74 mg/MJ) and oak pellets (147 $\pm$ 30 mg/MJ). For the beech pellets class A2, the NO_2 volume fraction ranged from 13.7 mL/m^3 to 129.7 mL/m^3, averaging 93.7 mL/m^3, with a mass concentration under normal conditions of 276 mg/mL, higher than the recorded average values of the A1 class beech pellet NO_2 emissions. The difference in the NO_2 content between the two beech pellet types can be attributed to the higher oxygen volume fraction during combustion of the A1 pellets, indicating a lower flame temperature and thus lower NO_x production from air nitrogen, as well as the higher nitrogen content of the A2 class beech pellets, which converted into NO_x during combustion (see Table 3). The calculated NO_2 emission factor value was 171 mg/MJ, slightly higher than the values reported for the pine, spruce, and oak pellets in previous studies [60–62].

The sulfur dioxide volume fraction in the exhaust gas stream exhibited low average values of 1.5 mL/m^3 and 1.6 mL/m^3, with average mass fractions under referent conditions of 6.08 mg/m^3 and 6.47 mg/m^3, for beech pellets class A1 and A2, respectively. The SO_2 emissions observed in thermochemical conversion facilities' exhaust gas streams are notably influenced by the sulfur content present in the fuel. Given the low sulfur content of beech pellets (see Table 3), these low emissions are consistent with expectations. Typically, solid wood biofuels contain trace amounts of sulfur or soluble forms of sulfur. In our experiment with beech wood pellets, we ensured uniform quality by pelletizing them cylindrically without alkaline-based additives or washing processes, thereby minimizing the initial sulfur and non-metallic element removal through mixing or pre-treatment. The slightly higher values observed for the beech A2 pellets, despite their non-detected sulfur content, can be attributed to CH_4 interference with the detection method. The calculated emission factors based on the fuel energy content were 4.1 mg/MJ for the A1 pellets and 4.0 mg/MJ for the A2 pellets, falling at the lower end of the spectrum compared to the values reported in a study on emissions from small-scale boilers. In that study, the emission factors ranged from 0.05 mg/MJ to 13.3 mg/MJ for wood pellets and from 37.6 mg/MJ to 41.4 mg/MJ for crop straw pellets [63].

The volume fraction and mass fraction under standard conditions of total organic carbon in the exhaust gas for the A1 beech pellets were measured at 26.4 mL/m^3 and 61.46 mg/m^3, respectively. Similar to the CO values, the measured values for the A2 class beech pellets were lower, at 11.5 mL/m^3 and 26.75 mg/m^3, under standard conditions. The observed higher emissions of both pollutants from the A1 beech pellets can be attributed to incomplete combustion, likely stemming from the higher moisture content of the A1 pellets compared to the A2 pellets, as indicated by data in Table 3. Additionally, the higher chimney draught during combustion of the A1 pellets, as evidenced by a higher oxygen volume fraction in the exhaust gas, may further contribute to the observed emissions differences between the A1 and A2 pellets.

The stable combustion of the A1 and A2 class beech pellets, coupled with the low emissions of gaseous pollutants, aligns with the values reported for various wood pellets obtained in earlier studies. These findings underscore the suitability of beech pellets as a high-quality biofuel for combustion in household pellet stoves.

4. Conclusions

This study provides valuable insights into the properties of Serbian beech (*Fagus Sylvatica*) biomass pellets and their potential utilization in small-scale combustion units. The comprehensive analysis of the beech pellets, covering the physicochemical properties, fuel quality, and ash characteristics, demonstrates their suitability as a desirable wood biofuel. Moreover, based on their elemental composition, ash content, and moisture content, the beech pellets meet the requirements for the high-quality class ENplus A1 and ENplus A2 specified by the normative reference ISO 17225–2:2021.

The combustion of beech pellets in the small-combustion appliance was found to be efficient, resulting in complete combustion and the production of fine gray ash residues. The recorded emissions of NO_x and SO_2 were notably low, underscoring the environmentally friendly nature of the beech pellets. However, the emissions of organic gaseous pollutants and CO exhibited some variability, likely due to the inherent limitations of the test appliance, indicating the need for further refinement of combustion technology for residential applications involving solid biofuel. Nonetheless, the measured emissions did not significantly deviate from those observed in previous studies involving different types of wood pellets.

Overall, this study highlights the favorable characteristics and importance of beech pellets as a renewable, low-emission fuel. By offering an effective means of diversifying the energy mix, promoting sustainable energy practices, and mitigating poor air quality in urban areas of Serbia, beech pellets represent a promising solution for advancing toward a greener and more environmentally conscious future.

Author Contributions: Conceptualization, V.M.D.; methodology, V.T. and V.M.D.; validation, V.T. and Z.B.; formal analysis, V.M., V.T. and Z.B.; investigation, V.M.D. and Z.B.; resources, V.T.; data curation, V.M. and Z.B.; writing—original draft preparation, V.M.; writing—review and editing, V.M.D. and V.M.; visualization, V.M.; supervision, V.M.D.; project administration, V.M.D.; funding acquisition, V.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author.

Acknowledgments: The authors gratefully acknowledge the European Commission for their coordination and support throughout the project IMATEC within the Erasmus + Programme, Key Action 1, which facilitates scientific collaboration among European research institutions. We would also like to express special gratitude to the analytical expert group at the coordinating institutions for their invaluable insights, excellent consulting, and outstanding expertise. Their contributions have been instrumental in the success of this research endeavor.

Conflicts of Interest: The authors declare no conflicts of interest.

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