Marcin HERKOWIAK[1], Mariusz ADAMSKI[1], Zbigniew DWORECKI[1], Bogusława WALISZEWSKA[2], Krzysztof PILARSKI[1], Kamil WITASZEK[1], Gniewko NIEDBAŁA[1], Magdalena PIEKUTOWSKA[3]
[1] Poznan University of Life Sciences, Institute of Biosystems Engineering, Poznań, Poland
[2] Institute of Wood Chemical Technology, Poznań, Poland
[3] Koszalin University of Technology, Department of Agrobiotechnology, Faculty of Mechanical Engineering
ul. Racławicka 15-17, 75-620 Koszalin, Poland
e-mail: mariusz.adamski1@wp.pl ; magdalena.piekutowska@poczta.fm
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ANALYSIS OF THE POSSIBILITY OF OBTAINING THERMAL ENERGY FROM COMBUSTION OF SELECTED CEREAL STRAW SPECIES

Summary

Wheat, corn and rapeseed straw can be used as a raw material for the production of biofuels used to generate heat energy. Due to the growing interest in renewable fuels, including straw, it is reasonable to test the energy suitability of these fuels. The aim of the study was to compare the combustion heat and calorific value of particular straw species. The most important parameters enabling comparison of the above mentioned fuels were determined, which include: humidity, combustion heat and calorific value. The moisture content of individual wood samples was: 6.32% for wheat straw, 8.40% for corn straw and 8.49% for rapeseed straw. The analysis showed that the moisture content of the straw samples tested was at a similar level. Combustion heat analysis allowed to obtain the following results: 16.10 MJ·kg^{-1} for wheat straw, 16.60 MJ·kg^{-1} for rapeseed straw and 17.30 MJ·kg^{-1} for maize straw. The highest combustion heat was observed for corn straw. The same parameter for rapeseed straw was lower by 0.7 MJ·kg^{-1} than for maize straw. The lowest combustion heat of 16.10 MJ·kg^{-1} was observed for wheat straw. The calorific value of the samples tested was: 14.80 MJ·kg^{-1} for wheat straw, 15.30 MJ·kg^{-1} for rapeseed straw and 16.10 MJ·kg^{-1} for maize straw. The highest calorific value was found for corn straw. The calorific value of wheat straw was lower by about 9%, while rapeseed straw was lower by about 5% in comparison to maize straw. On the basis of the conducted research and literature data concerning the yields of straw of various cereal species, the amount of energy possible to obtain per hectare of cultivation was estimated. With the yield per hectare for: wheat straw 3.2 Mg d.m., rapeseed straw 3.3 Mg d.m., maize straw 12.5 Mg d.m. can be obtained for: wheat straw 47.36 GJ·ha^{-1}, rapeseed straw 50.49 GJ·ha^{-1}, maize straw 201.25 GJ·ha^{-1}.
***Key words**: combustion heat, calorific value, straw, biomass*

ANALIZA MOŻLIWOŚCI POZYSKANIA ENERGII CIEPLNEJ ZE SPALANIA WYBRANYCH GATUNKÓW SŁOMY ZBÓŻ

Streszczenie

Słoma pszenna, kukurydziana oraz rzepakowa może stanowić surowiec do produkcji biopaliw wykorzystywanych na cele pozyskiwania energii cieplnej. W związku z rosnącym zainteresowaniem paliwami odnawialnymi, w tym słomą zasadnym jest badanie przydatności energetycznej tych paliw. Celem badań było porównanie ciepła spalania oraz wartości opałowej poszczególnych gatunków słomy. Określono najważniejsze parametry umożliwiające porównanie wyżej wymienionych paliw, do których zaliczamy: wilgotność, ciepło spalania oraz wartość opałową. Wilgotność poszczególnych próbek drewna wynosiła: 6,32% dla słomy pszennej, 8,40% dla słomy kukurydzianej, oraz 8,49% dla słomy rzepakowej. Przeprowadzona analiza wykazała, że wilgotność badanych próbek słomy była na podobnym poziomie. Badanie ciepła spalania umożliwiło uzyskanie następujących wyników: 16,10 MJ·kg^{-1} dla słomy pszennej, 16,60 MJ·kg^{-1} dla słomy rzepakowej oraz 17,30 MJ·kg^{-1} dla słomy kukurydzianej. Najwyższe ciepło spalania zaobserwowano dla słomy kukurydzianej. Ten sam parametr dla słomy rzepakowej był o 0,7 MJ·kg^{-1} niższy niż dla słomy kukurydzianej. Najniższym ciepłem spalania 16,10 MJ·kg^{-1} charakteryzowała się słoma pszenna. Wartość opałowa badanych próbek wynosiła: 14,80 MJ·kg^{-1} dla słomy pszennej, 15,30 MJ·kg^{-1} dla słomy rzepakowej oraz 16,10 MJ·kg^{-1} dla słomy kukurydzianej. Najwyższą wartością opałową charakteryzowała się słoma kukurydziana. Wartość opałowa słomy pszennej była niższa o około 9%, natomiast słomy rzepakowej niższa o około 5% w porównaniu do słomy kukurydzianej. Na podstawie przeprowadzonych badań oraz danych literaturowych dotyczących wielkości plonów słomy różnych gatunków zbóż oszacowano ilość możliwej do uzyskania energii z jednego hektara uprawy. Przy plonie z jednego hektara dla: słomy pszennej 3,2 Mg s.m., słomy rzepakowej 3,3 Mg s.m, słomy kukurydzianej 12,5 Mg s.m. można uzyskać dla: słomy pszennej 47,36 GJ·ha^{-1}, słomy rzepakowej 50,49 GJ·ha^{-1}, słomy kukurydzianej 201,25 GJ·ha^{-1}.
***Słowa kluczowe**: ciepło spalania, wartość opałowa, słoma, biomasa*

1. Introduction

Climate warming and air pollution resulting from the combustion of fossil fuels increase interest in renewable fuels. The highest potential among renewable fuels possible to use in Poland is shown by solid fuels [2]. This is mainly due to the profitability of using these fuels, including both their prices and investment costs, in installations enabling their combustion [1].

By imposing obligations on Poland by the European Union to increase the share of energy from renewable sources, the popularization of fuels of plant origin, including straw, is observed [11].

Straw is defined as the dried stems of cereal crops, the dried stems of rape, flax or leguminous plants as a by-product of agricultural production. There are several ways of using straw, among which it is worth mentioning:

- use as litter in animal husbandry,

- use as an ingredient in feedingstuffs,
- replenishment of soil organic matter by ploughing up post-harvest residues,
- use as an ingredient in substrates for the production of mushrooms,
- use for energy purposes,
- use as a material for thermal insulation of buildings [4].

Straw yield depends on both cereal species and variety, as well as on soil, weather conditions in a given vegetation period and the production technology used (including fertilization, growth regulators and forecrop). Due to the dependence of straw yield on so many factors, it is difficult to determine straw yields. The amount of straw yield obtained is additionally determined by the amount of mowing. It is estimated that its increase by 5 centimetres contributes to a decrease in straw yield by 10% [9].

A straw balance is used to determine the quantity of straw that can be used for energy purposes. This balance takes into account the production and distribution of straw to the aforementioned needs for fodder, bedding, ploughing and mushroom bedding. The difference between the production and distribution of straw is its surplus that can be used for energy needs [3].

The area under cereals in Poland ranges from 7.8 to 8.5 million hectares. The total harvest of cereal straw in 2010-2014 amounted to 30.9 million Mg, where 80.3% was cereal straw, 10.9% corn straw, 7.7% rapeseed straw and 1.1% leguminous straw. According to forecasts, in 2030 the share of cereal straw in production will decrease to 72.1%, while the share of corn straw will increase to 16% and rapeseed straw to 10.5% [7]. On the other hand, after deducting the consumption of straw for purposes such as feed production, litter and substrates for mycelium, it turned out that in the years 2010-2014 it was possible to use an average of 12.1 million Mg of straw for energy purposes. At the same time, it is predicted that in 2020 the surplus of straw will amount to 13.1 million Mg, and in 2030 even 14.3 Mg [10].

2. The aim of study

The aim of the study was to determine and compare the energy value of wheat, rapeseed and corn straw and to compare these values with the current state of knowledge. In order to achieve the aim of the study, moisture, combustion heat and calorific values of particular straw species were determined. Additionally, it was envisaged to use the data from literature and research to determine the amount of energy that could be obtained from the combustion of surplus straw in Poland.

3. Methodology

3.1. Preparation of test material

The samples used for the test were obtained from wheat, rapeseed and maize straw in an air-dry state, which could be used for the production of solid biofuels. The material used was ground to a grain size of less than 0.2 mm (Fig. 1). The samples obtained in this way were used to perform the tests.

The most important parameters enabling comparison of the above mentioned parts of plants, which include: humidity, combustion heat and calorific value, were determined. These parameters were determined at the Institute of Chemical Wood Technology at the University of Life Sciences in Poznań.

Source: own elaboration / Źródło: opracowanie własne

Fig. 1. Samples of maize straw (left) and rapeseed straw (right) used for testing

Rys. 1. Próbki słomy kukurydzianej (z lewej) oraz rzepakowej (z prawej) użyte do badań

3.2. Determination of moisture content

To determine the moisture content, the dryer-weighing method according to PN-EN ISO 18134-3 [14] was used. This method consists in measuring the loss in weight caused by evaporation of water during drying at 105-110˚C. The test was carried out on three samples from each straw species (Fig. 2). The weight of moist and dry samples was determined with the accuracy of 0.01 g.

Source: own elaboration / Źródło: opracowanie własne

Fig. 2. The prepared sample for testing moisture content

Rys. 2. Przygotowane próbki do badania wilgotności

3.3. Determination of the combustion heat

The determination of combustion heat and calorimeter value was performed (Fig. 3). Samples in the form of tablets weighing about 1 g were used for the study. For this purpose, the previously obtained wood samples were used. The obtained tablets were each time placed in a crucible being a part of a calorimetric bomb. The sample was ignited by a resistance wire touching it at least in two places. Combustion heat was determined by the complete combustion of the material sample in an oxygen atmosphere under pressure in a calorimetric bomb submerged in a water jacket and simultaneous measurement of water temperature rise.

The test was based on the PN-C-04375-2:2013-07 standard concerning the testing of solid and liquid fuels, determination of combustion heat in a calorimetric bomb and calculation of calorimetric value [13].

Source: own elaboration / Źródło: opracowanie własne

Fig. 3. General view of the position of calorimetric research (left), calorimetric bomb (right)
Rys. 3. Widok ogólny stanowiska do badań kalorymetrycznych (z lewej), złożona bomba kalorymetryczna (z prawej)

3.4. Determination of calorific value

The calorific value was determined using a formula:

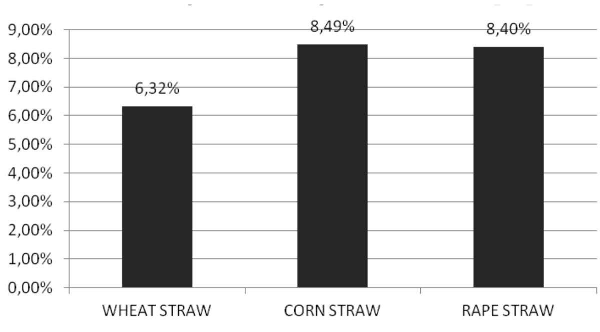
$Q_{ia}=Q_{sa}-P(W_a+H_w(H_a))$ [$J \cdot g^{-1}$],
where:
Q_{ia} – calorific value in analytical state [$J \cdot g^{-1}$],
Q_{sa} – the calorific value of the fuel in the analytical state [$J \cdot g^{-1}$],
P – heat of water evaporation at 25ºC 1% content = 24,42 [$J \cdot g^{-1}$],
W_a – moisture content of the analytical sample [%],
H_w – hydrogen to water conversion factor = 8,94,
H_a – hydrogen content of the analytical sample [%].

The results obtained earlier concerning combustion heat and moisture content were substituted to the formula. Data on hydrogen content were obtained from literature for wheat straw 5.8%, rapeseed straw 5.9%, maize straw 5.3% [6].

4. Results
4.1. Moisture

The moisture content of individual straw samples was: 6.32% for wheat straw, 8.40% for corn straw, and 8.49% for rapeseed straw. The analysis showed that the moisture content of the straw samples tested was at a similar level. The results of moisture content of the straw samples tested are presented in the graph below (Fig. 4).

Obtained results of moisture content of less than 10% prove very good drying of straw used in the tests.



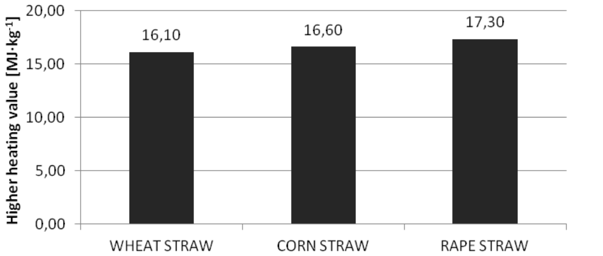
Source: own elaboration / Źródło: opracowanie własne

Fig. 4. Humidity test samples of straw [%]
Rys. 4. Wilgotność badanych próbek słomy [%]

4.2. Higher heating value

Higher heating value is the amount of heat released during the complete combustion of a unit of fuel mass in an oxygen atmosphere. This parameter takes into account the heat of condensation of water vapour.

Higher heating value testing enabled the following results to be obtained: 16.10 $MJ \cdot kg^{-1}$ for wheat straw, 16.60 $MJ \cdot kg^{-1}$ for rapeseed straw, and 17.30 $MJ \cdot kg^{-1}$ for maize straw. The highest combustion heat was observed for corn straw. The same parameter for rapeseed straw was 0.7 $MJ \cdot kg^{-1}$ lower than for maize straw. Wheat straw was characterized by the lowest combustion heat of 16.10 $MJ \cdot kg^{-1}$. The results of combustion heat are presented in Fig. 5.



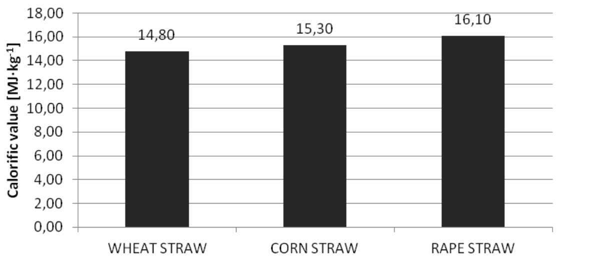
Source: own elaboration / Źródło: opracowanie własne

Fig. 5. Higher heating value of the tested samples of straw [$MJ \cdot kg^{-1}$]
Rys. 5. Ciepło spalania badanych próbek słomy [$MJ \cdot kg^{-1}$]

4.3. Calorific value

The calorific value is a parameter that determines the amount of heat generated during the complete combustion of the fuel without taking into account the heat of condensation of water vapour. For this reason, the calorific value of a given sample is lower than its combustion heat and depends on its moisture content.

The calorific value of the tested samples was: 14.80 $MJ \cdot kg^{-1}$ for wheat straw, 15.30 $MJ \cdot kg^{-1}$ for rapeseed straw and 16.10 $MJ \cdot kg^{-1}$ for maize straw. The highest calorific value was found for corn straw. The calorific value of wheat straw was lower by about 9%, while rapeseed straw was lower by about 5% in comparison to corn straw. The calorific value of the studied wood species is presented in Fig. 6.

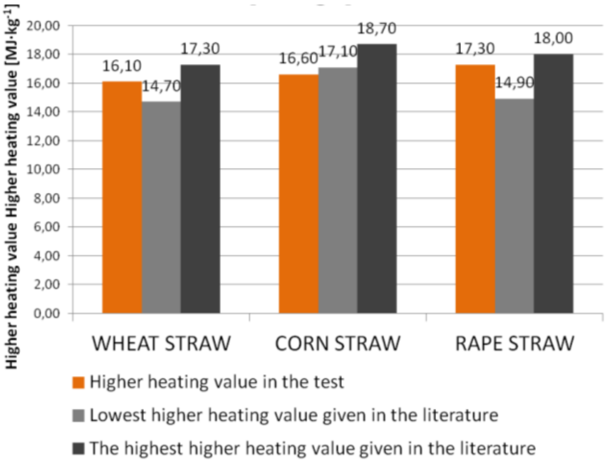


Source: own elaboration / Źródło: opracowanie własne

Fig. 6. Calorific value of the tested samples of straw [$MJ \cdot kg^{-1}$]
Rys. 6. Wartość opalowa próbek słomy [$MJ \cdot kg^{-1}$]

5. Analysis of results
5.1. Analysis of the obtained combustion heat results

On the basis of the results concerning the combustion heat obtained in the presented study and earlier studies described in the literature [4, 8, 9] presented in the above Fig. 7, it can be noticed that the results concerning wheat and maize straw do not differ from the literature reports in this respect. In the case of rapeseed straw, the combustion heat is visibly lower than the lowest predicted value of this parameter in literature by 0.5 $MJ \cdot kg^{-1}$.



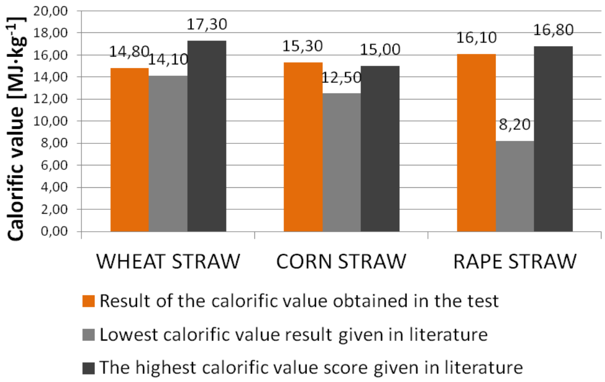
Source: elaboration based on own research and [4, 6, 8, 9]
Źródło: opracowanie na podst. badań własnych oraz [4, 6, 8, 9]

Fig. 7. Summary of obtained results of higher heating values tests with literature data [MJ·kg^{-1}]
Rys. 7. Zestawienie uzyskanych wyników badań ciepła spalania z danymi literaturowymi [MJ·kg^{-1}]

5.2. Analysis of the obtained results of the calorific value

The results obtained as a result of the experiment were compared with the results available in the literature. The results were focused on the results taking into account the moisture content of the raw material up to 20%, due to the adequacy of such a raw material to be used in the way of combustion.

On the basis of the results presented in the above Fig. 8 concerning the calorific values obtained in the presented study and earlier studies described in the literature [4, 5, 6, 8, 9], it can be



Source: elaboration based on own research and [4, 5, 6, 8, 9]
Źródło: opracowanie na podst. badań własnych oraz [4, 5, 6, 8, 9]

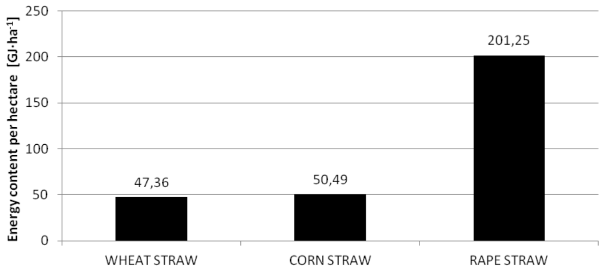
Fig. 8. Comparison of the obtained results of tests of calorific value with literature data [MJ·kg^{-1}]
Rys. 8. Zestawienie uzyskanych wyników badań wartości opałowej z danymi literaturowymi [MJ·kg^{-1}]

noted that the results obtained concerning wheat and maize straw do not differ from the literature reports in this respect. In the case of rapeseed straw, the combustion heat is visibly higher than the highest reported value of this parameter in the literature by 0.3 MJ·kg^{-1}. A higher calorific value result than in the previous studies should be explained by a lower moisture content in the tested sample than in the samples of previous researchers.

5.3. The amount of energy that can be obtained per hectare of crop

On the basis of the average straw yields per hectare and the results of the calorific value, the amount of energy possible to be obtained from 1 hectare of cultivation was estimated. According to literature it is possible to obtain wheat straw yield at the level of 3.0-3.4 Mg·ha^{-1} [9], rapeseed straw 3.3 Mg·ha^{-1} [4], and maize straw even 12-14 Mg·ha^{-1} [12].

The data obtained from the literature on the amount of possible to obtain raw material in the form of straw were used to calculate the achievable amount of energy in the combustion method depending on the previously obtained results of calorific values. The results are presented in Table 1 and Fig. 9.



Source: own elaboration / Źródło: opracowanie własne

Fig. 9. Quantities of energy obtained from selected straws
Rys. 9. Ilość pozyskanej energii z wybranych rodzajów słomy

The amount of energy available per hectare was 47.36 GJ-ha^{-1} for wheat straw, 50.49 GJ-ha^{-1} for rapeseed straw, corn straw and maize straw, respectively.

Due to similar calorific values and the assumed yield, a comparable amount of energy per hectare is noticeable in the case of rapeseed and wheat straw. Due to the four times higher predicted corn straw yield compared to the other straw species studied, the four times higher amount of energy per hectare is also estimated.

Table 1. Energy production per hectare of selected straws
Tab. 1 . Produkcja energii z jednego hektara wybranych gatunków słomy

Raw material	Higher heating value	Calorific value	Expected yield	Energy quantity per hectare		
	GJ·Mg^{-1}	GJ·Mg^{-1}	Mg·ha^{-1}	GJ·ha^{-1}	kWh·ha^{-1}	MWh·ha^{-1}
wheat straw	16,10	14,80	3,2	47,36	13 155,56	13,16
corn straw	16,60	15,30	3,3	50,49	14 025,00	14,03
rape straw	17,30	16,10	12,5	201,25	55 902,78	55,90

Source: own elaboration / Źródło: opracowanie własne

6. Conclusions

The research carried out allowed us to specify the following conclusions:

1. The straw used for the study was characterized by a low moisture content, and the results of combustion heat and calorific value above 15 $MJ \cdot kg^{-1}$ indicate the possibility of using these plants for energy purposes in the combustion process.
2. The highest combustion heat was obtained for corn straw (17.30 $MJ \cdot kg^{-1}$), rapeseed straw (16.60 $MJ \cdot kg^{-1}$) was characterized by a slightly lower value. Wheat straw (16.10 $MJ \cdot kg^{-1}$) was characterized by the lowest combustion heat. In comparison with literature data concerning this parameter, it was shown that the results obtained in the study on wheat and maize straw were within the limits set by the results of earlier published studies. On the other hand, the determined combustion heat of rapeseed straw slightly differed from the values of this parameter suggested in literature. Combustion heat was 3% lower than the lowest values given in literature.
3. The calorific value at the obtained moisture content was: wheat straw: 14.80 $MJ \cdot kg^{-1}$, rapeseed straw: 15.30 $MJ \cdot kg^{-1}$, maize straw: 16.10 $MJ \cdot kg^{-1}$. In comparison with literature data concerning this parameter, it was shown that the value obtained in the study for wheat and maize straw was within the limits determined by the results of earlier published studies. On the other hand, the determined combustion heat of rapeseed straw slightly differed from the values of this parameter suggested in literature. Combustion heat was 2% higher than the highest value given in literature. This difference should be explained by a lower moisture content in the sample, as compared to the samples analysed in the available scientific publications.
4. Comparable differences between combustion heat and calorific value resulted from humidity conditions of the tested samples.
5. On the basis of the conducted research and literature data concerning the yields of straw of various cereal species, the amount of energy possible to obtain per hectare of cultivation was estimated. With the yield per hectare for: wheat straw 3.2 Mg d.m., rapeseed straw 3.3 Mg d.m., maize straw 12.5 Mg d.m. can be obtained for: wheat straw 47.36 $GJ \cdot ha^{-1}$, rapeseed straw 50.49 $GJ \cdot ha^{-1}$, maize straw 201,25 $GJ \cdot ha^{-1}$.
6. Due to the fact that the yield of corn straw is four times higher than that of the other examined species, four times more energy is expected to be obtained per 1 hectare of cultivation. This means that the potential of maize straw as a raw material for biofuel production is much higher.

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