

Article

Assessment of the Possibility of Using Hemp Biomass (*Cannabis Sativa* L.) for Energy Purposes: A Case Study

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Abstract: During testing, the possibility of using hemp biomass for energy purposes was assessed. The criteria assessed were the physical and chemical properties of hemp biomass, as well as the combustion process of straw and briquettes made of it in a low-power boiler. The results were made and compared with currently applicable standards. Technical and chemical properties of hemp biomass are comparable with the best plants used for energy purposes. Studies have also shown the susceptibility of hemp biomass compaction. However, large emissions recorded during the combustion of the tested forms of biofuels from hemp straw in light of applicable standards disqualify this fuel for use in grate-type heating devices with air fed under the grate. It would be advisable to carry out research on the total costs of pellet production and their use in heating devices with a retort burner, while taking into account this biofuel's ashes' susceptibility of sintering.

Keywords: hemp; biomass transformation; combustion; bioenergy

1. Introduction

Hemp (*Cannabis sativa* L.) is grown for various purposes of using the fibre, chaff and seeds. It is one of the oldest non-food crops in the world. In Europe, hemp, together with flax, were the most important fibre plants from the 16th to 18th centuries. Later, hemp cultivation diminished but, recently, in many countries, such as Germany, France, the Netherlands, Great Britain, Spain and Italy, interest in this plant is growing, particularly in properties other than fibre [1,2]. Hemp has been rediscovered as an interesting industrial plant with great uses that can be grown under a wide range of agro-ecological conditions, and is more efficient compared to many other plants [3–5]. Due to biological and agrotechnical features corresponding to economic, environmental and social criteria, this plant fits very well with the concept of sustainable development. It is important that hemp biomass is also processed into a number of hemp-derived products, including oil, essential oils or CBD (cannabidiol) substances, building material and biofuel, thereby producing many components that have been of great interest to people lately. Properties of this plant have made it an excellent raw material for the development of multi-output systems through gradual distribution of biomass into several useful components. This feature is ahead of many other industrial crops, from which only one type of raw material is usually extracted [2,5].

Hemp as a species also has one major drawback: it is associated with the production of illegal drugs. As a consequence, only registered hemp cultivars that are reported for cultivation can be the source of this valuable raw material.

Growing hemp is not difficult and requires little or often no biocides for cultivation because this plant effectively suppresses weeds and has limited requirements for the fertilizers used and crop rotation. The main problem may be establishing a crop because hemp is very sensitive to poor soil structure and water shortage or excess during the early stages of growth. There is also a high degree of heterogeneity in cultivation. This is partly due to sexual dimorphism: differences in growth and development rates between male and female plants are large. Larger plants suppress smaller ones, thus, the variation between plants can become significant. Male plants tend to age earlier [6–8]. In terms of growing hemp, due to the abundant vegetative part of the plants, large biomass increases (up to 50 cm/month) show great opportunities to use solar energy and CO₂ during photosynthesis (up to 2.5 Mg·ha⁻¹), which strengthens its position in the group of energy plants contributing to renewable energy sources. Particularly important is the pile root system of hemp, which can use nutrients and water found in deeper layers of soil, which creates good conditions for its production as well as obtaining high yields of organic matter. These features are important in connection with global warming and the lowering of the ground water level, especially in areas with small amounts of precipitation (<550 mm) [4,5,9–11].

In terms of its energy use, it is important that the green crop yield from hemp is, on average, 14.5 t·ha⁻¹ [12] (calculated on the dry matter), of which 70–75% are hemp shives (by-products of hemp processing), which are usually left in the field, constituting organic fertilizer [5]. It is possible to obtain approximately 10.5 t·ha⁻¹ of raw material, which can be potentially used for energy purposes. At the same time, hemp biomass shows a significant variation in fuel properties (calorific value, heat of combustion, ash content, ash softening temperature) depending on the season in which the harvest takes place. Research conducted by Prade et al. [13–15] shows a qualitative advantage of hemp harvested in spring and winter over that harvested in autumn, e.g., the heat of combustion of hemp biomass collected in August–December was, on average, 18.4 MJ·kg⁻¹, versus that collected in January–April of 19.1 MJ·kg⁻¹, while research by Kołodziej et al. [16] indicate that the heat of combustion of these plants is greater than the heat of Jerusalem artichoke (*Helianthus tuberosus*) (16.5 MJ·kg⁻¹) and only slightly smaller than the heat of burning *Miscanthus*, ca. 19.8 MJ·kg⁻¹.

Features of the raw materials of plant origin have a decisive influence on the process of their pressure agglomeration and on the quality of the obtained product [10,17]. There are three main activities necessary to produce molded solid fuel: drying, comminution and molding. Each of them, due to the mechanical properties of the fibre, requires an individual approach, however, due to the energy consumption of these processes, it would be expedient to use hemp biomass in the form of bales and cubes for energy purposes [18,19]. Broader possibilities of using hemp biomass are given by its thermochemical transformation in biogas and ethanol production where both wet and ensiled biomass can be used [20]. However, these processes, according to Kreuger [21], are economically dependent on the market prices of the raw material and require the cheapest raw materials for profitability. At the same time, the use of silage hemp for this production is very uncertain, because the ensilage process is not yet very popular in the Lublin region. In Lublin region however biomass is available on the market as a residue from hemp seed production. As indicated by Ivanova et al. [22], grinding the hemp to a particle diameter of 8 mm requires an energy consumption of 117 kWh·t⁻¹, which is about 50% smaller than the briquetting capacity for fruit biomass at 25 kg·h⁻¹. However, compaction itself requires an energy demand of about 110 kWh·t⁻¹, which is almost 40% more energy-intensive than for fruit wood. At the same time, problems related to cutting the hemp biomass are the subject of research on reducing its energy consumption and optimizing the efficiency of this process [23,24]. Therefore, when assessing the energy use of hemp, energy balance and energy efficiency are important, which are key to clarifying the following doubts: indicating how much energy the crop produces per

unit of energy input; and the energy balance can reveal existing reserves and optimization of energy expenditure in the production process.

In the absence of high-pressure aggregation, the energy density of the plant material is low. Increasing this parameter is obtained by using plant biomass compacted to form cylindrical bales or cubes. However, the use of such biofuels is possible in boilers that are used in a specific group of installations and loading and achieved capacities often limit the possibility of using such devices. Thus, these forms of biofuels, intended for heating single-family buildings, are very popular in Poland [25–28].

This analysis also serves as a measure of economic sustainability, as well as environmental impact LCA (life cycle assessment) and the possibility of reducing the CO₂ emission (greenhouse gases). However, studies from the literature show that hemp has high dry matter content and good energy concentration per hectare. Moreover, hemp has a good ratio of energy efficiency to input and is, therefore, an above-average energy crop. With respect to other energy crops, the advantages also occur outside the energy balance, e.g., they relate to the low level of required pesticides and good competition in relation to weeds [29]. There is little information in the available literature on the study of hemp briquette burning in low-power heating devices that would allow a more complete assessment of their suitability for energy use. It is important that the combustion of biomass fuels may favour the formation of increased loads of pollutants, both dust and gas, introduced into the environment, which was also observed when burning the hemp biomass pellets [10].

The aim of the study was to assess the possibility of using hemp biomass for energy purposes. The research took into account the physical and chemical characteristics of hemp biomass, as well as assessing the combustion process in a low-power boiler, as well as the straw and briquettes made of it in terms of their impact on the natural environment.

2. Materials and Methods

2.1. Cultivation of Hemp in the Lublin Province

The document that indicates the basic legal regulations regarding hemp cultivation in Poland is the Act of 29 July 2005 on Counteracting Drug Addiction [30]. In this document, hemp is considered to be a “plant of the hemp species (*Cannabis sativa* L.), in which the sum of the content of delta-9-tetrahydrocannabinol and tetrahydrocannabinolic acid (delta-9-THC-2-carboxylic acid) in flowering or fruiting the tops of plants from which the resin has not been removed, does not exceed 0.20% on a dry weight basis”. This Act also indicates that the cultivation of hemp can only be carried out for the needs of the textile, chemical, cellulose, paper, food and cosmetics, pharmaceutical, building materials and seed industries. An important provision of this legal act is that cultivation can be carried out in certain designated areas and the purchase of seed should be confirmed by the purchase invoice and label. The current regionalization of hemp cultivation in Lublin province is governed by Resolution No. IV/100/2019 of the Lublin Regional Assembly of 11 March 2019 on determining the total area intended for the cultivation of poppy and fibrous hemp and the regionalization of these crops in Lublin province in 2019 [31]. Following the records of these documents from the last three years, an increase in the total area intended for cannabis cultivation is clearly visible, as in 2019, 10,466 ha was indicated, in 2018, 10,800 ha, and in 2017 there were only 191 ha. The increase in this area in the last two years resulted from the number of applications submitted by entities interested in growing this plant. The growing industry is also reacting to increased interest from farmers in hemp cultivation, which provides new cultivars with the following characteristics: trace content (not exceeding 0.2% Δ^9 THC); stable single-stem; increased yield of fibre, seeds, biomass per hectare; improving the quality of the fibre; increasing the content of CBD cannabinoid and other non-psychoactive cannabinoids. The increased interest in hemp is also evidenced by the number of registered cultivars. There were 12 hemp cultivars registered in the EU (European Union) in 1995 (of which seven were French), while

in 2004 the number of registered hemp cultivars increased to 45, in 2008 the list contained 46 and, currently, the number of cultivars registered in the EU is over 60 [32,33].

2.2. Raw Materials for Research

During the research, 45 kg of hemp straw of the Finola cv. was used (industrial type, oil is produced from the main seed yield [34]), which was obtained from a farm located in the eastern part of Lublin province. The accumulated material in the air-dry state was subjected to two comminutions. The first was carried out using an axe chopper with two sickle knives to obtain the chaff, which is shown in Figure 1a. The second, using a 15 kg portion of crushed hemp straw in the first stage, was carried out in a H-111 flail shredder with sieves with 20 mm hole diameter and powered by a 7.5 kW electric motor, obtaining the material as in Figure 1b. The two fractions of the obtained material were subjected to a compaction process in a hydraulic piston briquetting machine with a cylindrical sleeve with a diameter of 50 mm, driven by an electric motor with a power of 5.5 kW, at a set working pressure of 30 MPa, obtaining from the fraction crushed with an A-type chaff cutter, while from the fraction subjected to shredding, making type B briquettes.

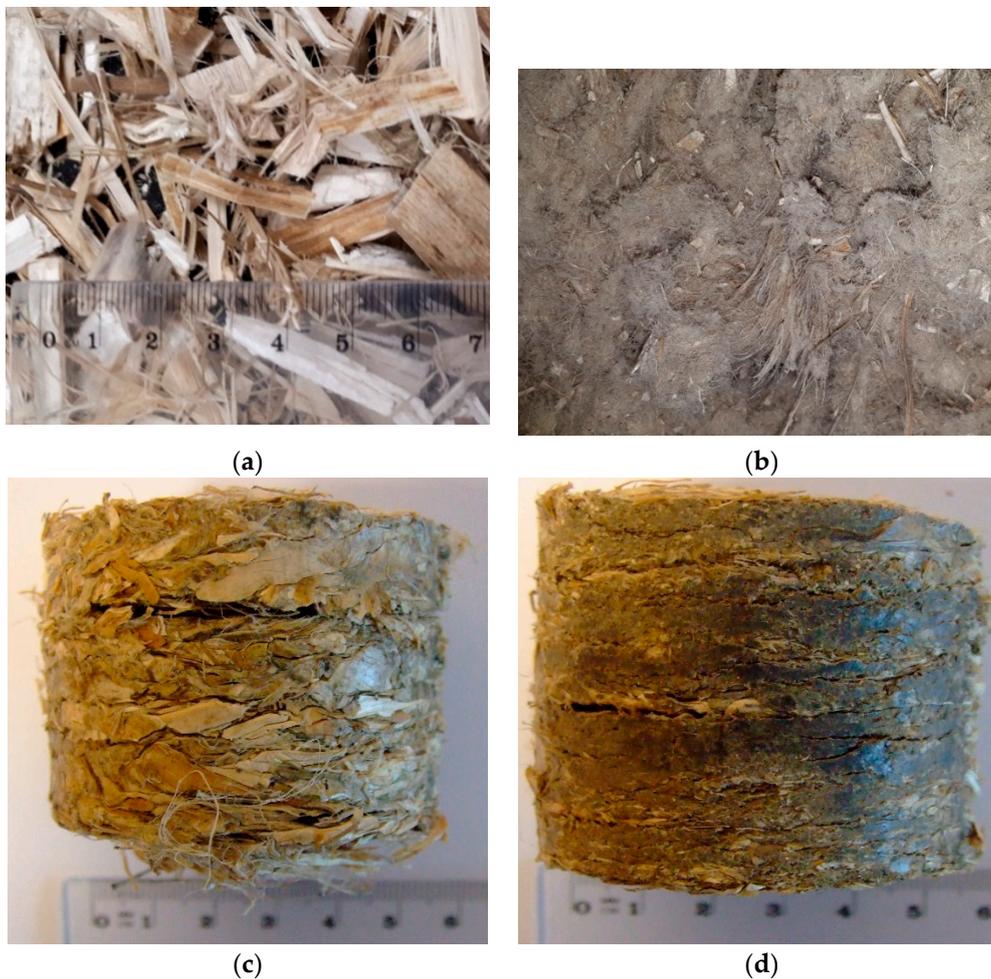


Figure 1. Shredded hemp biomass: (a) forage harvester; (b) with beater shredder with 20 mm sieves; (c) type A briquettes; (d) type B briquettes.

The specific approach associated with cutting such durable biomass should be emphasized. This problem was partially analysed during the research of Kakitis [23] and Kronbergs et al. [24].

2.3. Elemental and Technical Analysis of the Biomass

The tested material, after crushing, was subjected to elemental analysis to determine the contents of C, H, N and S and technical analysis determining the content of moisture, volatile components and calorific value based on the heat of combustion and ash content. The research material was prepared in accordance with EN ISO 14780:2017 [35]. Obtained material was ground in an IKA 11 analytical mill. For analysis, the fraction with grain sizes from 0.25 to 0.5 mm was sieved.

The elemental composition (C, H, N, S) of the combustible substance was determined from dry samples. Carbon, hydrogen, nitrogen and sulphur were determined using a LECO CHN 628 elemental analyser. The content of carbon, hydrogen and nitrogen in dry biomass was determined by instrumental methods (C and H by high-temperature combustion with IR detection; N by the catharometric method) according to EN ISO 16948:2015 [36], a 0.1 g portion weighed in accordance with the requirements of analysis. Sulphur content was determined by high-temperature combustion with IR detection in accordance with EN ISO 16994:2016 [37] in a 0.3 g aliquot. Determination of moisture, volatile compounds and ash was performed using a LECO TGA 701 thermogravimeter. The moisture content was determined by the thermogravimetric method in accordance with the requirements of the standard EN ISO 18134 [38], volatile compounds EN ISO 18123:2016 [39], ash EN ISO 18122:2016 [40], and a sample weighing about 1 g was prepared for analysis.

The calorific value was determined on the basis of the calorimetric heat of combustion, using an isoperbolic Parr 6400 calorimeter, burning the prepared pellets from the tested fuel weighing just over 1 g, in accordance with EN ISO 18125:2017 [41].

2.4. Analysis of Physical Characteristics of the Briquettes

Measurements of the physical characteristics of the briquettes produced in the hydraulic piston briquetting machine included length, diameter, mass, bulk density and mechanical durability.

Determining the length and diameter, 10 random briquettes taken from a 1000 g sample (± 10 g) were tested in triplicate. The length of the briquettes was determined using a caliper with a measurement accuracy of ± 1 mm, while their mass was measured using a laboratory balance with a measurement accuracy of ± 0.1 g. The diameter of the tested briquettes varied slightly and was approximately 50 mm (± 0.5 mm).

The bulk density of the briquettes was determined on the basis of measurements including geometrical dimensions and mass and calculated according to the formula:

$$\rho_o = \frac{4 \cdot 10^6 \cdot m}{\pi \cdot d^2 \cdot l} \left(\text{kg} \cdot \text{m}^{-3} \right) \quad (1)$$

where:

- ρ_o is the volume density of the briquette ($\text{kg} \cdot \text{m}^{-3}$),
- m is the briquette mass (g),
- d is the external diameter of the briquette (mm), and
- l is the briquette length (mm).

Measurements of the mechanical durability of the briquettes were carried out on the test stand in accordance with the PN-EN ISO 17831-2: 2016-02 [42] standard. The drum rotational speed was 21 rpm^{-1} ($\pm 0.1 \text{ rpm}^{-1}$), the test time was 5 min and the sample weight was 2000 g (± 100 g). After the durability test, the tested briquette samples were screened on a 31.5 mm sieve. Mechanical durability of the briquettes was determined according to the formula:

$$D_U = \frac{m_A}{m_E} \cdot 100 (\%) \quad (2)$$

where:

- D_U is the mechanical durability of briquettes (%),

m_A is the mass of briquettes after durability test (g), and
 m_E is the mass of briquettes before the durability test (g).

2.5. Combustion Tests

Combustion tests of the accumulated test material were carried out using a test stand (Figure 2), the integral element of which was an upper combustion boiler with a fixed grate, charged periodically, in which an air flow was directed under a grate with a fan at a speed of $1 \text{ m}\cdot\text{s}^{-1}$.

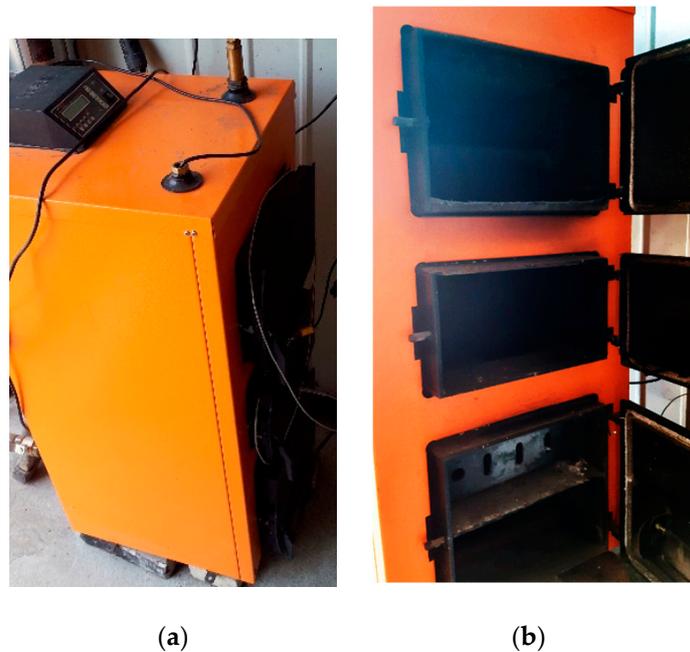


Figure 2. Upper combustion boiler: (a) side view; (b) front view.

The volume of the combustion chamber for the heat exchanger was 35.1 dm^3 ($0.26 \text{ m} \times 0.3 \text{ m} \times 0.45 \text{ m}$). Above the combustion chamber, there was a heat exchanger with horizontal partitions with water channels. The ash chamber was below the water grate, in which the ash container was placed. Fuel loading and ash removal was done manually. The water capacity of the water jacket was 30 dm^{-3} , and that of the accumulation tank was 400 dm^{-3} . Such a system was to ensure similarity to real chambers and enable the combustion process to be carried out, as in low-power heating devices. The flue gas was taken from the chimney at a distance of 1 m from the boiler flue. The measuring probe was connected to a PGD-100 exhaust gas dryer from Madur Eljack Electronics, from which the exhaust gas was sent to the exhaust gas analyser. During testing, a Photon portable exhaust gas analyser was used from the same company as the gas dryer. It is a device working on the basis of nondispersive infrared sensors (NDIR) for the following gases: CO, CO₂, NO and SO₂. The temperature was measured using a K-type thermocouple, which was located at the flue gas intake.

The course of the tests consisted of burning three 1 kg portions of crushed biomass and briquettes. Measurements of the flue gas composition were carried out constantly from the moment the fuel was put on the stabilized embers layer until the reaction was over. Results of the discussed parameters were automatically recorded in the analyser database every 4 s, with the simultaneous recording of the data recording time. After completing the tests, the database created in this way was transferred to a PC.

2.6. Statistical Analysis of Test Results

The test results were statistically analysed with STATISTICA 13.1 software from StatSoft, Poland. The mean and standard deviation, as well as minimum, maximum, kurtosis and skewness coefficient values, were given for the statistical description of the results. Additionally, the Shapiro–Wilk test

verified the compliance of results with the normal distribution, and the Brown–Forsyth test estimated the homogeneity of the variance. Subsequent tests of analysis of the results obtained during the combustion tests were conducted using one-way ANOVA variance analysis. When the variance was found to be homogeneous, the Kruskal–Wallis test was used. A significance level of $\alpha = 0.05$ was assumed for all tests.

3. Results and Discussion

The average values of the results obtained (from three replicates) characterizing the biofuels used are presented in Tables 1 and 2.

Table 1. Technical and chemical properties of biomass of hemp.

Parameter	Symbol	Unit	Value
Total moisture	W_t^r	%	10.977 ± 0.015
Volatile parts	V^d	%	69.630 ± 0.096
Heat of combustion	Q_s^d	$\text{MJ}\cdot\text{kg}^{-1}$	18.089 ± 0.034
Calorific value	Q_i^d	$\text{MJ}\cdot\text{kg}^{-1}$	16.636 ± 0.031
Ash	A^d	%	2.51 ± 0.135
	C^d	%	43.366 ± 0.276
Elemental composition	H^d	%	6.669 ± 0.040
	N^d	%	0.248 ± 0.049
	S^d	%	0.056 ± 0.002

Table 2. Physical properties of briquettes made of hemp.

Parameter	Symbol	Unit	Briquettes Type A	Briquettes Type B
Length	L	mm	48 ± 22	51 ± 13
Diameter	D	mm	52 ± 0.5	53 ± 0.5
Mass	m	kg	86.75 ± 44.89	93.51 ± 30.91
Bulk density	–	$\text{kg}\cdot\text{m}^{-3}$	828 ± 71	818 ± 82
Mechanical durability	DU	%	98.17 ± 0.25	97.57 ± 0.21

The hemp biomass tested was characterized by comparable technical and chemical characteristics with the results of tests presented by other researchers assessing the usefulness of this plant for energy purposes [4,10]. Particularly noteworthy here is the content of volatiles at the level of 69%, as well as relatively high, comparable to that for oak wood, combustion heat with an average value of $18.089 \text{ MJ}\cdot\text{kg}^{-1}$ and a low ash content at the level of 2.5% (Table 1). In terms of the parameters assessed, these values were also among the best biomass species for energy purposes [43–45], while the high content of volatile organic compounds indicated during research can improve the energy conversion efficiency in the case of fluidized fuel combustion [46]. The amount of hemp biomass yield was not analysed during the study. Data available in the literature [10] indicate that about 10 tons of hemp biomass from one hectare can be used for energy purposes. By comparing these data with the possibility of growing hemp in 2019 in the Lublin province, one can dispose of just over 100,000 tons of biomass, which contains (taking into account its heat of combustion, Table 1) 1.7 PJ of energy, which is equivalent to approximately 85,000 tons of hard coal with a calorific value of $20 \text{ MJ}\cdot\text{kg}^{-1}$.

The improvement of the geometrical parameters of hemp biomass is obtained from the compacting process. Additionally, briquettes produced during the tests (Table 2) were characterized by desirable geometrical features, thus meeting the assumptions of appropriate quality standards [43–45]. Statistical analysis carried out between A and B type briquettes in terms of length, diameter, mass and density did not show significant differences with a probability p of 0.428, 0.727, 0.700 and 0.783, respectively. Only the observed difference between the analysed types of briquettes in terms of mechanical durability was confirmed statistically with a probability of $p = 0.034$. The visible impact of comminution on

the mechanical durability of hemp biomass briquettes was also demonstrated during studies by Ivanova et al. [22], as well as during research on the compaction of other raw materials [47].

The basic parameters characterizing the combustion process are presented in Table 3 and the content in exhaust gas, as well as CO, NO, SO₂, CO₂ emission, are presented in Table 4.

Table 3. Parameters of the combustion process.

Assortment	Combustion Speed (kg·h ⁻¹)	Excess Air Coefficient (–)	Exhaust Gas Temperature (°C)
Hemp straw	5.14 ± 0.10	2.06 ± 3.23	354.0 ± 153.7
Type A briquettes	4.30 ± 0.08	4.16 ± 3.74	297.2 ± 104.8
Type B briquettes	3.93 ± 0.07	5.48 ± 4.44	234.9 ± 82.4

Table 4. Emission of CO, NO, SO₂ and CO₂ during the combustion of hemp straw and type A and B briquettes.

Assortment	Values	CO ppm	CO mg·m ⁻³ At 10% O ₂	NO ppm	NO mg·m ⁻³ At 10% O ₂	SO ₂ ppm	SO ₂ mg·m ⁻³ At 10% O ₂	CO ₂ %
Hemp straw	Minimum	0	0	0	0	0	0	0
	Maximum	19,750	34,964	399	587	794	342	14.39
	Average	7405	7260	174	180	131	61	8.60
	Standard deviation	5735	9841	80	182	195	65	4.78
	Kurtosis	−0.18	0.30	−0.19	−1.31	4.82	1.22	−1.51
	Skewness coefficient	1.04	1.24	−0.04	0.13	2.15	1.50	−0.24
Type A briquettes	Minimum	0	0	0	0	0	0	0
	Maximum	9010	8429	228	345	92	143	12.1
	Average	4237	2938	136	138	32	49	6.90
	Standard deviation	1792	1802	64	119	18	34	3.29
	Kurtosis	0.05	1.32	−1.34	−1.49	1.91	0.18	−1.30
	Skewness coefficient	0.76	1.22	−0.12	0.29	1.49	1.07	−0.07
Type B briquettes	Minimum	0	0	0	0	0	0	0
	Maximum	9935	3686	284	353	94	107	9.48
	Average	3429	1565	135	108	37	46	5.03
	Standard deviation	2459	741	62	88	24	26	2.27
	Kurtosis	−0.04	−0.08	−0.35	0.25	−0.52	−0.17	−0.83
	Skewness coefficient	0.91	1.02	0.47	1.01	0.88	0.82	−0.02

Interpretation of the obtained results regarding the content of CO, NO and SO₂ in the exhaust gas refers to the adopted combustion criteria, the characteristic feature of which was the use of a grate combustion system with fuel ignition from below and air distribution under the grate. The obtained values of these compounds were diversified due to the periodicity of fuel feeding to the boiler and the phase of the combustion process. Immediately after 1 kg of fuel was placed on the stabilized embers layer, the temperature increased and the volatiles evaporated from the fuel, mainly represented by the maximum values of CO, NO and SO₂.

Under the test conditions, burning of crushed hemp straw occurred most rapidly with significant CO, NO and SO₂ emissions. Its compaction to type A briquettes led to a 60% reduction in CO emissions, 25% NO emissions and 20% SO₂ emissions during combustion. On the other hand, combustion of type B briquettes made of additionally crushed hemp biomass in relation to crushed straw led to further stabilization of the combustion process and reduction of emissions of the analysed compounds in the flue gas by 80%, 40% and 25%, respectively (Table 4). The difference of parameters (Table 3) could have resulted from better contact of type A briquettes with hot gases, due to their greater "external

roughness" (Figure 1c) caused by the less fragmented raw material fraction. Similar results were obtained by Ryu et al. [48] comparing the combustion rate and weight loss during the development of ignition for different sized wood particles. For larger particles, the ignition front speed was higher than for smaller particles. In addition, Yang and his team [49] noted that smaller particle sizes result in high CO emissions. Statistical analysis carried out in terms of combustion parameters showed significant differences between the tested biofuel assortments. The obtained values were comparable with data presented by other researchers analysing the emission of hemp biomass biofuels [10], and they were close to the literature values for wood biomass and energy plants [50–53].

At the same time, it is worth noting that, while briquetting, CO emissions were acceptable for this type of boiler, falling into class 3 according to PN-EN 303-5:2012 [54]; however, they did not meet the requirements of the ecodesign requirements for solid fuel boilers [55].

4. Conclusions

During the tests, the possibility of using hemp biomass for energy purposes was assessed. The criteria assessed were the physical and chemical properties of hemp biomass, as well as the combustion process in a low-power boiler, of straw and briquettes made of it. A review of the literature, as well as research results, indicate that hemp biomass is an interesting and valuable energy resource. The energy potential that lies in the area of the Lublin region that can be cultivated is around 1.7 PJ. Technical and chemical properties of hemp biomass are comparable with the best plants used for energy purposes. There are important parameters, such as the content of volatile matter, at the level of 69%, relatively high heat of combustion, with an average value of $18.089 \text{ MJ}\cdot\text{kg}^{-1}$, comparable with that for oak wood, and low ash content at the level of 2.5%.

Research has also shown the susceptibility of hemp biomass to compaction, which resulted in type A and B briquettes with the desired geometrical features. At the same time, a small, but statistically significant, impact of fragmentation on the durability of these molded biofuels was observed. At the same time, it would be advisable to conduct comprehensive research taking into account the energy balance in terms of improving the energy efficiency of the preparation process for compaction and hemp biomass agglomeration as well as taking into account the full costs of producing such biofuels.

Under the test conditions, the biofuel used was in the form of hemp straw briquettes in a process in which the characteristic feature was the use of a grate combustion system with fuel ignition from below. The air distribution under the grate was acceptable in terms of CO, NO and SO₂ emissions and, for this type of boiler, CO emissions were in the 3rd class according to PN-EN 303-5:2012 [54]; however, it did not meet the requirements of the ecodesign requirements for solid fuel boilers [55]. The environmental load of CO, NO and SO₂ gas components was significantly influenced by the additional fragmentation of hemp biomass, from which the B-type briquettes made during combustion emitted the smallest amounts of these compounds.

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