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THERMOPHYSICAL AND CHEMICAL PROPERTIES OF BIOMASS OBTAINED FROM WILLOW COPPICE CULTIVATED IN ONE- AND THREE-YEAR ROTATION CYCLES*

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Abstract

Most of the energy today is obtained from fossil fuels, which are becoming more expensive and less available. Energy from biomass produced on agricultural land is an alternative option. Energy crops should guarantee high yield and good quality parameters, associated with their use in energy production. This study analysed the thermophysical and chemical properties of biomass obtained from 15 new clones of willow selected in the Department of Plant Breeding and Seed Production of the University of Warmia and Mazury in Olsztyn. The plants were cultivated in one- and three-year rotation cycles, run in 2009-2011 at two research stations: in Bałdy and in Łężany. The energy content as well as elemental and physical properties of biomass were analysed. The higher heating value was better in biomass from one-year shoots (on average 19.66 MJ kg^{-1} d.m.). The highest value of this parameter was recorded for the clone of *Salix acutifolia* UWM 093 (20.04 MJ kg^{-1} d.m.). The higher heating value in biomass of three-year old clones was on average lower by 0.06 MJ kg^{-1} d.m. The lower heating value in biomass increased in longer willow coppice harvest cycles. The highest lower heating value was recorded for the clone UWM 035 of *Salix pentandra* (9.27 MJ kg^{-1}) harvested in a three-year cycle, whereas the lowest one was achieved by the clone of *Salix dasyclados* UWM 155 (7.55 MJ kg^{-1}) harvested in a one--year cycle. The average moisture content in three-year shoots was 50.01% d.m., being higher by 2.31% in one-year shoots. The ash content was lower in biomass harvested in three-year rotation. In conclusion, willow biomass obtained in a three-year harvest cycle contains less of undesirable elements and proves to be better quality fuel than biomass obtained in a one-year harvest cycle.

Key words: higher and lower heating value, thermophysical properties, chemical properties, short rotation coppices, willow biomass, harvest cycles.

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INTRODUCTION

Apart from food and environmental safety, energy safety is one of the key factors to the existence and development of our civilisation. Most of the energy today is obtained from fossil fuels, which are becoming more expensive and less available. Biomass is an alternative option. Its annual potential for use as an energy source is estimated to be 2900 EJ year^{-1} (Krzyżaniak et al. 2013). The EU Directive 2009/28/EC and the Energy Policy of Poland define it as a target to raise the share of renewable energy sources in the total energy consumption to 15% by 2020 and to 20% by 2030. Importantly, it is to be expected that the consumption of forest biomass for energy purposes is likely to decrease as woodlands are to be protected against excessive exploitation. Another goal is to promote sustainable biomass production on agricultural land for energy purposes (including biofuels) in order to avoid competition between renewable energy production and agriculture. Moreover, efforts will be made to increase diversification of energy sources and to create the optimum conditions for the development of distributed energy generation, based on locally available matter. Therefore, great hopes are placed in energy crop production.

Energy crops should ensure high yield and good quality parameters, associated with their use in energy production. Other features, very important in agriculture, are a high yield of dry matter per hectare, low energy consumption and production cost, low content of contaminants and low fertilisation needs (Mckendry 2002).

The total area of land under perennial energy crops in Poland is small (10,202 ha). It is worth underlining that of all domestic sources of "green" energy, solid biomass will continue to be the main fuel in the generation of renewable energy. The trees and shrubs used as sources of energy that are most frequently mentioned in literature include: willow (*Salix* L.), poplar (*Populus* L.) and black locust (*Robinia pseudoacacia* L.) (Grünewald et al. 2009, Stolarski et al. 2011, Serapiglia et al. 2012, Buchholz, Volk 2013).

Plantations of tree species, established on agricultural land, are referred to as short rotation coppice. Wood in such systems is harvested every one to six years. The biomass is usually of better quality than forest biomass or industrial and communal waste. The type of biomass fuel, including its physical and chemical characteristics, affects the entire process of its utilisation (transport, technology of combustion, gas emission and generating solid waste). Therefore, the characteristics of biomass as fuel should include a low moisture content, high energy content, adequate proportion of fixed carbon to volatile matter, low ash content and an appropriate content of alkaline metals. Importantly, values of the above parameters differ depending on the biomass type – straw, perennial semi-wood plants, wood (Mckendry 2002, Stolarski et al. 2014). On the other hand, the thermophysical and chemical properties of wood biomass will differ depending on the species, cultivar and clone, plant organs, harvest cycle duration (e.g. 1-3 years), fertilisation technology and the habitat conditions (Adegbidi et al. 2001, Tharakan et al. 2003, Chin et al. 2013, Krzyżaniak et al. 2014).

The aim of this study was to determine the thermophysical and chemical properties of biomass of 15 new clones of willow cultivated in one- and three -year rotation cycles.

MATERIAL AND METHODS

Field experiments

Experiments on willow coppice were carried out in 2009-2011, in two research stations of the University of Warmia and Mazury in Olsztyn (UWM), located in Bałdy and in Łężany Two controlled field experiments involved 15 willow clones from the collection of the Department of Plant Breeding and Seed Production of UWM:

1. *Salix acutifolia* UWM 093.
2. *Salix alba* UWM 095.
3. *Salix dasyclados* UWM 155.
4. *Salix fragilis* UWM 195.
5. *Salix pentandra* UWM 035.
6. *Salix triandra* UWM 198.
7. Seven clones of *Salix viminalis:* UWM 006, UWM 063, UWM 067, UWM 144, UWM 145, UWM 146, UWM 196.
8. *Salix viminalis* x *Salix amygdalina* UWM 054.
9. *Salix viminalis* x *Salix purpurea* UWM 033.

In each experiment, clones were planted in a completely randomized design in three replicates. At the research station in Bałdy (53°35′ N, 21°08′ E), the field experiment was started in 2008. The plantation was set up on mud -muck soil developed on calcareous gyttia lying on the loamy subsoil. The soil was classified as soil IVb in the Polish soil classification system. The groundwater table was determined at below 80 cm. Cuttings (25 cm long) were planted in the second decade of April, at the density of 48 thousand pieces per ha. The plants were harvested in annual cycles (2009, 2010, 2011). At the research station in Łężany (53°58′ N, 20°36′ E), the field experiment was commenced in 2008. The soil under the experiment was classified as incomplete proper brown soil developed from medium loam on light silty clay. In agronomic terms, it was classified as IVa class, defective wheat complex. The groundwater table was below 150 cm. Cuttings (25 cm long) were planted in the third decade of April, at 25 thousand pieces per ha. The crops were harvested in a three-year cycle (2011).

Laboratory analyses

Representative samples of biomass were taken from the plots during harvest. To this end, entire willow shoots were cut into pieces and placed in plastic bags. The samples were then transported to the laboratory of the Department of Plant Breeding and Seed Production of the UWM. Immediately afterwards (no later than one day after collection and storage in a fridge, to preserve the initial moisture content), thermophysical and chemical properties of the biomass were determined. All determinations were conducted in three replications.

The moisture content was determined by the drying-weighing method, in accordance with Polish Standard PN-80/G-04511 (drying at 105±2°C until constant weight). The higher heating value (HHV) of the biomass of the willow clones was determined in accordance with PN-81/G-04513 in an IKA C2000 calorimeter by the dynamic method. The HHV and moisture content of biomass were used to calculate the lower heating value (LHV). The content of ash, volatile matter and fixed carbon was determined with a thermogravimetric analyser ELTRA TGA THERMOSTEP. This device operates in accordance with the following standards: ASTM D-5142, D-3173, D-3174, D-3175 and PN-G-04560:1998, PN- ISO 562. The carbon, hydrogen and sulphur content in willow biomass was determined with an Eltra CHS 500 automatic analyser, intended for concurrent determination of those elements. The device works in line with the following standards: ISO-10694, ASTM E 1915-97, D-1552, D-4239, D-1619, DIN EN 13137 as well as PN-G-04584 and PN-G-04517. The chlorine content in biomass was determined with the Eschka mixture. The nitrogen content in biomass was determined by the Kjeldahl method (modified by Zinneke) with a K-435 mineraliser and a B-324 BUCHI distiller. The content values of the elements were used to calculate the oxygen content.

The results of determinations of the moisture content, HHV and LHV are presented in tables for all the clones used in the experiment. The content of ash, solid and volatile parts, as well as the concentrations of C, H, S, N, Cl and O are shown in figures as mean, minimum and maximum values for plants cultivated in one- and three-year cycles, which was due to editorial considerations.

Statistical analysis

The experiment results were analysed using Statistica 9.1 PL software (StatSoft Inc.). The arithmetic mean and standard deviation were calculated for all examined features. The analysis of variance (Anova) was applied and the Tukey test (HSD) was used to determine homogenous groups (the level of significance of $\alpha = 0.05$) and correlation coefficients between the examined attributes.

RESULTS AND DISCUSSION

The average HHV of willow shoots in both harvest cycles was 19.63 MJ kg^{-1} d.m. (Table 1). The significantly highest HHV was recorded for the clone UWM 093 of *Salix acutifolia* (19.90 MJ kg^{-1} d.m.). A homogenous group with the significantly lowest value of the feature included UWM 198

Table 1

Higher Heating Value (MJ kg^{-1} d.m.) of willow biomass cultivated in one-year and three-year rotation cycles

Species	Clone	Annual harvest cycle	Triennial harvest cycle	Average
S. acutifolia	UWM 093	20.04±0.09 *a*	19.76±0.02 *c*	19.90±0.15 *a*
S. alba	UWM 095	19.58±0.07 *e*	19.64±0.00 *d*	19.61±0.03 *d*
S. dasyclados	UWM 155	19.53±0.14 *f*	19.45± 0.02 *g*	19.49±0.05 *f*
S. fragilis	UWM 195	19.56±0.09 *f*	19.42±0.04 *g*	19.49±0.08 *f*
S. *pentandra*	UWM 035	19.88±0.05 *b*	19.84±0.05 *b*	19.86±0.04 *b*
S. triandra	UWM 198	19.46±0.12 *g*	19.18±0.01 *h*	19.32±0.15 *g*
S. viminalis	UWM 006	19.68±0.17 *c*	19.58±0.03 *e*	19.63±0.06 *d*
	UWM 063	19.53±0.11 *f*	19.56±0.02 *f*	19.54±0.02 *e*
	UWM 067	19.56±0.10 *f*	19.50±0.04 *f*	19.53±0.04 *e*
	UWM 144	19.60±0.08 *e*	19.80±0.03 *b*	19.70±0.11 *c*
	UWM 145	19.73±0.04 *c*	19.75±0.03 *c*	19.74±0.03 *c*
	UWM 146	19.69±0.04 *c*	19.60±0.01 *e*	19.65±0.05 *d*
	UWM 196	19.66±0.10 *d*	19.59±0.01 *e*	19.62±0.04 *d*
S. viminalis x *S. amygdalina*	UWM 054	19.66±0.10 *d*	19.46±0.00 *g*	19.56±0.11 *e*
S. viminalis x *S. purpurea*	UWM 033	19.72±0.15 *c*	19.82±0.01 *b*	19.77±0.06 *c*
Mean		19.66±0,17 *a*	19.60±0.18 *b*	19.63±0.16

± standard error of the mean; *a*, *b*, *c*… homogenous groups

Salix triandra (19.32 MJ kg^{-1} d.m.). Higher average values of the HHV were recorded for the clones harvested in the one-year cycle (19.66 MJ kg^{-1} d.m.), being lower by 0.06 MJ kg^{-1} d.m. for the three-year cycle. The significantly highest HHV was recorded for UWM 093 *Salix acutifolia* in the one-year harvest cycle (20.04 MJ kg^{-1} d.m.). Another homogenous group included the UWM 035 *Salix pentandra* clone in the same harvest cycle (19.88 MJ kg^{-1} d.m.). A homogenous group with the significantly lowest HHV included UWM 198 *Salix triandra* in the three-year harvest cycle. The HHV was significantly positively correlated with the content of carbon, nitrogen, sulphur and with the content of fixed carbon (Table 2).

Table 2

Pearson correlations coefficients between analysed biomass features

Specification	Moisture content	HHV	LHV	Fixed carbon	Volatile matter	Ash	C	H	N	S	Cl
Moisture content*	1.00	0.04	**0.98**	**0.52**	**-0.53**	**0.52**	-0.15	**-0.51**	**0.55**	**0.54**	**0.43**
HHV	0.04	1.00	0.14	**0.23**	**-0.26**	0.07	**0.22**	0.06	**0.28**	**0.34**	0.11
LHV	**-0.98**	0.14	1.00	**-0.47**	**0.48**	**-0.50**	**0.19**	**0.51**	**-0.49**	**-0.47**	**-0.41**
Fixed carbon	**0.52**	**0.23**	**-0.47**	1.00	**-0.97**	**0.65**	0.14	**-0.39**	**0.87**	**0.77**	**0.61**
Volatile matter	**-0.53**	**-0.26**	**0.48**	**-0.97**	1.00	**-0.77**	-0.14	**0.30**	**-0.88**	**-0.76**	**-0.58**
Ash	**0.52**	0.07	**-0.50**	**0.65**	**-0.77**	1.00	-0.02	**-0.26**	**0.69**	**0.56**	**0.44**
C	-0.15	**0.22**	**0.19**	0.14	-0.14	-0.02	1.00	**0.28**	**0.23**	-0.11	-0.11
H	**-0.51**	0.06	**0.51**	**-0.39**	**0.30**	**-0.26**	**0.28**	1.00	**-0.34**	**-0.39**	**-0.38**
N	**0.55**	**0.28**	**-0.49**	**0.87**	**-0.88**	**0.69**	**0.23**	**-0.34**	1.00	**0.76**	**0.53**
S	**0.54**	**0.34**	**-0.47**	**0.77**	**-0.76**	**0.56**	-0.11	**-0.39**	**0.76**	1.00	**0.47**
Cl	**0.43**	0.11	**-0.41**	**0.61**	**-0.58**	**0.44**	-0.11	**-0.38**	**0.53**	**0.47**	1.00

* Significat correlations (p value ≤0,05) are indicated in bold

The average moisture content of willow shoots was 51.17% in both harvest cycles (Table 3). The significantly highest moisture content was found in the biomass of the UWM 155 *Salix dasyclados* clone (54.18%). The value of this characteristic was the lowest in UWM 035 *Salix pentandra* (48.50%). The other clones made up 5 homogenous groups with the moisture content of biomass ranging from 53.17 to 49.12%. A significantly higher moisture content in biomass (52.32%) was recorded in the one-year harvest cycle for all the clones. This property was lower in value by 2.31% in the three-year harvest cycle The significantly highest moisture content was found in biomass of UWM 155 *Salix dasyclados* in the one-year harvest cycle (54.56%), while being significantly the lowest in biomass of UWM 196 *Salix viminalis* in the three-year harvest cycle (47.06%). The same homogenous group included UWM 195 *Salix fragilis*, UWM 198 *Salix triandra*, UWM 035 *Salix pentandra* and UWM 063 *Salix viminalis*, all cultivated in the three-year harvest cycle.

The average LHV of willow biomass was 8.34 MJ kg^{-1} (Table 4). The significantly highest value of this property was recorded for biomass of UWM 035 *Salix pentandra* (9.04 MJ kg^{-1}). Another homogenous group included UWM 063 *Salix viminalis*, UWM 093 *Salix acutifolia* and UWM 196 *Salix viminalis*. The LHV for their biomass was 8.64, 8.73 and 8.78 MJ kg^{-1}, respectively. The other clones made up four homogenous groups with the LHV ranging from 8.43 MJ kg^{-1} (UWM 195 *Salix fragilis*) to 7.61 MJ kg^{-1} (UWM 155 *Salix dasyclados*). Regarding the harvest cycles, a higher LHV

Table 3

Moisture content (%) of willow biomass cultivated in one-year and three-year rotation cycles

Species	Clone	Annual harvest cycle	Triennial harvest cycle	Average
S. acutifolia	UWM 093	51.01±1.90 f	49.02±0.03 *g*	50.02±1.07 *e*
S. alba	UWM 095	52.93±1.25 *c*	51.35±0.18 *f*	52.14±0.86 *c*
S. dasyclados	UWM 155	54.56±2.83 *a*	53.79±0.07 *b*	54.18±0.52 *a*
S. fragilis	UWM 195	52.62±1.29 *d*	48.18±0.20 *h*	50.40±2.39 *e*
S. *pentandra*	UWM 035	49.56±1.17 *g*	47.44±0.06 *h*	48.50±1.14 g
S. triandra	UWM 198	51.98±1.61 *e*	48.25±0.05 *h*	50.11±2.01 *e*
S. viminalis	UWM 006	52.31±1.22 *d*	51.05±0.21 *f*	51.68±0.73 *c*
	UWM 063	51.44±0.80 *e*	47.82±0.20 *h*	49.63±1.95 *f*
	UWM 067	52.84±1.92 *c*	51.22±0.00 *f*	52.03±0.98 *c*
	UWM 144	53.79±1.66 *b*	52.55±0.41 *d*	53.17±0.83 *b*
	UWM 145	53.52±2.10 *b*	52.41±0.37 *d*	52.97±0.81 *b*
	UWM 146	52.91±1.96 *c*	49.47±0.16 *g*	51.19±1.85 *d*
	UWM 196	51.17±0.98 *f*	47.06±0.17 *h*	49.12±2.21 *f*
S. viminalis x *S. amygdalina*	UWM 054	50.89±0.70 *f*	50.60±0.21 *g*	50.74±0.21 *d*
S. viminalis x *S. purpurea*	UWM 033	53.29±1.22 *b*	49.99±0.14 *g*	51.64±1.77 *c*
Mean		52.32±2.00 *a*	50.01±2.01 *b*	51.17±2.06

± standard error of the mean; *a*, *b*, *c*… homogenous groups

was recorded for biomass harvested in the three-year cycle (8.58 MJ kg^{-1} on average). The significantly highest value of the feature (9.27 MJ kg^{-1} for UWM 035 *Salix pentandra*) was determined in the same harvest cycle. On the other hand, the significantly lowest LHV was found for UWM 155 *Salix dasyclados* (7.55 MJ kg^{-1}) obtained in a one-year harvest cycle. The LHV was significantly negatively correlated with the biomass moisture content, fixed carbon, the content of ash, nitrogen, sulphur and chlorine (Table 2).

The average ash content in biomass from willow shoots was 12.8 g kg^{-1} d.m. for both harvest cycles. The significantly highest value of the feature was recorded for UWM 195 *Salix fragilis* (15.9 g kg^{-1} d.m.), whereas the lowest one was determined for UWM 198 *Salix triandra* (11.0 g kg^{-1} d.m.). The content of ash in the biomass of willow coppice harvested in a one-year cycle was higher by 3.0 g kg^{-1} d.m. than in that harvested in a three-year cycle (Figure 1). The significantly highest content was found in biomass of UWM 195 *Salix fragilis* harvested in the one-year cycle (19.7 g kg^{-1} d.m.). The significantly lowest ash content was determined in biomass of UWM 033 *Salix viminalis* x *S. purpurea*, harvested in the three-year cycle (9.2 g kg^{-1} d.m.).

The content of fixed carbon in the biomass was 208.3 g kg^{-1} d.m. in both harvest cycles. The significantly highest value of the parameter was deter-

Table 4

Lower heating value (MJ kg^{-1}) of willow biomass cultivated in one-year and three-year rotation cycles

Species	Clone	Annual harvest cycle	Triennial harvest cycle	Average
S. acutifolia	UWM 093	8.57±0.46 *d*	8.88±0.00 *b*	8.73±0.16 *b*
S. alba	UWM 095	7.93±0.29 *h*	8.30±0.04 *e*	8.11±0.20 *d*
S. dasyclados	UWM 155	7.55±0.65 *i*	7.68±0.01 *i*	7.61±0.10 *f*
S. fragilis	UWM 195	7.98±0.29 *h*	8.89±0.02 *b*	8.43±0.49 *c*
S. *pentandra*	UWM 035	8.82±0.25 *b*	9.27±0.01 *a*	9.04±0.24 *a*
S. triandra	UWM 198	8.08±0.33 *g*	8.75±0.01 *d*	8.41±0.36 *c*
S. viminalis	UWM 006	8.11±0.23 *g*	8.34±0.06 *e*	8.22±0.14 *c*
	UWM 063	8.23±0.21 *f*	9.04±0.04 *a*	8.64±0.43 *b*
	UWM 067	7.94±0.40 *h*	8.26±0.02 *f*	8.10±0.20 *d*
	UWM 144	7.75±0.38 *i*	8.11±0.10 *g*	7.93±0.23 *e*
	UWM 145	7.86±0.47 *h*	8.12±0.07 *g*	7.99±0.18 *e*
	UWM 146	7.98±0.44 *h*	8.70±0.04 *d*	8.34±0.39 *c*
	UWM 196	8.35±0.18 *e*	9.22±0.03 *a*	8.78±0.47 *b*
S. viminalis x *S. amygdalina*	UWM 054	8.41±0.12 *e*	8.38±0.04 *e*	8.40±0.04 *c*
S. viminalis x *S. purpurea*	UWM 033	7.91±0.27 *h*	8.69±0.04 *d*	8.30±0.42 *c*
Mean		8.10±0.47 *b*	8.58±0.44 *a*	8.34±0.46

± standard error of the mean; *a*, *b*, *c*… homogenous groups

mined in biomass of UWM 196 *Salix viminalis* (217.0 g kg^{-1} d.m.). The other clones made up seven homogenous groups with the content of this element ranging from 212.1 g kg^{-1} d.m. (UWM 145 *Salix viminalis*) to 202.8 g kg^{-1} d.m. (UWM 195 *Salix fragilis*). With respect to the harvest cycles, the significantly highest fixed carbon content was found in biomass of willow cultivated in the one-year cycle (218.9 g kg^{-1} d.m.) – Figure 1. The value of this characteristic was 21.3 g kg^{-1} d.m. lower in biomass harvested from plants cultivated in the three-year cycle. The significantly highest value was determined for UWM 054 *Salix viminalis* x *Salix amygdalina*, cultivated in the one-year cycle. Another homogenous group was composed of the clones UWM 196 and UWM 145 *Salix viminalis* (both 244.8 g kg^{-1} d.m.) and UWM 033 *Salix viminalis* x *S. purpurea* (223.3 g kg^{-1} d.m.) in the same harvest cycle. The significantly lowest content of fixed carbon was determined in biomass of UWM 195 *Salix fragilis* cultivated in the three-year cycle.

The content of volatile matter in biomass of willow cultivated in both harvest cycles averaged 778.7 g kg^{-1} d.m. The significantly highest value of this feature was found for UWM 198 *Salix triandra* (786.7 g kg^{-1}d.m.). The

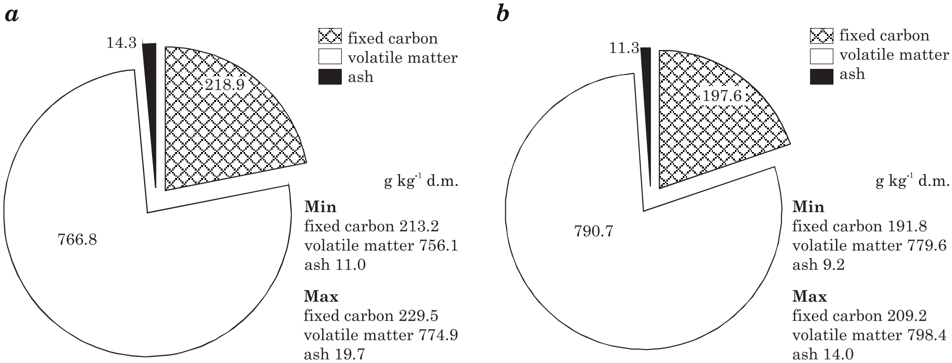

Fig. 1. Fixed carbon, volatile matter and ash content (g kg^{-1}) in biomass of willow cultivated in one-year (*a*) and three-year (*b*) rotation cycles

other clones made up seven homogenous groups with values ranging from 783.3 g kg^{-1} d.m. (UWM 035 *Salix pentandra*) to 770.7 g kg^{-1} d.m. (UWM 196 *Salix viminalis*). The biomass of willow cultivated in the three-year harvest cycle contained more volatile matter (by an average of 23.9 g kg^{-1} d.m.) than the biomass of plants cultivated in the one-year cycle (Figure 1). The content of this component was the highest in biomass of UWM 198 *Salix triandra* cultivated in a three-year cycle. The same homogenous group also included UWM 054 *Salix viminalis* x *S. amygdalina* cultivated in the three-year rotation. The other clones made up 10 homogenous groups, with the volatile matter content ranging from 796.5 g kg^{-1} d.m. to the significantly lowest value of 756.1 g kg^{-1} d.m. (UWM 054 *Salix viminalis x S. amygdalina*, in the one-year harvest cycle).

The average content of carbon element in biomass of plants cultivated in both harvest cycles was 509.1 g kg^{-1} d.m., with values ranging from 522.3 to 501.2 g kg^{-1} d.m. Biomass harvested in the one-year cycle contained 1.4 g kg^{-1} d.m. more of this component than in the three-year cycle (Figure 2). The highest carbon content was found in biomass of UWM 093 *Salix acutifolia* (527.5 g kg^{-1} d.m.) cultivated in the one-year cycle, and the lowest one was in UWM 144 *Salix viminalis* from the three-year harvest cycle.

The hydrogen content in biomass of both harvest cycles averaged 63.0 g kg^{-1} d.m. The highest content of this element was found in biomass of UWM 093 *Salix acutifolia*. The other clones made up five homogenous groups with the hydrogen content ranging from 63.9 to 61.8 g kg^{-1} d.m. The biomass of willow harvested in the three-year cycle contained more hydrogen (63.5 g kg^{-1} d.m.) than in the one-year cycle (62.5 g kg^{-1} d.m.) – Figure 2. The significantly highest content of this element was found in biomass of UWM 093 *Salix acutifolia* cultivated in the three-year cycle (67.6 g kg^{-1} d.m.). The highest content of this element in plants cultivated in the one-year cycle was not qualified until the third homogenous group, being lower by 3.9 g kg^{-1} d.m. The significantly lowest hydrogen content througho-

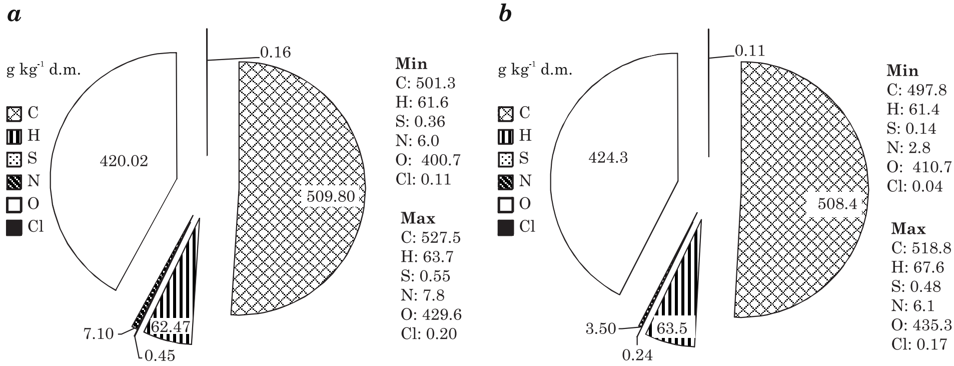

Fig. 2. Elemental analysis of willow biomass (g kg^{-1}) cultivated in one-year (*a*) and three-year (*b*) rotation cycles

ut the whole experiment was found in biomass of UWM 067 *Salix viminalis* cultivated in the three-year cycle.

The nitrogen content in willow biomass averaged 5.3 g kg^{-1} d.m. The significantly highest content of the element was found in biomass of UWM 095 *Salix alba* (6.9 g kg^{-1} d.m.). On the other hand, UWM 144 *Salix viminalis* contained the significantly smallest amount of this element (4.4 g kg^{-1} d.m.). The biomass of willow cultivated in the one-year harvest cycle contained, on average, twice as much nitrogen as the biomass of clones grown in the three -year harvest cycle (Figure 2). The significantly highest content of nitrogen was found in the biomass of UWM 145 and UWM 146 *Salix viminalis* (7.8 g kg^{-1} d.m.) from the one-year harvest cycle. The same homogenous group contained four other clones cultivated in the same harvest cycle. The significantly lowest nitrogen content was found in the clones cultivated in the three-year harvest cycle: UWM 196 and UWM 144 (2.8 g kg^{-1} d.m.), both of the *Salix viminalis* species.

The content of sulphur in the biomass of the clones used in the experiment, in both harvest cycles, averaged 0.34 g kg^{-1} d.m. The highest content of this element was found in the biomass of UWM 144 *Salix viminalis* (0.45 g kg^{-1} d.m.), being significantly the lowest in the biomass of UWM *Salix triandra* (0.13 g kg^{-1} d.m.). As for the harvest cycles, the sulphur content in biomass of willow cultivated in the one-year cycle (Figure 2) was nearly double than that from the three-year cycle. The significantly highest content of this parameter was found in the biomass of UWM 095 *Salix alba* cultivated in the one-year cycle (0.55 g kg^{-1} d.m.). The same homogenous group included UWM 035 *Salix pentandra*. The other clones made up six homogenous groups with the content of sulphur ranging from 0.49 g kg^{-1} d.m. in UWM 146 *Salix viminalis* and UWM 033 *Salix viminalis* x *S. purpurea* (cultivated in the one-year harvest cycle) to 0.14 g kg^{-1} d.m. in UWM 155 *Salix dasyclados* (in the three-year harvest cycle).

The average chlorine content in the biomass of clones cultivated in the one-year and three-year harvest cycles was 0.14 g kg^{-1} d.m. The significantly highest content of this element was determined in the biomass of UWM 195 *Salix fragilis* and UWM 196 *Salix viminalis* (0.17 g kg^{-1} d.m.). The same homogenous group also included UWM 095 *Salix alba* and UWM 155 *Salix dasyclados* with the chlorine content lower by 0.01 g kg^{-1} d.m. The other clones made up three homogenous groups. The significantly lowest chlorine content was determined in the biomass of UWM 054 *Salix viminalis* x *S. amygdalina*. The biomass of the clones cultivated in the one-year cycle contained more chlorine (0.16 g kg^{-1} d.m.) than in the three-year cycle (0.11 g kg^{-1} d.m.) – Figure 2. The significantly highest Cl content was found in biomass of UWM 196 *Salix viminalis* cultivated in the one-year harvest cycle (0.20 g kg^{-1} d.m.). A homogenous group with the lowest chlorine content was made up of UWM 067 *Salix viminalis* and UWM 054 *Salix viminalis* x *S. amygdalina* cultivated in the three-year cycle (0.05 and 0.04 g kg^{-1} d.m., respectively).

The amount of energy (higher and lower heating value) as well as the thermophysical and chemical composition of biomass (carbon, sulphur, hydrogen, nitrogen as well as ash and moisture content) are very important characteristics of biomass used for energy purpose and production of biomaterials. For example, ash and chlorine formed in the process of biomass combustion (responsible for particulate emission and corrosion), affect the operation of boilers, installation safety and its later use or utilisation. The composition of feedstock also influences the quality of bio-products obtained by thermochemical conversions (WILSON et al. 2013).

The higher heating value determined in this study was slightly higher when biomass was grown in the one-year harvest cycle. The higher HHV of one-year willow shoots resulted from those shoots having more bark and, consequently, more lignin than older plants (KLASNJA et al. 2002, KOMOROWICZ et al. 2009). FIJAŁKOWSKA and STYSZKO (2011) showed that the HHV varied in biomass of 9 willow clones, ranging from 18.45 to 18.77 MJ kg^{-1} d.m. STOLARSKI (2009) examined 5 willow cultivars: Duotur and Corda (*Salix alba*), Tur, Turbo and UWM 046 (*Salix viminalis*) and found the lower and higher heating values to be diverse as well. The HHV averaged 19.2 MJ kg^{-1}. The highest HHV was determined in biomass of cv. Tur. The HHV of willow biomass is high compared to other types of biomass. For example, the HHV of stems of Virginia mallow ranged from 17.17 to 18.50 MJ kg^{-1} d.m. (SZYSZLAK-BARGLOWICZ et al. 2012). On the other hand, the HHV of giant miscanthus, most frequently cultivated as an energy crop, ranged from 16.58 to 17.96 MJ kg^{-1} d.m. (KOMOROWICZ et al. 2009).

The moisture content of willow biomass in this study decreased as the harvest cycle was prolonged. This relationship was confirmed by STOLARSKI (2009) for willow grown in one-, two-, and three-year harvest cycles. The moisture content in willow wood was high compared to the biomass of perennial semi-wood plants and grasses. The moisture content in Virginia mallow harvested in December was 25.7%, thus being much lower than in willow shoots – 52.9% on average (BORKOWSKA 2005). In addition, the moisture content in grasses is lower than in willow (as determined in this study), varying from 16.0 to 26.2% depending on a species (Stolarski 2008).

The lower heating value (the amount of energy which can be utilised) was equal to 8.58 MJ kg^{-1} in this study, when willow was harvested in the three-year cycle and 8.10 MJ kg^{-1} in the one-year harvest cycle. Therefore, it increased as the harvest cycle duration was extended from one to three years. This characteristc was strongly and negatively correlated to the moisture content in biomass. The LHV of willow wood immediately after harvest is lower compared to that of perennial plants or grasses. However, willow shoots can be stored (seasoned) to reduce their moisture content by as much as 70-80% (Gigler et al. 2000).

The ash content in biomass harvested every three years was lower by 3.0 g kg^{-1} d.m. compared to the one-year harvest cycle. The ash content decreasing with an increasing harvest cycle duration has been confirmed in other studies (Klasnja et al. 2002, Komorowicz et al. 2009, Stolarski 2009, Krzyżaniak et al. 2014). The relationship is associated with less bark vs wood in older (thicker) shoots. The value of ash content determined in wood of *Salix alba* ranged from 5.2 to 8.9 g kg^{-1} d.m. On the other hand, its value in the bark of shoots ranged from 47.7 to 59.4 g kg^{-1} d.m. The authors mentioned that the share of bark in willow biomass was from 26.7% in a one-year harvest cycle down to just 16.7% in a two-year cycle (Klasnja et al. 2002). Tharakan et al. (2003) determined an average ash content in biomass of 30 clones of willow cultivated in a three-year harvest cycle to be 20 g kg^{-1} d.m. The value ranged from 13 in *Salix purpurea* 94003 to 27 g kg^{-1} d.m. in the hybrid *S. erio* 39 x *S. petiolaris* 47 S599. Interestingly, willow wood contains less ash than perennial plants or grasses, where the values can be up to 30-50 g kg^{-1} d.m. (Tharakan et al. 2003, Kalembasa 2006, Stolarski 2008, Brosse et al. 2012).

The content of undesirable elements, such as nitrogen, sulphur and chlorine, in willow biomass decreased with the duration of a harvest cycle changed from one to three years. However, willow biomass harvested in shorter cycles still contains less sulphur and chlorine than grass and semi-wood species (Kalembasa et al. 2005, Stolarski et al. 2014). This is important for the environment and technologies, because chlorine causes corrosion whereas sulphur and nitrogen are responsible for the emission of hazardous gases (sulphur and nitrogen oxides) to the atmosphere in the process of biomass combustion. For energy producers, it is essential to secure a supply of good quality energy feedstock from a documented source e.g. forest or agricultural biomass, which – for example in Poland – is a necessary condition for obtaining a ‘green certificate’. That is why power generating companies are interested in receiving so-called ‘fuel cards’, which contain information about the termophysical and chemical properties of biomass (Szymanowicz 2011). Another equally important issue in the search for good quality and composition of solid biomass fuels is the low cost of generating electricity from combustion or co-combustion of this feedstock, as compared to other renewable energy sources (Lüschen, Madlener 2013). This makes biomass an energy source. Additionally lignocellulose biomass can be used for production of second generation ethanol or synthesis gas, which can also be used for the production of biofuels, heat or electricity (Tijmensen et al. 2002, Nanda et al. 2012, Stolarski et al. 2013).

CONCLUSIONS

The demand for biomass in Poland and in the European Union will continue to rise because of the binding regulations pertaining to the use of renewable sources of energy. A large share of biomass for energy generation should be produced in a sustainable manner, saving nature valuable areas. Some of the biomass will be recovered from waste, by-products and residues of the wood processing industry and agriculture, but most will be derived from dedicated energy crops, e.g. short rotation willow coppice. It is presumed that such plantations will be established on farmland of worse quality, less suitable for growing food or fodder crops. Thus, biomass will be grown in compliance with the sustainability requirements but it will be of better quality than biomass derived from waste or residues.

The study presented in this paper has been performed to determine the quality of biomass from 15 new clones of willow grown in a one- and three-year harvest cycle. The analyses have demonstrated that the biomass of plants harvested in the one-year cycle was characterized by higher HHV. However, a higher moisture content in woody matter means a lower LHV (that is usable energy) compared to biomass from plants harvested in the three-year cycle. Also, the content of undesirable components in fuel (ash, sulphur, nitrogen and chlorine) was lower in the biomass of plants grown in the three-year rotation cycle. Thus, the willow biomass obtained in the three -year harvest cycle contained less of undesirable elements and proved to be better quality fuel than biomass obtained in the one-year harvest cycle. The research on the biomass quality from willow short rotation coppice, presented above, can be useful for energy industry and for selection of proper feedstock, suitable for requirements of a given facility or the conversion method it employs. These results are part of the research on Polish varieties and clones of willow developed at the Department of Plant Breeding and Seed Production of the University of Warmia and Mazury in Olsztyn. The whole research framework comprises studies on productivity of plants, economic efficiency, energy generation efficiency, and the effect of cultivation of energy crops on the environment. These issues will be discussed in the following articles.

REFERENCES

Adegbidi H.G., Volk, T.A., White, E.H., Abrahamson, L.P., Briggs, R.D., Bickelhaupt, D.H. 2001. *Biomass and nutrient removal by willow clones in experimental bioenergy plantations in New York State*. Biomass Bioenergy, 20: 399-411.

Borkowska H. 2005. *Changes of dry matter content in Salix viminalis and Sida hermaphrodita yields of biomass depending on harvest date*. Ann. UMCS, 60: 155-161. (in Polish)

Brosse N., Dufour A., Meng X.Z., Sun Q.N., Ragauskas A. 2012. *Miscanthus: a fast-growing crop for biofuels and chemicals production*. Biofuel. Bioprod. Biorefin., 6: 580-598.

Buchholz T., Volk T. 2013. *Profitability of willow biomass crops affected by incentive programs*. Bioenergy Res., 6: 53-64.

Chin K.L., H'ng P.S., Chai E.W., Tey B.T., Chin M.J., Paridah M.T., Luqman A.C., Maminski M. 2013. *Fuel characteristics of solid biofuel derived from oil palm biomass and fast growing timber species in Malaysia*. Bioenergy Res., 6: 75-82.

Fijałkowska D., Styszko L. 2011. *Higher heating value of willow biomass*. Rocz. Ochr. Śr., 53: 875-890. (in Polish)

Gigler J.K., Van Loon W.K.P., Van Den Berg J.V., Sonneveld C., Meerdink G. 2000. *Natural wind drying of willow stems*. Biomass Bioenergy, 19: 153-163.

Grünewald H., Böhm C., Quinkenstein A., Grundmann P., Eberts J., Wühlisch G. 2009. *Robinia pseudoacacia* L.*: A lesser known tree species for biomass production*. Bioenergy Res., 2: 123-133.

Kalembasa D. 2006. *Amount and chemical composition of ash from biomass of energy plants*. Acta Agrophys., 7: 909-914. (in Polish)

Kalembasa D., Janinhoff A., Malinowska E., Jaremko D., Jeżowski S. 2005. *Content of sulphur in selected clones of Miscanthus grass*. J. Elem., 10: 309-314. (in Polish)

Klasnja B., Kopitovic S., Orlovic S. 2002. *Wood and bark of some poplar and willow clones as fuelwood*. Biomass Bioenergy, 23: 427-432.

Komorowicz M., Wróblewska H., Pawłowski J. 2009. *Chemical composition and energetic properties of biomass from selected renewable energy sources*. Ochr. Śr. Zas. Nat., 40: 402-410. (in Polish)

Krzyżaniak M., Stolarski M.J., Szczukowski S., Tworkowski J. 2013. *Life cycle assessment of willow produced in short rotation coppices for energy purposes*. J. Biobased Mater. Bioenergy, 7(5): 566-578.

Krzyżaniak M., Stolarski M.J., Waliszewska B., Szczukowski S., Tworkowski J., Załuski D., Śnieg M. 2014. *Willow biomass as feedstock for an integrated multi-product biorefinery*. Ind. Crop. Prod., 58: 230-237.

Lüschen A., Madlener R. 2013. *Economic viability of biomass cofiring in new hard-coal power plants in Germany*. Biomass Bioenergy, 57: 33-47.

Mckendry P. 2002. *Energy production from biomass*. Part 1. *Overview of biomass*. Biores. Technol., 83: 37-46.

Nanda S., Mohanty P., Pant K., Naik S., Kozinski J., Dalai A. 2012. *Characterization of North American lignocellulosic biomass and biochars in terms of their candidacy for alternate renewable fuels*. Bioenergy Res., 6(2): 1-15.

Serapiglia M., Cameron K., Stipanovic A., Abrahamson L., Volk T., Smart L. 2012. *Yield and woody biomass traits of novel shrub willow hybrids at two contrasting sites*. Bioenergy Res., 6: 1-14.

Stolarski M. 2008. *Content of carbon, hydrogen and sulphur in biomass of some shrub willow species*. J. Elem., 13(4): 655-663.

Stolarski M. 2009. *Agrotechnical and economic aspects of biomass production from willow coppice (Salix spp.) as an energy source*. Faclulty of Environmental Management and Agriculture, University of Warmia and Mazury in Olsztyn, Olsztyn, p. 145. (in Polish)

STOLARSKI M., KRZYZANIAK M., ŚNIEG M., SŁOMIŃSKA E., PIÓRKOWSKI M., FILIPKOWSKI R. 2014. *Thermophysical and chemical properties of the biomass of perennial crops depending on a harvest period*. Int. Agrophys., 28: 201-211.

STOLARSKI M., SZCZUKOWSKI S., TWORKOWSKI J., KRZYZANIAK M. 2013. *Cost of heat energy generation from willow biomass*. Renew. Energy, 59:100-104.

STOLARSKI M.J., SZCZUKOWSKI S., TWORKOWSKI J., WROBLEWSKA H., KRZYZANIAK M. 2011. *Short rotation willow coppice biomass as an industrial and energy feedstock*. Ind. Crop. Prod., 33: 217-223.

SZYMANOWICZ R. 2011. *Generation of energy from renewable sources in a process of combustion in a mixture with secondary fuels*. Energ., 5: 298-305. (in Polish)

SZYSZLAK-BARGLOWICZ J., ZAJAC G., PIEKARSKI W. 2012. *Energy biomass characteristics of chosen plants*. Int. Agrophys., 26: 175-179.

THARAKAN P.J., VOLK T.A., ABRAHAMSON L.P., WHITE E.H. 2003. *Energy feedstock characteristics of willow and hybrid poplar clones at harvest age*. Biomass Bioenergy, 25: 571-580.

TIJMENSEN M.J.A., FAAIJ A.P.C., HAMELINCK C.N., VAN HARDEVELD M.R.M. 2002. *Exploration of the possibilities for production of Fischer Tropsch liquids and power via biomass gasification*. Biomass Bioenergy, 23: 129-152.

WILSON D, DALLUGE D, ROVER M., HEATON E., BROWN R. 2013. *Crop management impacts biofuel quality: influence of switchgrass harvest time on yield, nitrogen and ash of fast pyrolysis products*. Bioenergy Res., 6: 103-113.