Journal of Elementology ISSN 1644-2296

Stolarski M.J, Rybczyńska B., Krzyżaniak M., Lajszner W., Graban Ł., Peni D., Bordiean A. 2019.
Thermophysical properties and elemental composition of agricultural and forest solid biofuels versus fossil fuels.
J. Elem., 24(4): 1215-1228. DOI: 10.5601/jelem.2019.24.1.1819

RECEIVED: 23 February 2019
ACCEPTED: 19 May 2019

ORIGINAL PAPER

THERMOPHYSICAL PROPERTIES AND ELEMENTAL COMPOSITION OF AGRICULTURAL AND FOREST SOLID BIOFUELS VERSUS FOSSIL FUELS*

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Abstract

Solid biomass is a promising alternative to traditional energy resources, able to successfully reduce the negative effects of climate change. The structure of energy production from renewable sources shows that solid biofuels have the largest share in Poland and the EU28. Thus, solid biofuels constitute an important and interesting alternative to solid fossil fuels. However, due to its wide variety of origin, logistics and processing technology, the properties and quality of solid biofuels may vary. Therefore, the aim of the study was to determine the thermophysical properties and elemental composition of solid biofuels of agricultural and forestry origin compared to solid fossil fuels. The research material were 20 types of solid fuel, including 16 renewable and 4 fossil fuels obtained from plantations of the University of Warmia and Mazury in Olsztyn and from two heat generation and distribution enterprises (Olsztyn and Grudziądz). The experiment confirmed that selected solid biofuels from agriculture and forestry are a good alternative to fossil fuels like coal in terms of some thermophysical properties and elemental compositions. The content of ash in coal fuels was 3- to16-fold higher than in agricultural and forest origin biofuels. Moreover, the content of sulphur in coal fuels was from 5- to 31-fold higher than in agricultural and forest biofuels. Considering the above, the use of solid biofuels for energy generation may create a less negative effect on the environment than coal fuels.

Keywords: biomass, solid biofuels, cereal straw, energy crops, coal, thermophysical properties, elementary composition.

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* This paper is based on a study carried out at the University of Warmia and Mazury in Olsztyn, Faculty of Environmental Management and Agriculture, Department of Plant Breeding and Seed Production, topic number 20.610.008-300 and it was co-financed by the National (Polish) Centre for Research and Development (NCBiR), titled "Environment, agriculture and forestry", No. BIOSTRATEG3/344128/12/NCBR/2017.

INTRODUCTION

The use of non-renewable fossil resources, such as coal, natural gas or oil, has a significant impact on the development and technical progress of civilization. However, the use of fossil fuels adversely affects the climate and environment. Emissions resulting from combustion of such fuels are released into the atmosphere, causing environmental degradation (Stolarski et al. 2013*a*). Moreover, global resources of these fuels are limited and their quantities are systematically decreasing. This influences prices and has an impact on energy dependency and insecurity in countries where fossil fuels are imported (Lucia 2008, Matsakas et al. 2016). Poland is one of the largest consumers of coal in Europe (Bioenergy Europe 2018). The structure of energy consumption per capita shows that 32.5% of energy comes from hard coal, while in the EU it is only 2.7% (GUS 2018). It is important to find new sources of renewable energy that can be used on a large scale for domestic, commercial and industrial purposes (Afzal et al. 2010, Matsakas et al. 2016).

Biomass is considered to be entirely organic, non-fossil material of biological origin which includes parts of plants as well as residues from agriculture and forestry, and is a renewable energy source owing to the incorporation of solar energy. The benefits of using biomass as a renewable energy source, according to Nelson et al. (2018), are numerous: it is easily renewable, it enriches the environment, it is carbon neutralizing, it is a source of hydrocarbon components, it improves energy security stability, it creates new jobs in rural areas, it improves air quality, etc. The component which makes biomass so precious and important in the field of green energy is lignocellulose, which represents almost half of the vegetal matter of the plants, produced by photosynthesis with solar energy and organic soil resources, consisting of cellulose, hemicellulose and lignin (Abdeshahian 2010). Solid biomass is currently a promising alternative to traditional energy, as it can successfully reduce the negative effects of climate change. Plants use CO_2 from the atmosphere to build their biomass and thus neutralize CO_2 emissions resulting from the transformation of biomass into energy (Eseyin et al. 2015, Stolarski et al. 2015). Solid biofuels are the most important source of environmentally-friendly energy because they present a low negative impact on environment compared to conventional sources. Thus, solid biofuels can be produced from residues, such as forestry (branches, shrubs, etc.), agriculture (different types of straws, energy plants, etc.), from different industrial sectors using agricultural or forestry biomass and from urban greenery maintenance.

In Europe, Poland is a country which has many possibilities of using solid biofuels, obtained from agricultural land and forests which occupy its territory. The contribution of energy from renewable sources to total primary energy in 2016 in Poland was 13.6%, compared with 27.9% in the EU28 (GUS 2018). The structure of energy production from renewable sources shows that in Poland and the EU28, solid biofuels have the largest share (71.1% and 44.7%, respectively). In 2017, 67.9% of all renewable energy in Poland originated mainly from solid biomass. Other sources of renewable energy included wind power, which contributed 14% of renewable energy, and liquid biofuels (10.0%). This means that solid biomass/biofuels have more advantages in a country where agriculture and forestry can offer the raw materials for bioenergy. Thus, solid biofuels constitute an important and interesting alternative to solid fossil fuels. However, it should be underlined that due to its wide variety of origin, logistics and processing technology, the properties and quality of solid biofuels may vary. Considering the above, the aim of the present study was to determine the thermophysical properties and elemental composition of solid biofuels of agricultural and forestry origin compared to solid fossil fuels as raw material used for energy production.

MATERIALS AND METHODS

Types of solid fuel samples and their analysis

The elementary research material were samples of 16 solid biofuels of agricultural and forestry origin, obtained from (i) experimental plantations of the University of Warmia and Mazury in Olsztyn (UWM) carried out by the Production and Experimental Enterprise in Łężany; (ii) the District Heat Generation and Distribution Plant in Grudziądz (OPEC); (iii) the Municipal Heat Generation and Distribution Plant in Olsztyn (MPEC). Conventional fuel, i.e. black coal as fine coal and eco-pea coal (*ekogroszek*) were used for comparison. These two types of fossil fuel were obtained from both of the above heat generation and distribution enterprises. In total, 20 types of solid fuel, including 16 renewable and 4 fossil fuels, were examined. Table 1 presents the particular fuel types and their origin.

Samples of all the solid fuels were taken from the storage site in compliance with the relevant sampling procedures and transported to the Energy Material Analytical Laboratory (the UWM). Analytical samples were prepared in accordance with PN-EN 14780:2011 standard. Moisture content was determined according to PN-EN 18134-1: 2015-11 standard. Ash content was determined with the oven method at 550°C, according to PN-EN ISO 18122: 2016-01. The higher heating value (HHV) of assayed fuels was determined in an IKA C2000 calorimeter based on the dynamic method, according to PN-EN ISO 18125: 2017 standard. Based on the moisture content and HHV, lower heating value (LHV) of fuels was calculated according to PN-EN ISO 18125: 2017. The contents of carbon, hydrogen and sulphur were analyzed using a high temperature automatic ELTRA CHS 500 analyzer according to the PN-G-04584: 2001 standard. Nitrogen content tests were performed using the Kjeldahl method in a K-435 mineralizer and a BUCHI B-324 distillery according to PN-EN ISO 20483, and the chlorine content was

Table 1

Types of the examined solid fuels and their origin

Origins	Fuel type	Type of energy source
Agricultural biomass	Wheat straw	residues from agriculture
	Rapeseed straw	
	Rye straw	
	Ryegrass straw	
	Corn stover	
	Mixed straw pellets	
	Palm Kernel Shell (PKS)	imported biomass
	Miscanthus straw (OPEC)	energy crops
	Miscanthus straw (UWM)	
	Willow – seasoned chips (Żubr variety)	
	Willow – seasoned chips (Ekotur variety)	
	Poplar – seasoned chips (Max-5 clone)	
	Black locust – seasoned chips	
Forest biomass	Pine pellets	wood industry residues
	Mixed briquettes	
	Forest wood chips	forest residues
Fossil fuels	Fine coal (OPEC)	hard coal – conventional fuels
	Fine coal (MPEC)	
	Coal – *ekogroszek* (OPEC)	
	Coal – *ekogroszek* (MPEC)	

determined using an Eschka mixture according to PN-ISO 587. All analysis were done in three replications.

Statistical analysis

The statistical analysis of the results was performed with Statistica PL software. The arithmetic means were calculated for all studied parameters. Subsequently, homogeneous groups with a significance level of $P<0.05$ were determined using the Tukey's significance test. The correlation coefficients between the analyzed features were also calculated.

RESULTS AND DISCUSSION

The moisture content of the tested fuels averaged 19.06%, with a standard deviation of 13.38 (Table 2). Seven homogeneous groups were differentiated for this feature. Corn stover had the highest moisture content (69.8%), while forest wood chips had almost half of the corn moisture value (36.29%)

Table 2

Characteristics of the moisture content, HHV and LHV of the studied fuels

Fuel type	Moisture content (%)	HHV (MJ kg^{-1} d.m.)	LHV (MJ kg^{-1})
Wheat straw	16.20±0.17^{e}	18.68±0.01^{m}	15.26±0.04^{f}
Rapeseed straw	27.98±0.09^{c}	18.93±0.02^{l}	12.95±0.02^{g}
Rye straw	15.99±0.41^{e}	18.67±0.03^{m}	15.29±0.08^{f}
Ryegrass straw	15.35±0.10^{e}	19.03±0.02^{k}	15.74±0.01^{e}
Corn stover	69.80±5.67^{a}	18.28±0.05^{o}	3.82±1.16^{h}
Miscanthus straw (OPEC)	16.03±0.18^{e}	19.23±0.03^{j}	15.76±0.04^{e}
Miscanthus straw (UWM)	14.75±0.55^{e}	19.70±0.01^{i}	16.43±0.13^{e}
Mixed straw pellets	12.46±0.10^{e}	18.48±0.03^{n}	15.87±0.05^{e}
Willow chips (Żubr)	16.57±0.11^{e}	19.76±0.04^{i}	16.08±0.01^{e}
Willow chips (Ekotur)	16.96±0.86^{e}	19.54±0.04^{i}	15.81±0.22^{e}
Poplar chips (max-5 clone)	16.86±0.16^{e}	19.88±0.03^{h}	16.12±0.01^{e}
Black locust chips	15.52±0.18^{e}	19.60±0.04^{i}	16.18±0.04^{e}
Palm Kernel Shell (PKS)	8.89±0.17^{g}	21.15±0.04^{e}	19.05±0.07^{c}
Pine Pellets	8.20±0.69^{g}	20.50±0.04^{f}	18.62±0.13^{c}
Mixed briquettes	11.34±0.06^{f}	19.62±0.04^{i}	17.11±0.05^{d}
Forest wood chips	36.29±7.46^{b}	20.00±0.04^{g}	11.86±1.70^{g}
Fine coal (OPEC)	18.67±0.09^{d}	27.17±0.04^{b}	21.64±0.01^{b}
Fine coal (MPEC)	18.97±2.02^{d}	24.70±0.03^{d}	19.55±0.57^{c}
Coal – *ekogroszek* (OPEC)	11.19±0.55^{f}	26.52±0.02^{c}	23.28±0.18^{a}
Coal – *ekogroszek* (MPEC)	13.23±1.12^{e}	27.55±0.03^{a}	23.59±0.36^{a}
Mean	19.06±13.38	20.85±2.96	16.50±4.20

± standard deviation; *a*, *b*, *c*... homogenous groups

and were in the second homogenous group (b). The next group (c) included rapeseed straw (27.98%). Eleven types of fuels were classified in one homogenous group (e). The lowest moisture content was determined for pine pellets (8.20%) and the PKS (8.89%) homogenous group (g). The moisture content of short rotation coppice seasoned chips (black locust, willow and poplar) was also low at 15-17%, owing to the storage and natural drying of the shoots under proper conditions. In another study conducted by Stolarski et al. (2013*b*), it was found that the moisture content in fresh black locust, poplar and willow chips was much higher (between 47% and 53%). It should be underlined that the moisture content of wood chips also depends on the method and conditions of storage (Afzall et al. 2010, Krzyżaniak et al. 2016). The moisture content of both fine coals was around the same value, whereas eco-pea coal (*ekogroszek*) from MPEC had higher moisture content (2 percentage points - p.p.) than from OPEC. As can be seen in Figure 1, biofuels of agri-

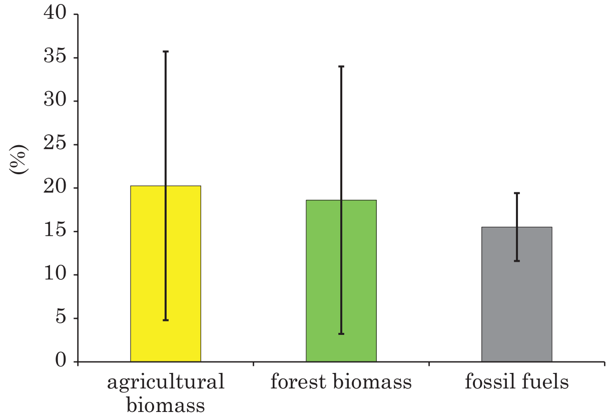

Fig. 1. Mean moisture content (%) in agricultural and forest solid biofuels and fossil fuels (error bars represent standard deviations)

cultural origin were characterized by the highest moisture content (20.3%) compared to forest biofuels, where this value was around 2 p.p. lower, although the lowest moisture content was determined for fossil fuels (on average 15.5%).

The moisture content in fuels causes significant problems during the ignition and combustion process. A high amount of generated heat is lost to heating and evaporation of water, which leads to a decrease in useful energy. The price of the biomass is calculated depending on the biomass LHV, which also includes its moisture content (GENDEK et al. 2018). Fuel humidity depends on which part of the plant is used, what type of biomass is obtained and the time of year it was harvested (NIEDZIÓŁKA et al. 2006). The means of transport and storage are also significant. STOLARSKI et al. (2014, 2018) also found a difference between perennial energy crop genotypes and their harvesting periods.

The HHV of the tested solid fuels averaged 20.85 MJ kg^{-1} d.m., with a standard deviation of 2.96 (Table 2). Fifteen homogeneous groups were identified for this feature. *Ekogroszek* from MPEC had the highest HHV 27.55 MJ kg^{-1} d.m., which was classified as a homogeneous group (a). Fine coal from OPEC was the second homogeneous group (b) and its HHV amounted to 27.17 MJ kg^{-1} d.m. Moreover, statistical tests showed that fossil fuels were found in the first four homogenous groups. The next three homogenous groups were represented by samples from forest origins: PKS in the fifth homogenous group (21.15 MJ kg^{-1} d.m.), pine pellets (20.5 MJ kg^{-1} d.m.) and seventh homogenous group was represented by forest wood chips with a HHV at 20 MJ kg^{-1} d.m. The HHV of seasoned black locust, willow and poplar chips ranged from 19.5 to 19.9 MJ kg^{-1} d.m. The lowest HHV was for corn stover (18.28 MJ kg^{-1} d.m). HHV was significantly positively correlated with fixed carbon and the content of carbon, sulphur and nitrogen, although it was negatively correlated with the content of hydrogen and volatile matter (Table 3).

Table 3

Simple correlation coefficients between the analyzed properties

Specification	Moi-sture	HHV	LHV	Ash	Fixed carbon	Volatile matter	C	H	S	N	Cl
Moisture	1.00	-0.23	-0.81	-0.02	-0.16	0.13	-0.26	0.14	-0.05	0.06	0.22
HHV	-0.23	1.00	0.75	0.70	0.98	-0.94	0.98	-0.86	0.77	0.75	-0.16
LHV	-0.81	0.75	1.00	0.42	0.69	-0.65	0.76	-0.60	0.49	0.41	-0.25
Ash	-0.02	0.70	0.42	1.00	0.83	-0.89	0.60	-0.92	0.87	0.83	0.33
Fixed carbon	-0.16	0.98	0.69	0.83	1.00	-0.99	0.93	-0.93	0.83	0.83	-0.03
Volatile matter	0.13	-0.94	-0.65	-0.89	-0.99	1.00	-0.88	0.96	-0.87	-0.85	-0.06
C	-0.26	0.98	0.76	0.60	0.93	-0.88	1.00	-0.80	0.67	0.63	-0.30
H	0.14	-0.86	-0.60	-0.92	-0.93	0.96	-0.80	1.00	-0.87	-0.79	-0.11
S	-0.05	0.77	0.49	0.87	0.83	-0.87	0.67	-0.87	1.00	0.87	0.25
N	0.06	0.75	0.41	0.83	0.83	-0.85	0.63	-0.79	0.87	1.00	0.19
Cl	0.22	-0.16	-0.25	0.33	-0.03	-0.06	-0.30	-0.11	0.25	0.19	1.00

* red color – significant correlation

Eight homogeneous groups were identified for LHV (Table 2). The average LHV for all fuels was 16.50 MJ kg^{-1} and the standard deviation was 4.20. The highest LHV was found in *ekogroszek* from two companies (over 23 MJ kg^{-1}), which were classified as a homogeneous group (a). In the literature, it was found that this parameter for coal was higher and amounted to 26.7 MJ kg^{-1} (Stolarski et al. 2016). Fine coal from OPEC was in the next group (b) with LHV 21.64 MJ kg^{-1}. The third group (c) included fine coal from MPEC with the lowest LHV of all analyzed fossil fuels. This group also included PKS (19.05 MJ kg^{-1}) and pine pellets (18.62 MJ kg^{-1}). The LHV value of PKS in other studies ranged from 13.10 to 18.70 MJ kg^{-1} (Jagustyn 2013). The highest value of this feature among eight fuels qualified for the homogeneous group (e) was from straw from the UWM plantation (16.43 MJ kg^{-1}). This group also included other tested plants of forest origin as well as *Miscanthus* straw from OPEC and pellets from mixed straw. This parameter for black locust was 16.18 MJ kg^{-1}, although Stolarski et al. (2013*b*) found LHV was seven p.p. lower for fresh black locust. The next homogenous group (f) consists of two types of straws (wheat and rye) with LHV around 15 MJ kg^{-1}. In two studies, it was found that LHV for wheat straw was 17.3 MJ kg^{-1} (McKendry 2002, Niedziółka, Zuchniarz 2006). Another homogenous group (g) was represented by two types of biomass: rape straw and forest wood chips with LHVs 12.95 and 11.86 MJ kg^{-1}, respectively. The lowest LHV (3.82 MJ kg^{-1}) was found in corn stover, which was classified in the last homogeneous group (h) due to its very high moisture content. While analyzing the LHV in respect to fuel origin, it was established that the highest average LHV was found for fossil fuels (22.01 MJ kg^{-1}) – Figure 2. The forest biofuels

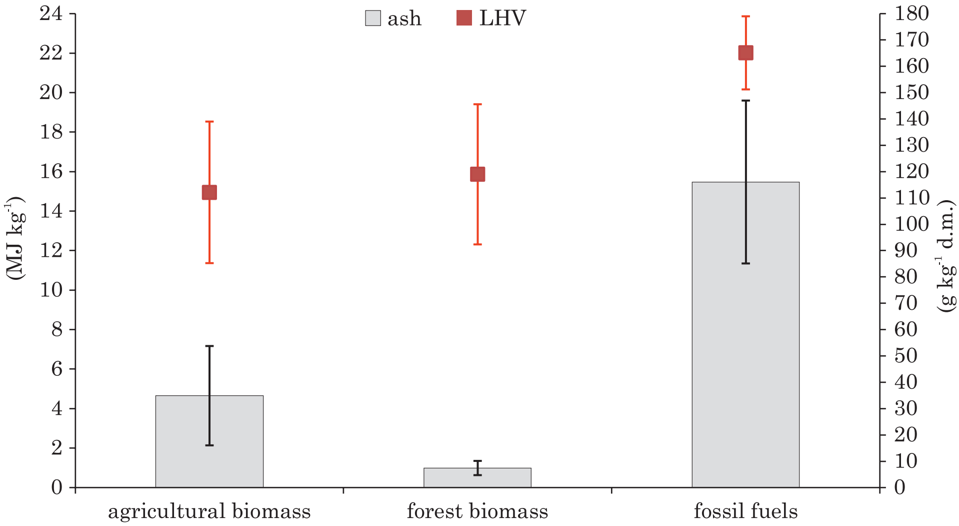

Fig. 2. Mean LHV (MJ kg^{-1}) and ash content (g kg^{-1} d.m.) in agricultural and forest biofuels and fossil fuels (error bars represent standard deviations)

had the second-highest value of this feature (15.86 MJ kg^{-1}) and agricultural biomass had the lowest result, with an average value of 14.95 MJ kg^{-1}.

The average value of fixed carbon content in all fuels was 281.9 g kg^{-1} d.m. with a standard deviation of 141.8 (Table 4). The highest value of this parameter was determined for coals (the first three groups (a, b and c). Fine coal from OPEC contained the highest value of fixed carbon (574.8 g kg^{-1} d.m.). The next homogenous group was represented by PKS, with a fixed carbon content of 272.9 g kg^{-1} d.m. Biomass was characterized by a significantly lower value of this feature than fossil fuels (around 200 g kg^{-1} d.m.). The average content of volatile matter in the analyzed fuels was 671.1 g kg^{-1} d.m. The average volatile matter for biofuels from agricultural and forest biomass was 758.1 g kg^{-1} d.m. The highest value of this characteristic was found for pine pellets (799.0 g kg^{-1} d.m.). Almost 50 p.p. less volatile matter was determined in fossil fuels. The lowest content of volatile matter was found in fine coal from MPEC (303.4 g kg^{-1} d.m.). High values of volatile matter in black locust, poplar and willow (770.9-781.5 g kg^{-1} d.m.) were also reported in other studies (Stolarski et al. 2013*b*).

An important parameter in the evaluation of thermophysical properties of fuels is the content of ash, which adversely affects the energy value of fuel (McKendry 2002). On average, for all tested types of fuels, the ash content was 47.0 g kg^{-1} d.m., with a standard deviation 40.9 (Table 4). The highest ash content was found in fossil fuels. Fine coal from MPEC, which represents homogenous group (a), contained 162.4 g kg^{-1} d.m. of ash. The average content of ash in all hard coal fuels was 116.1 g kg^{-1} d.m. (Figure 2). The lowest ash content was determined in forest origin biomass (7.4 g kg^{-1} d.m.

Table 4

Characteristics of the fixed carbon, volatile matter and ash content of the studied fuels

Fuel type	Fixed carbon (g kg^{-1} d.m.)	Volatile matter (g kg^{-1} d.m.)	Ash content (g kg^{-1} d.m.)
Wheat straw	206.0±0.1^{e}	730.5±0.1^{g}	63.5±0.2^{d}
Rapeseed straw	206.9±1.0^{e}	738.4±1.1^{g}	54.7±0.2^{e}
Rye straw	201.6±0.2^{f}	744.4±0.5^{f}	54.0±0.4^{e}
Ryegrass straw	215.0±0.8^{e}	758.3±0.9^{e}	26.7±0.1^{h}
Corn stover	204.2±0.6^{e}	751.5±1.1^{e}	44.2±0.5^{f}
Miscanthus straw (OPEC)	204.2±0.1^{e}	766.5±0.8^{d}	29.2±0.6^{g}
Miscanthus straw (UWM)	207.4±0.6^{f}	775.0±0.1^{c}	17.6±0.7^{l}
Mixed straw pellets	208.9±2.1^{e}	725.1±2.3^{h}	66.1±0.1^{d}
Willow chips (Żubr)	209.1±1.7^{e}	776.9±2.4^{c}	14.0±0.7^{m}
Willow chips (Ekotur)	216.2±3.8^{e}	766.2±4.6^{d}	17.6±0.9^{l}
Poplar chips (max-5 clone)	218.6±0.2^{e}	759.3±0.6^{e}	22.1±0.5^{j}
Black locust chips	204.5±0.2^{e}	775.0±0.2^{c}	20.4±0.4^{k}
Palm Kernel Shell (PKS)	272.9±0.2^{d}	703.5±0.0^{i}	23.5±0.2^{i}
Pine Pellets	196.7±1.2^{g}	799.0±1.3^{a}	4.3±0.1^{o}
Mixed briquettes	217.2±1.7^{e}	773.4±1.9^{c}	9.4±0.3^{n}
Forest wood chips	204.6±0.1^{e}	786.9±0.2^{b}	8.5±0.3^{n}
Fine coal (OPEC)	574.8±0.6^{a}	326.5±0.1^{j}	98.6±0.5^{c}
Fine coal (MPEC)	534.2±0.5^{c}	303.4±0.0^{k}	162.4±0.5^{a}
Coal – *ekogroszek* (OPEC)	565.4±0.8^{b}	334.1±0.5^{j}	100.6±0.3^{b}
Coal – *ekogroszek* (MPEC)	570.2±0.5^{a}	327.2±0.1^{j}	102.6±0.6^{b}
Mean	281.9±141.8	671.1±177.0	47.0±40.9

± standard deviation; *a*, *b*, *c*... homogenous groups

on average), while agricultural biofuels contained almost by three p.p. more ash than forest biofuels. In other research, the ash content in agricultural biomass from willow, poplar and black locust was between 14.1-21.0 g kg^{-1} d.m., and 40 g kg^{-1} d.m. in wheat straw (McKendry 2002, Stolarski et al. 2013*b*). Moreover, the literature data show that the ash content in PKS ranged from 13-108 g kg^{-1} d.m. (Jagustyn et al. 2013), while in our research it equalled 23.5 g kg^{-1} d.m. Moreover, the ash content in solid biofuels may also be differentiated during the processes of biomass conversion into briquettes or pellets. This is particularly noticeable when raw feedstock has high moisture content and requires additional drying. When drying chipped raw feedstock with hot air, very fine biomass fractions may roast, resulting in an increase of the ash content in fuel, i.e. briquettes or pellets, which may be higher than in raw feedstock. In some cases, the content of ash in pellets or briquettes could be lower than its content in the raw feedstock. This may occur in the production of fuels from baled straw because straw can be contaminated with mineral parts of soil during baling, but subsequently the soil particles can be separated from raw feedstock during straw chipping before the feedstock is compressed.

We also determined the elemental composition of solid fuels. The major constituent of fuels are carbon and hydrogen, which have a high concentration compared to other constituents such as sulphur, nitrogen and chlorine, whose concentrations were much lower, but can form pollutant emissions for the environment. Nitrogen is used by plants as a macronutrient, being important for their growth. The use of high-nitrogen coal in combustion processes results in an increase in NOx emissions to the environment (FAN et al. 2017). The average carbon content in all tested fuels was 542.5 g kg^{-1} d.m. with a standard deviation of 73.5 (Table 5). The highest amount (632-693 g kg^{-1} d.m.) was determined for coals (the first two homogenous groups). In forest biofuels,

Table 5

Content of carbon, hydrogen, nitrogen, sulphur and chlorine in the studied fuels

Fuel type	C (g kg^{-1} d.m.)	H (g kg^{-1} d.m.)	N (g kg^{-1} d.m.)	S (g kg^{-1} d.m.)	Cl (g kg^{-1} d.m.)
Wheat straw	469.8±1.0^{h}	55.3±0.2^{b}	11.7±0.1^{h}	1.27±0.03^{f}	1.97±0.03^{e}
Rapeseed straw	468.9±2.8^{h}	54.6±0.3^{b}	12.6±0.1^{f}	3.15±0.04^{d}	4.18±0.03^{a}
Rye straw	479.3±0.3^{g}	57.1±0.1^{a}	5.7±0.1^{l}	0.58±0.00^{i}	4.18±0.03^{a}
Ryegrass straw	486.1±2.6^{g}	57.7±0.6^{a}	8.3±0.1^{i}	1.04±0.02^{g}	3.70±0.05^{b}
Corn stover	474.4±0.8^{g}	57.2±0.1^{a}	12.1±0.2^{g}	0.77±0.01^{h}	2.27±0.01^{c}
Miscanthus straw (OPEC)	512.5±3.3^{f}	58.1±0.7^{a}	3.4±0.2^{n}	0.48±0.03^{j}	1.38±0.05^{f}
Miscanthus straw (UWM)	511.8±2.4^{f}	57.8±0.5^{a}	4.7±0.1^{m}	0.51±0.02^{j}	1.44±0.03^{f}
Mixed straw pellets	474.9±2.2^{g}	51.5±1.1^{c}	8.8±0.0^{h}	1.29±0.03^{f}	1.90±0.04^{e}
Willow chips (Żubr)	527.5±1.8^{e}	57.3±1.0^{a}	6.5±0.1^{k}	0.50±0.00^{j}	0.41±0.01^{i}
Willow chips (Ekotur)	524.2±2.8^{e}	58.9±0.1^{a}	7.7±0.1^{j}	0.38±0.05^{k}	0.37±0.03^{i}
Poplar chips (max-5 clone)	524.3±1.8^{e}	58.4±0.1^{a}	8.7±0.0^{h}	0.47±0.01^{j}	0.17±0.02^{j}
Black locust chips	506.7±3.9^{f}	58.8±0.2^{a}	13.3±0.2^{e}	0.74±0.11^{h}	0.24±0.03^{j}
Palm Kernel Shell (PKS)	559.5±1.0^{c}	55.4±0.3^{b}	5.1±0.1^{m}	0.31±0.02^{k}	0.26±0.03^{j}
Pine Pellets	565.2±2.6^{c}	55.2±2.0^{b}	1.8±0.0^{p}	0.08±0.00^{m}	0.18±0.00^{j}
Mixed briquette	519.8±1.0^{e}	58.0±1.1^{a}	2.4±0.1^{o}	0.17±0.01^{l}	0.49±0.03^{i}
Forest wood chips	542.5±3.0^{d}	58.0±0.2^{a}	1.9±0.1^{p}	0.17±0.01^{l}	0.15±0.01^{k}
Fine coal (OPEC)	686.2±2.6^{a}	42.0±0.3^{d}	20.1±0.2^{b}	3.35±0.12^{c}	2.33±0.04^{c}
Fine coal (MPEC)	631.8±2.4^{b}	37.4±1.2^{e}	18.4±0.1^{d}	4.99±0.10^{b}	2.08±0.02^{d}
Coal – *ekogroszek* (OPEC)	691.7±3.7^{a}	44.4±0.6^{d}	19.4±0.2^{c}	2.72±0.02^{e}	0.65±0.05^{h}
Coal – *ekogroszek* (MPEC)	693.2±2.0^{a}	43.7±0.1^{d}	22.3±0.1^{a}	6.15±0.11^{a}	0.81±0.00^{g}
Mean	542.5±73.5	53.8±6.4	9.7±6.2	1.46±1.69	1.46±1.32

± standard deviation; *a*, *b*, *c*... homogenous groups the content of carbon was approximately by 10 p.p. lower than in fossil fuels, whereas in corn stover, which was included in the same homogeneous group (g) as rye straw and ryegrass and mixed straw pellets, it was 474.4 g kg^{-1} d.m. The lowest carbon content was determined in wheat and rapeseed straw. The carbon content was positively correlated with the nitrogen and sulphur content, and negatively with the content of hydrogen and chlorine (Table 3). Stolarski et al. (2013*b*) reported that the content of this element in willow and poplar biomass was 510.3 g kg^{-1} d.m. and 526.5 g kg^{-1} d.m., respectively, which was similar to the values obtained in the present study.

The average hydrogen content in all fuels tested was 53.8 g kg^{-1} d.m. with a standard deviation of 6.4 (Table 5). Significantly, the largest hydrogen content among the tested fuels was found in biomass from agriculture and forestry. For example, the hydrogen content in willow chips was 58.9 g kg^{-1} d.m., and in mixed straw pellets it was 51.5 g kg^{-1} d.m. The lowest content of hydrogen was found in fine coal from MPEC, 37.4 g kg^{-1} d.m. The nitrogen content in all analyzed types of biomass averaged 9.7 g kg^{-1} d.m. with a high standard deviation of 6.2. Significantly, the highest nitrogen content was determined in fossil fuels, 18.4-22.3 g kg^{-1} d.m. for fine coal and *ekogroszek* from MPEC, respectively. In turn, the lowest nitrogen content was in pine pellets and forest chips 1.8 g kg^{-1} d.m. and 1.9 g kg^{-1} d.m., respectively. In a study carried out by Stolarski et al. (2013*b*), the nitrogen content in willow and poplar biomass was 4.8 g kg^{-1} d.m. and 5.7 g kg^{-1} d.m., while in black locust it was 13.0 g kg^{-1} d.m. However, in the present study, the content of nitrogen in willow and poplar chips was slightly higher, while in black locust chips it was similar.

Concerning the sulphur content, thirteen homogeneous groups were distinguished, with an average value of 1.46 g kg^{-1} d.m. and a very high standard deviation of 1.69 (Table 5). The largest share of this element was found in fossil fuels (average 4.31 g kg^{-1} d.m.) – Figure 3. The highest content of sulphur was determined in from MPEC (6.15 g kg^{-1} d.m.) – Table 5. It is worth noting that agricultural and forestry biofuels were characterized by a much lower sulphur content (5-fold and 31-fold, respectively). Mixed briquettes and forest wood chips were in the same homogeneous group (l), having the sulphur content of 0.17 g kg^{-1} d.m. However, out of the agricultural origin biofuels, the lowest sulphur content was determined in the biomass of the willow variety Ekotur (0.38 g kg^{-1} d.m.). In other studies, the sulphur content in willow biomass ranged from less than 0.20 g kg^{-1} to 3.20 g kg^{-1} d.m. (Jagustyn et al. 2011).

The average chlorine content in the tested fuels was 1.46 g kg^{-1} d.m., and the standard deviation was 1.32 (Table 5). The highest average chlorine content was found in biomass of agricultural origin, (1.73 g kg^{-1} d.m. on average), while the lowest was in biofuels from forest biomass (0.27 g kg^{-1} d.m.) – Figure 3. A particularly high content of chloride in agricultural biomass was determined in rapeseed and rye straw (4.18 g kg^{-1} d.m.) – Table 5. A very low content of this element was established in wood chips obtained

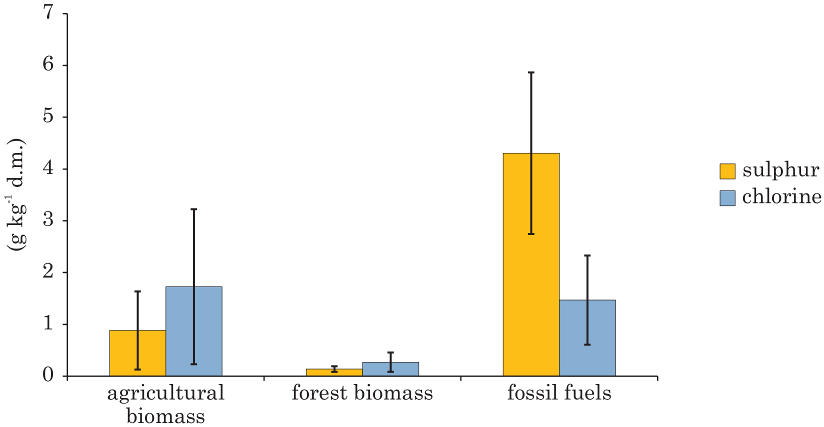

Fig. 3. Mean sulphur and chlorine content (g kg^{-1} d.m.) in agricultural and forest biofuels and fossil fuels (error bars represent standard deviations)

from both forest plants and energy crops (0.15-0.41 g kg^{-1} d.m.). It was also found that the chloride content in fossil fuels was high and in fine coal it was over 2.0 g kg^{-1} d.m., i.e. approximately 3-fold higher than in *ekogroszek*. JAGUSTYN et al. (2011) found that the chlorine content in coal fuels was below 0.8 g kg^{-1} d.m., whereas in wood biomass it ranged from below 0.05 g kg^{-1} d.m to 0.57 g kg^{-1} d.m. However, the chlorine content can be over 10.0 g kg^{-1} d.m in annual crops. A possible reason for a high content of chloride in crops may be the application of potassium fertilizers in the form of potassium chloride (BORKOWSKA, LIPIEŃSKI 2007). Differences in the analyzed thermophysical properties and elemental composition between agricultural and forest solid biofuels in comparison to fuels fossil are also confirmed in one of the most complete database Phyllis (https://phyllis.nl/).

CONCLUSIONS

This study confirmed that the selected solid biofuels from agriculture and forestry are a good alternative to fossil fuels in terms of some thermophysical properties and elemental compositions compared to those of traditional solid fuels like coal. The content of ash in coal fuels (fine coal and *ekogroszek*) was 3- to 16-fold higher than in agricultural and forest origin biofuels. Moreover, the content of sulphur in coal fuels was from 5- to 31-fold higher than in agricultural and forest biofuels. Considering the above, the use of solid biofuels for energy generation may cause a weaker negative effect on the environment than coal fuels. In general, coal fuels were characterized by a lower average moisture content, hence a higher heating value compared with unprocessed biomass fuels. Therefore, the LHV of fossil fuels was higher than the average LHV of agricultural and forest biofuels. However, it should be underlined that the seasoned (air-dried) solid biofuels in the form of wood chips and pellets or briquettes are a very interesting alternative to coal fuelsowing to the considerably lower content of ash, sulphur, nitrogen and chloride and a relatively high LHV.

ACKNOWLEDGEMENT

We would also like to thank the staff of the Department of Plant Breeding and Seed Production, Production and Experimental Enterprise in *Łężany*, OPEC Grudziądz, MPEC Olsztyn for their support. Dumitru Penni and Anna Bordiean are recipients of scholarships granted from the Programme Interdisciplinary Doctoral Studies in Bioeconomy (POWR.03.02.00-00-I034/16-00), which is funded by the European Social Funds.

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