Energy Performance of a Rotary Burner Using Pellets Prepared from Various Alternative Biomass Residues

Juraj Trnka,[a] Michal Holubčík,[a,]* Nikola Čajová Kantová,[b] and Jozef Jandačka [a]

Alternative biomass makes up a considerable portion of the waste from biomass processing in forestry and agriculture. The aim of this work was to create pellets from several sources of alternative biomass, *e.g.*, lawn clippings, corn husks, linden leaves, and pine needles, which were compared to pure wood pellets. Analysis of the fuel properties focused on their chemical composition, thermogravimetric analysis, calorific values, and ash melting temperatures. The power and emission parameters of the fuels were determined *via* an automatic pellet boiler. The primary issues in the combustion of the alternative biomass types were low calorific values, increased emissions, high ash contents, and low ash melting temperatures. The two primary options for solving these problems are the production of fuel mixtures with wood or the use of new combustion technologies. This work also dealt with the combustion of alternative biomass *via* a rotary burner. The results showed an increase in the ash content of the alternative biomass, which also led to the burner occasionally going out due to clogging with the accumulation of ash and sintering. Based on the results, only pellets from pine needles and corn husks can be recommended for further use.

Keywords: Alternative biomass; Rotary burner; Pellets; Combustion; Emissions

*Contact information: a: Department of Power Engineering, Faculty of Mechanical Engineering, University of Zilina, Univerzitna 1, Zilina 010 26 Slovakia; b: Research Centre, University of Zilina, Univerzitna 1, Zilina 010 26 Slovakia; *Corresponding author: michal.holubcik@fstroj.uniza.sk*

INTRODUCTION

The energy from biomass has the greatest potential among energies from renewable resources. Many of these energy-rich materials unnecessarily end up in landfills, fields, or forests, and a lot of energy and money is wasted on its disposal. In line with waste management improvements, new European policy goals are in place to stop the use of fossil fuels, *e.g.*, coal, and replace it with new green alternatives (Tzelepi *et al.* 2020).

Alternative biomass includes a large number of species, many of which are already in the research stage (Minajeva *et al.* 2021). However, in order to evaluate the maximum potential of an alternative biomass, it is necessary to choose a crop that is grown in large and economically interesting quantities, that also has good calorific properties, and are locally available (Mudryk *et al.* 2021). The largest source of alternative biomass is forestry waste. In Ukraine, research has been conducted on the use of individual parts of locally grown trees. These investigations were focused on thermogravimetric experiments of clean samples. It has been found that alternative tree parts have a higher ash and moisture content, which are related to a decreased calorific value. Pellets from alternative biomass have been compared with classical European standards (Korobiichuk *et al.* 2021). A study by Senila *et al.* (2020) also evaluated the possibility of making high-quality pellets from vineyards as an alternative wood source.

Further research has been devoted to the possibility of the combustion of three kinds of reed grass because it is a fast-growing invasive plant species. These studies were focused on the ash melting temperatures, emissions, and calorific values. It was found that all of the analyzed reed plants could be used as biofuels because the pellets of all these plants met the standard requirements for high-quality biofuels (Jasinskas *et al.* 2020).

Another experiment was performed on wheat waste after utilization in beer-making processes. Pellets for combustion were made and evaluated, and it was found that they had higher NOx emissions caused by nitrogenous bacterial content in the raw material (Arranz *et al.* 2021). Nevertheless, the research showed that the material had good pelletizing properties and was suitable for energy use.

Although the combustion of alternative biomass is in many respects an advantageous solution, it also carries certain risks. The most serious of these risks is due to the high ash contents and low melting points. The molten ash adheres to the walls of the combustion chamber and forms sintered matter and agglomerates, which then cause flame suffocation. Flame suffocation causes imperfect combustion and excessive emissions, which puts alternative biomass at a disadvantage compared to other fuels (Poláčik *et al.* 2021).

Many researchers have already tried to solve these problems in several ways. The most common examined solution is to co-burn alternative biomass with another more stable type of fuel (Mansour 2010). Some studies have also looked at the possibility of the thermal improvement of alternative biomass fuels *via* high-temperature pyrolysis and low-temperature torrefaction before actual combustion (Bridgeman *et al.* 2008; Sher *et al.* 2020).

Another alternative is the possibility of structural modifications of the combustion devices, especially burners adapted to burn biomass with low ash melting temperatures. Standard retort burners used for the automatic combustion of bulk fuels have a major disadvantage in the direction of the fuel supply and combustion, which takes place in the vertical plane. The problem with this technology is that the high temperature in combination with gravitational force holds the heavier ash particles in the burner, where they stick to the walls and cause clogging. Newer types of horizontal tube burners partially eliminate this problem by allowing fuel to fall out of the hearth more easily (Cardozo *et al.* 2014).

The use of a burner affects the development of operational problems related to sintering. Technologies of combustion that have continuous ash discharge systems seem advantageous. However, fuels such as wheat straw are more sensitive to burner type. These fuels need burners with a moving grate or some kind of automatic ash handling system. (Rebbling *et al*. 2020). However, the problem remains that ash deposits may partially accumulate at the bottom of the tube, and the material may sinter there. As such, the latest types of burners use a rotating combustion chamber that allows the permanent self-cleaning of the ash. A planetary gearbox allows for the slow rotation of the combustion chamber and the constant movement of ash away from the burner tube. This type of burner operates with a fully synchronized air and fuel supply on a single shaft (Jia *et al*. 2020; Smith *et al*. 2020). Horvat *et al.* (2021) was investigated rotary burner with two types of proposed combustion intensifiers. Its implementation brought significant emission reductions in CO and PM, and there was also an increase in combustion efficiency. A rotary burner was used also in the research of Pafčuga *et al.* (2021) for the combustion of wheat-straw pellets. In that work it was stated that a rotary burner allows the combustion of different types of biomass. Its construction is designed to reach higher energy from combustion (Pafčuga *et* *al*. 2021)

Based on the stated knowledge, it is important to address the issue of the combustion of alternative types of biomass. The combustion complications of alternative biomass are low calorific values, increased emissions, high ash contents, and low ash melting temperatures. This article deals with the investigation of the combustion of different alternative biomass fuels using a rotary burner. Pressed lawn clippings, corn husks, linden leaves, and pine needles were used as alternative biomass residues. Analysis of the fuel properties was realized and focused on their chemical composition, thermogravimetric analysis, calorific values, and ash melting temperatures. The used rotary burner should allow the permanent self-cleaning of the ash, and so also should allow continuous combustion. This burner is adapted to burn biomass with low ash melting temperatures and high ash contents. During combustion of biomass residues, power and emission parameters were measured.

MATERIALS AND METHODS

This work used four waste samples, *i.e.*, lawn clippings (in figures Lawn), corn husks, linden leaves, and pine needles, as the input material. These samples were compared with pure spruce pellets.

Lawns and meadows cover most man-made areas created for cattle grazing. However, with the gradual decline of livestock farming in many of these areas, grass requires constant mowing and becomes an unused waste product (Hadders and Olsson 1997). The lawn clippings were collected from the area surrounding the university.

Agricultural husks consist of a wide range of plant species and their parts. The vast majority are obtained from commonly cultivated crops, *e.g.*, cane, corn, wheat, and rice (Werther *et al.* 2000). Corn husk was chosen for this study because it is the second most grown crop in the world and as well as in Slovakia.

The leaves form a major part of the tree and are renewed every year, as well as being available in large quantities in autumn. Most of the waste leaves are collected annually from gardens, parks, and public green spaces. In this study, the leaves used were mostly linden leaves collected from a local city park.

Needles are the equivalent to leaves in colder and mountainous areas of the temperate zone where conifers grow predominantly. In addition, conifers are planted for decorative purposes in parks and gardens (Casal *et al.* 2010). In this study, pine needles were used and collected from the area surrounding the university.

During pellet production it is important to reach the quality specifications of final fuel, thereby obtaining optimal power and emission parameters of heat source. With increasing fuel quality – such as the higher value of the higher calorific value (*i.e.* the higher heating value), lower moisture, lower ash content, higher lignin content – the performance of the boiler increases. However, it is not enough to measure only input materials. It is important to achieve a higher energy density. For this reason, it was necessary to first crush and compress the fuel samples.

The obtained samples were therefore first naturally air-dried and then crushed using a hammer mill with the size of a maximum fraction of 6 mm. For the pelletization process, a small pellet press with a power of 7.5 kW was used. The input materials were pressed approximately at the same pressure. In general, small pellet presses operate at a lower pressure than larger ones, which are used in the pressing of industrially produced pellets.

However, during the pelletization process the pressure was not measured. In order to ensure the better connection of samples, water was added to them just before the pelletization process. The moisture content was in the range of 15% to 25% depending on the lignin content. The particle size was from 0.01 to 3 mm. The biggest size of particles could have been 6 mm. Afterwards, the newly formed pellets were air-dried again. The approximate temperature of the pellet air-drying was in a range from 22 to 24 °C, with the relative humidity from 40% to 50%, and the length of time of the air-drying was approximately 14 days. Due to the occasional use of the fan, an airflow occurred at a velocity of approximately 0.2 $m.s^{-1}$. Figure 1 shows the newly formed pellets obtained from pure spruce wood, corn husks, lawn clippings, pine needles, and linden leaves.

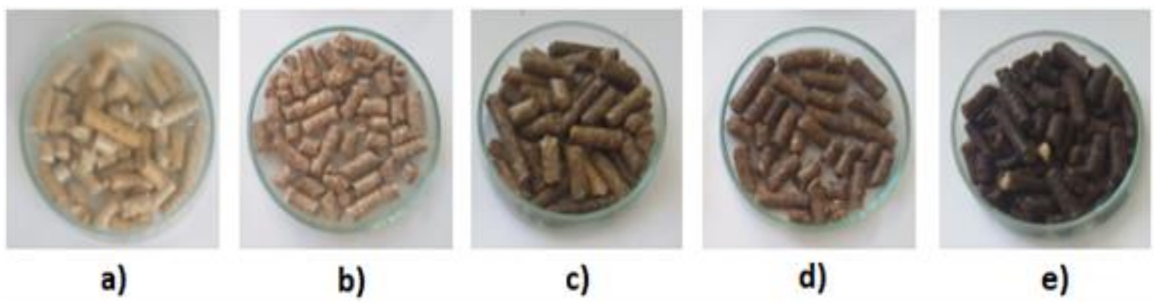


Fig. 1. Pellet samples: a) Spruce wood; b) Corn husks; c) Lawn clippings; d) Pine needles; and e) Linden leaves

For experimental measurements, an automatic pellet boiler with a maximal power of 18 KW was used. The pellets were combusted in a rotary burner with self-cleaning ability. The fuel and combustion air supply were fully automated *via* a screw feeder in the middle of the burner. During the combustion process, the basic parameters of the combustion process, *e.g.*, the emissions, temperatures, and chimney draft, were measured. The heat output of the boiler was determined by the temperature difference of the supply and return hot water pipes.

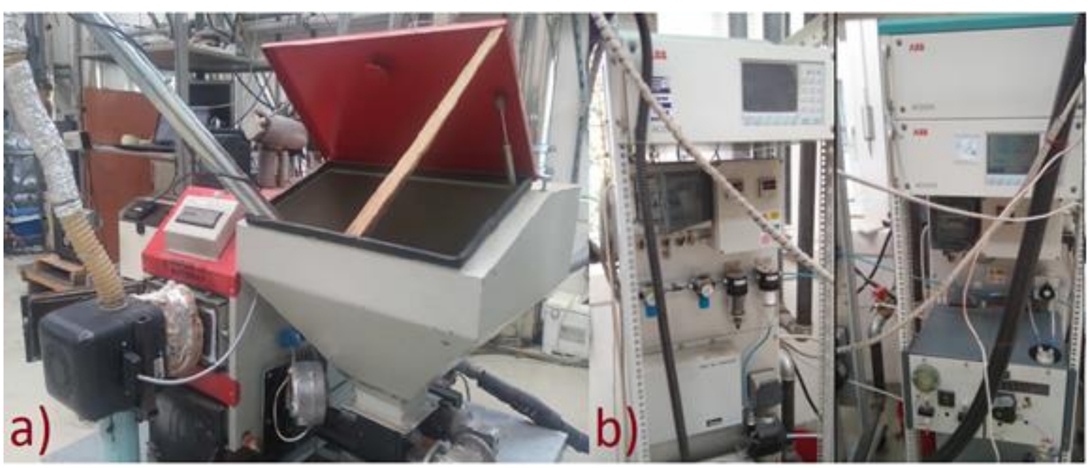


Fig. 2. The experimental combustion equipment: a) Boiler with burner; and b) Emission measuring devices

During the combustion of each sample, the same operating conditions were maintained. Approximately 6.5 kg of fuel was combusted during one 60 min measurement.

The standard deviation was also determined according to Eq. 1. A TCR ISOSTACK basic gravimetric analyzer was used to determine the particulate matter (PM) emission value. The resulting value of the PM emissions was determined from the deposits on precisely weighed dry glass fiber filters (Lee *et al.* 2000). To evaluate the gaseous emissions, two ABB gas analyzers were used. The experimental combustion equipment shows Fig. 2.

To determine the basic properties of the samples, measurements were taken using the following equipment: a LECO CHN 628, 628S elemental analyzer, a LECO 701 TGA thermogravimetric analyzer, a LECO AC 500 calorimeter, and a LECO AF 700, ash melting temperature analyzer with a pellet durability tester Ligno-Tester TEKPRO (LECO Corporation, Saint Joseph, France). For all measured values, the standard deviation was determined from the statistical set according to Eq. 1,

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2} \quad (1)$$

where σ is the standard deviation, N is the number of values in the statistics file, x_i is the value of the quantity, and $\bar{x}$ is the arithmetic mean of all the database values.

The chemical composition analysis was performed using a LECO CHN 628 and 628S. The devices determined the value of the contained elements from the flue gases resulting from the combustion of the individual samples.

Thermogravimetric analysis of the newly formed pellets using a thermogravimetric analyzer. This device works by gradually increasing the temperature to determine heat endurance at individual levels and measuring the weight of each fuel structural component. Using the difference in weight, the moisture, volatile matter, ash, and fixed carbon values are determined.

To determine the higher calorific values (HCV) also known as higher heating value of the individual samples, a LECO AC 500 calorimeter was used, and the lower calorific values (LCV) were subsequently calculated according to Eq. 2,

$$LCV = HCV - r_{h2o} \cdot (W_P + 8.94 \cdot x_H) \quad (2)$$

where r_{h20} is the water heat of vaporization (kJ/kg), W_p is the water content in the sample (wt.%), and 8.94 is the hydrogen to water conversion coefficient; and as shown in Eq. 3,

$$x_H = 0.01 \cdot H_h \cdot B_p \quad (3)$$

where H_h is the hydrogen content in the sample (wt.%), and B_p is volatile content in the sample (wt.%).

The LCV value is reduced by the HCV value by the heat absorbed during combustion by the evaporation of water vapor and is therefore much more important in conventional non-condensing combustion.

The next analysis with a thermogravimetric analyzer LECO 701 TGA provided results for the basic structural content of fuel sample. This device works by gradually increasing the temperature to determine heat endurance at individual levels and measuring the weight of each fuel structural component. Using the difference in weight, the moisture, volatile matter, ash, and fixed carbon values are determined.

The last analysis was based on determining the melting temperatures of the ash using a LECO AF 700 temperature analyzer. Measuring the ash melting temperatures is a basic criterion for combustible materials with a high ash content at low ash melting temperatures because it allows the prediction of whether the material will melt into a slag during combustion. Four standardized ash melting temperatures of the produced samples were determined on the basis of STN ISO standard 540 (2008), according to the following criteria: (1) the shrinkage temperature (ST), *i.e.*, the temperature at which melting begins and the first signs appear in the form of rounded edges of the pyramid of the test sample; (2) the deformation temperature (DT), *i.e.*, the temperature at which the test pyramid is completely rounded, without changing the height; (3) the hemisphere temperature (HT), *i.e.*, the temperature at which the test pyramid forms a hemisphere, where the height is equal to approximately half the base; and (4) the flow temperature (FT), *i.e.*, the temperature at which the ash pitch on a base forms a layer, the height of which is approximately one-third of the original test pyramid.

Determining the ash melting temperatures is especially important for some types of fuels, *i.e.*, those with lower ash melting temperatures, which cause combustion difficulties (Fang and Jia 2012).

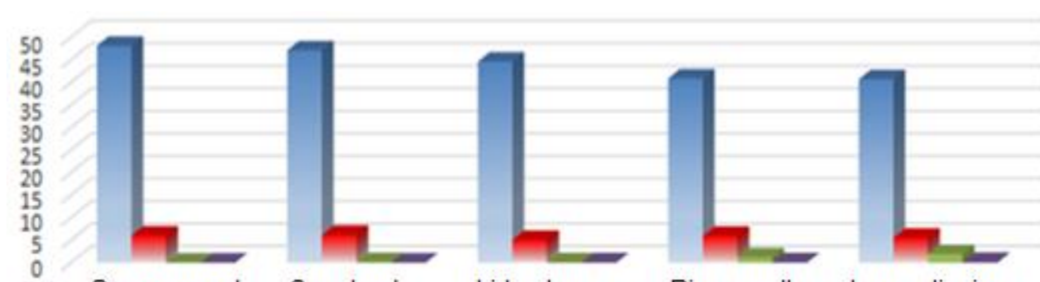
The mechanical durability test of the pellets is important to evaluate their quality with respect to the strength of the bonds. After inserting the sample into the tester according to ISO 17831-1: 2015, the first 30-second measurement of the Fine Material Amount (F) begins, and it is followed by the second 60-second measurement of Mechanical Durability (DU). From the differences in weights before and after the test, it is possible to determine the resulting hardness of the pellet in percent.

EXPERIMENTAL RESULTS

The first part of the results presents the main properties of newly formed pellets. These properties affected the combustion parameters as well as the smoothness of the combustion process. The second part of the results presents measured power and emission parameters with the use of a rotary burner during the combustion of formed pellets.

Evaluation of Basic Pellet Parameters

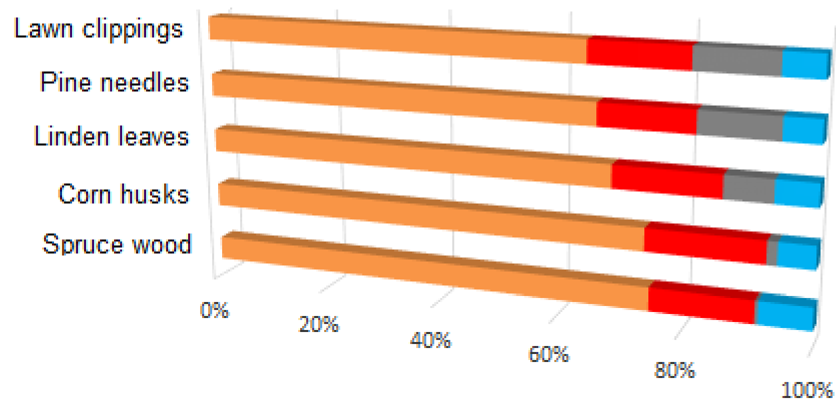
First graph on Fig. 3 represents the chemical analysis of the formed pellets, which showed the content of the basic combustible elements and the sulfur content, which may contribute to the increase in emissions. The proportion of carbon was the highest in the pure spruce pellet samples compared to the individual samples of alternative biomasses. However, the other elements had an upward trend. The lawn clippings sample showed a higher nitrogen and sulfur values, which was likely due to excessive soil fertilization.



[%]	Spruce wood	Corn husks	Liden leaves	Pine needles	Lawn clippings
C	48.15 ± 0.35	47.17 ± 0.34	44.53 ± 0.33	40.92 ± 0.32	40.74 ± 0.31
H	6.05 ± 0.07	6.17 ± 0.07	5.07 ± 0.05	5.95 ± 0.06	5.56 ± 0.05
N	0.06 ± 0.01	0.17 ± 0.01	0.09 ± 0.02	1.17 ± 0.03	1.89 ± 0.03
S	0.03 ± 0.01	0.02 ± 0.01	0.09 ± 0.01	0.11 ± 0.01	0.20 ± 0.02

Fig. 3. Results of the elemental analysis of the fuel samples

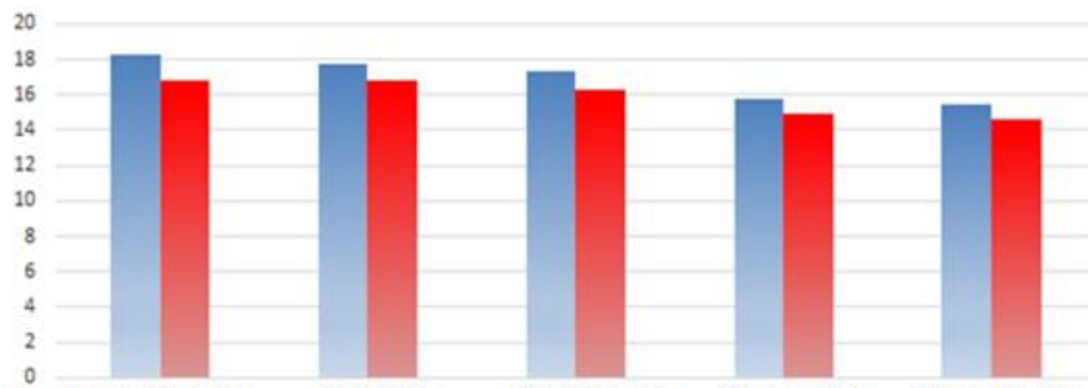
Figure 4 shows the results of thermogravimetric analysis. It can be noticed that pellets from alternative biomass sources had an increasing ballast content and decreasing combustible particle contents, *e.g.*, volatile matter and fixed carbon, compared with the spruce pellets. However, the considerable differences, *e.g.*, the minimum proportion of ash in corn husks and its major increase in the leaf and grass pellets, are clearly visible.



	Spruce wood	Corn husks	Linden leaves	Pine needles	Lawn clippings
Volatile matter	74.99 ± 0.46	74.12 ± 0.43	68.81 ± 0.41	66.35 ± 0.39	64.71 ± 0.38
Fixed carbon	16.31 ± 0.23	18.59 ± 0.25	17.07 ± 0.24	15.29 ± 0.21	15.98 ± 0.22
Ash	0.49 ± 0.05	1.60 ± 0.07	7.60 ± 0.15	12.58 ± 0.17	12.98 ± 0.18
Moisture	8.21 ± 0.11	5.69 ± 0.09	6.52 ± 0.12	5.78 ± 0.11	6.33 ± 0.09

Fig. 4. Results of the thermogravimetric analysis of the fuel samples

The measurement of calorific values shown in Fig. 5. confirms good calorific values of the alternative biomass samples, except for lawn clippings. The highest LCV was found in the corn husk pellets (16.79 ± 0.19 MJ·kg^{-1}).



[MJ·kg^{-1}]	Spruce wood	Corn husks	Linden leaves	Pine needles	Lawn clippings
HCV	18.29 ± 0.31	17.77 ± 0.29	17.31 ± 0.30	15.78 ± 0.29	15.44 ± 0.31
LCV	16.76 ± 0.21	16.79 ± 0.19	16.26 ± 0.20	14.91 ± 0.19	14.64 ± 0.21

Fig. 5. Results of the calorific values of the fuel samples

The results from measurement of ash melting temperatures are shown in Fig. 6. The findings confirmed that the tested alternative biomass had lower ash melting temperatures compared to standard wood.

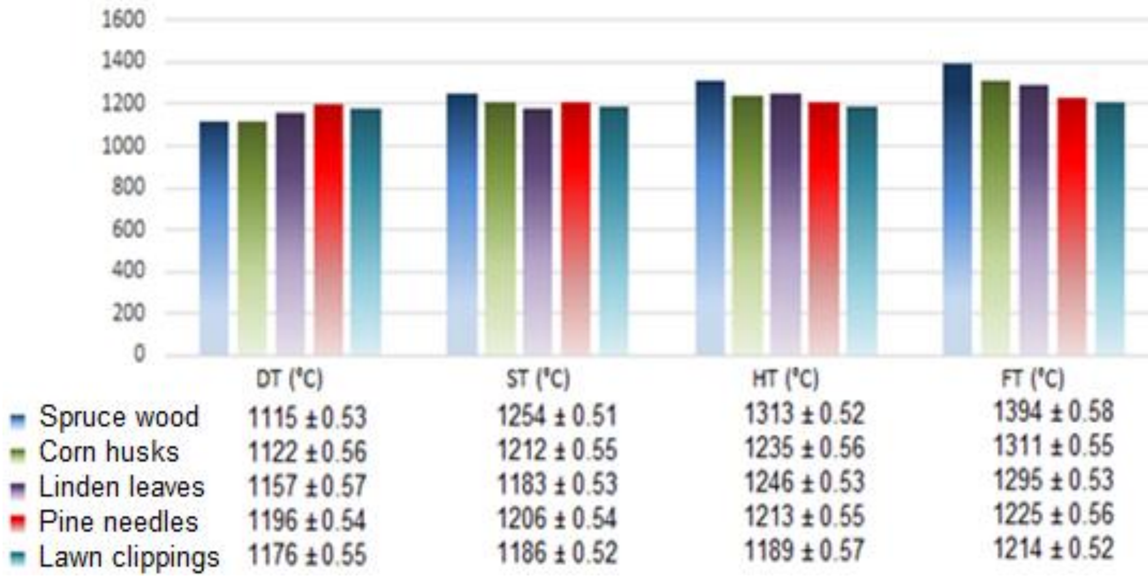


Fig. 6. Results of the ash melting temperature analysis

The last measured property of newly formed pellets was the mechanical durability. Their values are shown in the graph in Fig. 7. The results show that alternative pellets compared to industrial wood pellets had lower mechanical durability values, which may be due to the lower lignin content in the samples but also due to the application of different pressing technology.

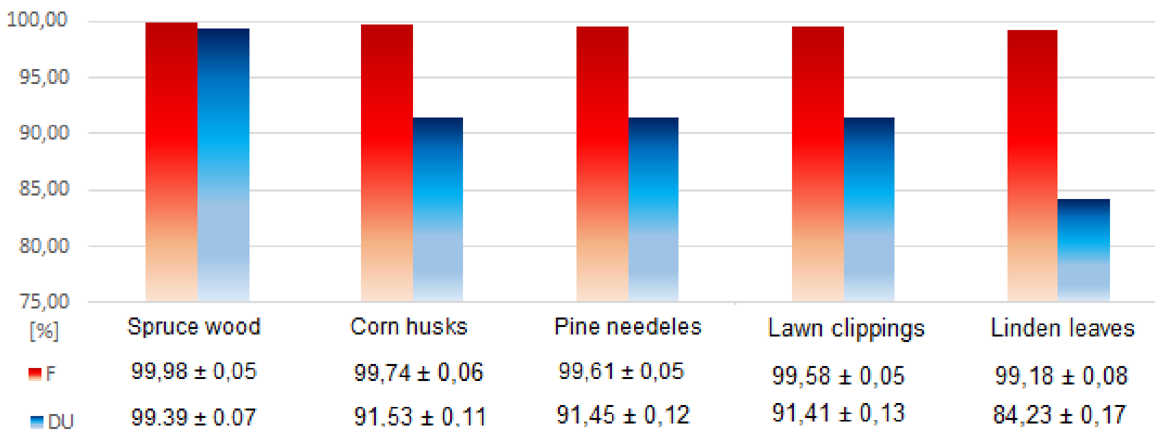


Fig. 7. Results of the durability analysis of samples

Evaluation of the Heat Output

The combustion of the alternative biomass pellets in comparison to spruce pellets was accompanied by several problems and even the deterioration of the operating parameters. The primary disadvantage of the alternative materials was that they were pressed at lower pressures, which caused a reduction in heat output and a lower combustion temperature (as shown in Table 1). The chimney draft was also affected, but its value was maintained at a level between 10 and 14 Pa, according to standard conditions.

Table 1. Experimental Results of the Power Parameters, Chimney Temperature, and Draft of the Produced Samples

Sample	*P* (kW)	*T* (°C)	*P* (Pa)
Spruce wood	13.43 ± 0.14	240.41 ± 0.47	12.85 ± 0.41
Corn husks	10.48 ± 0.15	224.84 ± 0.49	11.43 ± 0.42
Linden leaves	6.91 ± 0.16	159.33 ± 0.51	13.04 ± 0.43
Pine needles	5.61 ± 0.15	172.57 ± 0.48	11.99 ± 0.45
Lawn clippings	5.55 ± 0.15	158.59 ± 0.50	10.87 ± 0.42

The lower heat output was also caused by imperfect combustion and the clogging of the burner, which was partially caused by lower ash melting temperatures, but primary by the higher ash content of the fuels. The used burner could not prevent sintering during combustion, but these elements did not stick to the burner due to the rotating technology and gradually fell out of it. However, with the increased ash content of the samples, this self-cleaning ability was not sufficient, and the burner became clogged and went out (as shown in Fig. 8).

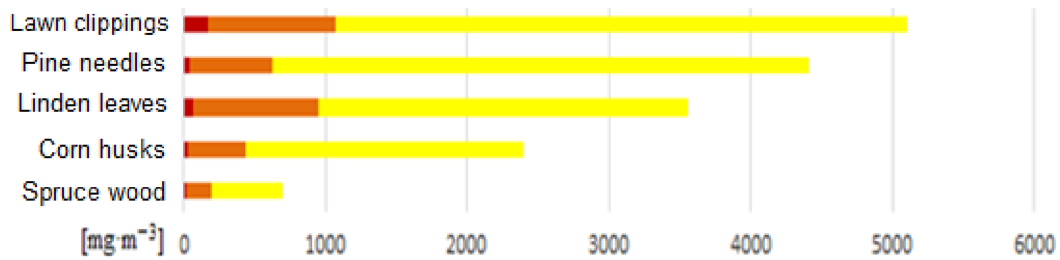
Fig. 8. The combustion process: a) Standardized burner operation; b) Burner clogging; and c) Clogged rotary burner after the combustion of alternative biomass samples

Emission Evaluation

When the burner went out, it not only caused a deterioration in the heat output but increased emission parameters. This can best be seen with the increase in carbon monoxide emissions, which are directly caused by the imperfect combustion process (Fig. 9).

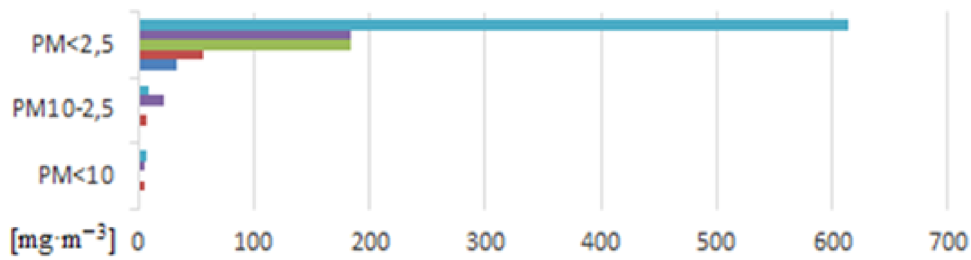
The formation of nitrogen oxide emissions was directly proportional to the decrease in combustion temperatures, which showed that the best results among the alternative biomass samples were corn husks, with a chimney temperature of approximately 220 °C. The production of sulfur oxides was influenced by the content in the individual samples.

Imperfect combustion conditions also affected the PM emissions concentrations, but other criteria affecting the PM emissions were the particle size and fuel structure. In this respect, pine needles, which came closest to the spruce pellets in terms of structure, had the lowest PM concentration after spruce wood. The highest PM concentration was found in the grass fiber pellets, which were fine and easily disintegrated (Fig. 10).



	Spruce wood	Corn husks	Linden leaves	Pine needles	Lawn clippings
SO2	17.37 ± 0.13	28.40 ± 0.15	68.85 ± 0.17	45.01 ± 0.16	166.89 ± 0.23
NOx	174.89 ± 0.24	413.17 ± 0.31	877.79 ± 0.39	580.32 ± 0.32	906.97 ± 0.41
CO	507.66 ± 0.37	1958.06 ± 0.72	2610.86 ± 0.81	3786.19 ± 0.87	4027.14 ± 0.93

Fig. 9. Evaluation of the gaseous emissions during the combustion of alternative biomass samples



	PM<10	PM10-2,5	PM<2,5
Lawn clippings	7.06 ± 0.12	8.37 ± 0.13	613.17 ± 0.67
Corn husks	6.28 ± 0.09	21.66 ± 0.23	183.74 ± 0.41
Linden leaves	1.84 ± 0.04	2.46 ± 0.05	183.68 ± 0.42
Pine needles	5.27 ± 0.07	7.19 ± 0.11	55.29 ± 0.31
Spruce wood	0.44 ± 0.02	1.61 ± 0.03	32.81 ± 0.25

Fig. 10. Evaluation of the PM emissions during the combustion of alternative biomass samples

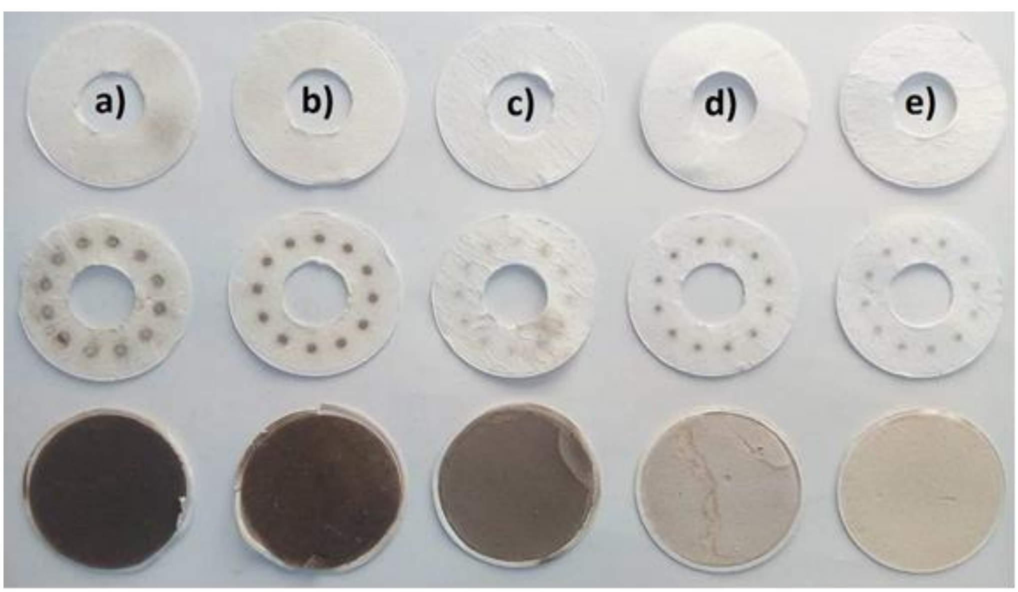


Fig. 11. The PM sedimentation filters: a) Pine needles; b) Linden leaves; c) Lawn clippings; d) Corn husk; and e) Spruce wood

The values plotted in Fig. 11 also showed that the combustion of alternative biomasses led to the largest increase in the PM, especially in the particles with aerodynamic diameters under 2.5 μm (PM 2.5), as shown by the sedimentation filters in Fig. 11.

The high PM particle values in the combustion of alternative biomass samples, in addition to operational problems, need to be addressed through the use of efficient secondary separators. In addition to the settled amount of particles, measuring filters also show their structure and color, which can be further investigated to determine the mineral composition of the fuel and reveal its reactivity with the environment, as well as the efficiency of separation.

CONCLUSIONS

1. The analysis showed higher ash contents in the alternative biomass samples. Based on this knowledge, it can be concluded that the deterioration of the combustion parameters was considerably more correlated with the ash content in the samples than their melting points. The rotary burner did not prove to be effective enough to burn all types of alternative biomass fuels.
2. The results showed better combustion properties and a reduction in some types of emissions from corn husks or pine needles when compared to the lawn clippings and linden leaves. Therefore, pure corn husks and pure pine needles are not suitable for pelletization. However, they could be used in lower proportions to the base material, *e.g.* wood sawdust. In the case of this use, the application of a rotary burner would also be sufficient without operation problems.
3. It is necessary to pay attention to the high level of ash content and its negative impact on the combustion process. Partially rotted biomass increases its share of ash by weight. The decomposing biomass particles also considerably affect the formation of PM particles. In some cases, it can be recommended that the combustion of alternative biomass only occurs in large amounts, where they can deal with the increased ash content much more efficiently as well as reduce emissions *via* introducing emission cleaning and separating PM particles.
4. In the case of the use of lawn clipping, corn husks, and linden leaves, a high concentration of especially PM2.5 was measured. For this reason, it is recommended to use a separation device when using these pure types of residual biomass.
5. Linden leaves, pine needles, and lawn clippings were combusted with significantly lower heat output. With the increased ash content of the samples, this self-cleaning ability was not sufficient. Solution could be used alternative biomass as additional material to pellets.
6. The results of the experiments show that alternative materials used in small heat sources can cause various problems and require a lot of attention for achieving an efficient combustion process with minimal negative impact on the environment. With this in mind, it is necessary to realize more research in this area.

ACKNOWLEDGMENTS

This work has been supported by the following projects: VEGA 1/0233/19 "Structural modification of a burner for the combustion of solid fuels in small heat sources"; VEGA 1/0479/19 "Influence of combustion conditions on the production of solid pollutants in small heat sources"; APVV- 17-0311 "Research and development of waste-free technology for decomposition and selection of undesirable components from process gas generated by a gasifier"; and APVV-15-0790 "Optimization of biomass combustion with low ash melting temperature".

REFERENCES

Arranz, I. J., Sepúlveda, F. J., Montero, I., Romero, P., and Miranda, M. T. (2021). "Feasibility analysis of brewers' spent grain for energy use: Waste and experimental pellets," *Applied Sciences* 11(6), 1-12. DOI: 10.3390/app11062740

Bridgeman, T. G., Jones, J. M., Shield, I., and Williams, P. T. (2008). "Torrefaction of reed canary grass, wheat straw and willow to enhance solid fuel qualities and combustion properties," *Fuel* 87(6), 844-856. DOI: 10.1016/j.fuel.2007.05.041

Cardozo, E., Erlich, C., Alejo, L., and Fransson, T. H. (2014). "Combustion of agricultural residues: An experimental study for small-scale applications," *Fuel* 115, 778-787. DOI: 10.1016/j.fuel.2013.07.054

Casal, M. D., Gil, M. V., Pevida, C., Rubiera, F., and Pis, J. J. (2010). "Influence of storage time on the quality and combustion behaviour of pine woodchips," *Energy* 35(7), 3066-3071. DOI: 10.1016/j.energy.2010.03.048

Fang, X., and Jia, L. (2012). "Experimental study on ash fusion characteristics of biomass," *Bioresource Technology* 104, 769-774. DOI: 10.1016/j.biortech.2011.11.055

Hadders, G., and Olsson, R. (1997). "Harvest of grass for combustion in late summer and in spring," *Biomass and Bioenergy* 12(3), 171-175. DOI: 10.1016/S0961-9534(96)00047-5

Horvat, I., Dović, D., and Filipović. P. (2021). "Numerical and experimental methods in development of the novel biomass combustion system concept for wood and agro pellets," *Energy* 231, article no. 120929. DOI: 10.1016/j.energy.2021.120929

Jasinskas, A., Streikus, D., Šarauskis, E., Palšauskas, M., and Venslauskas, K. (2020). "Energy evaluation and greenhouse gas emissions of reed plant pelletizing and utilization as solid biofuel," *Energies* 13(6), 1-14. DOI: 10.3390/en13061516

Jia, G., Li, L., and Zhang, D. M. (2020). "Effect analysis on combustion and emission characteristics of a rotary burner fueled by biomass pellet fuel," *Journal of Chemistry* 2020, 1-12. DOI: 10.1155/2020/3618382

Korobiichuk, I., Davydova, I., Korobiichuk, V., Shlapak, V., Panasiuk, A. (2021). "Measurement of qualitative characteristics of different types of wood waste in the forestries Zhytomyr Polissya," in: *Automation 2021: Recent Achievements in Automation, Robotics and Measurement Techniques*, R. Szewczyk, C. Zieliński, and M. Kaliczyńska (eds.), Springer Nature, Basingstoke, United Kingdom, pp. 297-308.

Lee, S. W., Pomalis, R., and Kan, B. (2000). "A new methodology for source characterization of oil combustion particulate matter," *Fuel Processing Technology* 65-66, 189-202. DOI: 10.1016/S0378-3820(99)00086-7

Minajeva, A., Jasinskas, A., Domeika, R., Vaiciukevičius, E., Lemanas, E., and Bielski, S. (2021). "The study of the faba bean waste and potato peels recycling for pellet production and usage for energy conversion," *Energies* 14(10), 1-14. DOI: 10.3390/en14102954

Mudryk, K., Jewiarz, M., Wróbel, M., Niemiec, M., and Dyjakon, A. (2021). "Evaluation of urban tree leaf biomass-potential, physico-mechanical and chemical parameters of raw material and solid biofuel," *Energies* 14(4), 1-14. DOI: 10.3390/en14040818

Pafčuga, M., Holubcik, M., Durcansky, P., Kapjor, A., and Malcho, M. (2021). "Small heat source used for combustion of wheat-straw pellets, "*Applied Sciences* 11(11), 5239. DOI: 10.3390/app11115239

Poláčik, J., Sitke, T., Pospíšil, J., Šnajdárek, L., and Lisý, M. (2021). "Emission of fine particles from residential combustion of wood: Comparison of automatic boiler, manual log feed stove and thermo-gravimetric analysis," *Journal of Cleaner Production* 279, 1-9. DOI: 10.1016/j.jclepro.2020.123664

Rebbling, A., Näzelius, I. L., Schwabl, M., Feldmeier, S., Schön, C., Dahl, J., Haslinger, W. Boström, D., Öhman, M., and Boman, C. (2020). "Prediction of slag related problems during fixed bed combustion of biomass by application of a multivariate statistical approach on fuel properties and burner technology," *Biomass and Bioenergy* 137, article no. 105557. DOI: 10.1016/j.biombioe.2020.105557

Senila, L., Tenu, I., Carlescu, P., Corduneanu, O. R., Dumitrachi, E. P., Kovacs, E., Scurtu, D. A., Cadar, O., Becze, A., Senila, M., *et al.* (2020). "Sustainable biomass pellets production using vineyard wastes," *Agriculture* 10(11), 1-21. DOI: 10.3390/agriculture10110501

Sher, F., Yaqoob, A., Saeed, F., Zhang, S., Jahan, Z., and Klemeš, J. J. (2020). "Torrefied biomass fuels as a renewable alternative to coal in co-firing for power generation," *Energy* 209, 1-13. DOI: 10.1016/j.energy.2020.118444

Smith, D. J., Sreedharan, V., Landon, M., and Smith Z. P. (2020). "Advanced design optimization of combustion equipment for biomass combustion," *Renewable Energy* 145, 1597-1607. DOI: 10.1016/j.renene.2019.07.074

STN ISO 540 (2008). "Hard coal and coke. Determination of ash fusibility," International Organization for Standardization, Geneva, Switzerland.

Tzelepi, V., Zeneli, M., Kourkoumpas, D.-S., Karampinis, E., Gypakis, A., Nikolopoulos, N., and Grammelis, P. (2020). "Biomass availability in Europe as an alternative fuel for full conversion of lignite power plants: A critical review," *Energies* 13(13), 1-26. DOI: 10.3390/en13133390

Werther, J., Saenger, M., Hartge, E.-U., Ogada, T., and Siagi, Z. (2000). "Combustion of agricultural residues," *Progress in Energy and Combustion Science* 26(1), 1-27. DOI: 10.1016/S0360-1285(99)00005-2

Article submitted: July 8, 2021; Peer review completed: August 2, 2021; Revised version received and accepted: August 6, 2021; Published: August 12, 2021.
DOI: 10.15376/biores.16.4.6737-6749