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# Energy Value of Yield and Biomass Quality of Poplar Grown in Two Consecutive 4-Year Harvest Rotations in the North-East of Poland

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**Abstract:** Bioenergy accounts for 61.7% of all renewable energy sources, with solid fuels accounting for 43% of this amount. Poplar plantations can deliver woody biomass for energy purposes. A field experiment with poplar was located in the north-east of Poland on good quality soil formed from medium loam. The study aimed to determine the yield, the energy value of the yield and the thermophysical properties and elemental composition of the biomass of four poplar clones harvested in two consecutive 4-year harvest rotations. The highest biomass energy value was determined in the UWM 2 clone in the second harvest rotation (231 GJ $ha^{-1}\cdot year^{-1}$). This value was 27–47% lower for the other clones. The biomass quality showed that poplar wood contained high levels of moisture and low levels of ash, sulphur, nitrogen and chlorine. This indicates that poplar can be grown in the north-east of Poland and that it gives a yield with a high energy value and beneficial biomass properties from the energy generation perspective.

**Keywords:** populus; biomass; yield energy value; lower heating value; ash content; sulphur

## 1. Introduction

Renewable energy sources (RES) are enjoying increasing interest, both on the global scale and in the European Union (EU-28) [1–6]. Energy from renewable sources accounted for 18.1% of the final gross energy consumption around the world in 2017 and 17.5% in the EU-28 [7]. It is noteworthy that bioenergy plays a major role as renewable energy in the EU-28 as it accounted for 61.7% of all RES, with solid fuels accounting for 43% of that amount. Bioenergy plays still a larger role as renewable energy in Poland as it accounted for 81.5% of all RES, with solid fuels accounting for 70.5% of that amount. Solid biomass is derived mainly as wood from forests and wood processing plants. Wood can also be obtained from plantations of woody crops (e.g., poplar, willow, black locust, eucalyptus) set up on agricultural land for biomass production in short harvest rotations. The production of biomass as feedstock for energy generation and industrial processes on short rotation woody crops (SRWC) plantations is still being developed in many countries in Europe [8–16], the USA and Canada [17–21].

Poplar is mainly grown in the southern regions of Europe [22–24]. Spain has the largest area of poplar plantations for paper production and (partly) for the power industry (135.7 thousand ha) in 2008 [22]. According to Bioenergy Europe data [25], poplar in the SRWC system in the EU-28 is grown on an area of 20,691 ha. The largest portion of this area is in Poland: approximately 9000 ha. Moreover, plantations of poplar in the SRWC system can be found in Hungary, Austria, Czech Republic, Romania and Sweden. This indicates that interest in the cultivation of poplar in the SRWC system is also growing in the north of Europe [26]. This stems mainly from the fact that paper mills are interested in obtaining this raw material for paper production; it is also an object of interest of plants converting biomass for energy generation. For example, in Poland, International Paper Kwidzyn initiated a poplar planting scheme with an area of 7.5 thousand ha [27,28]. Moreover, poplar is of great interest for future, large-scale biomass production to meet the demands of the bioenergy sector [26], in particular, in the cascade use of biomass in biorefineries. In this case, bioactive substances and other phytochemicals are first extracted and the post-extraction biomass is used for bioenergy production [29]. Poplar biomass can be burned in the form of wood chips, successfully processed to pellets [30] or gasified to obtain good-quality, low-contaminated syngas [31].

However, the production of poplar biomass in the north of Europe, including Poland, is still a relatively new issue and there is a shortage of data from long-term studies of the productivity of different cultivars or clones as well as energy value and quality of biomass. Therefore, the study aimed to determine the yield, energy value of yield and the thermophysical properties and elemental composition of the biomass of four cultivars of poplar harvested in two consecutive 4-year harvest rotations.

## 2. Materials and Methods

### 2.1. Setting up and Conducting the Field Experiment

The study was based on a field experiment with poplar located in the north-east of Poland, at the Didactic and Research Station (53°35′ N, 20°36′ E) of the University of Warmia and Mazury in Olsztyn. The experiment was conducted on good quality soil formed from medium loam. The soil pH was neutral-to-alkaline ($pH_{KCl}$ 7.14). The phosphorus, potassium and magnesium contents were: 69, 214 and 59 mg $kg^{-1}$.

Four clones of poplar *Populus balsamifera* L. were grown in the experiment: UWM 1, UWM 2, UWM 3, UWM 4. Eighty-eight 20-cm cuttings of each clone were planted in mid-April 2007. The experiment was performed in one-way strip design with four replications, 22 cuttings were planted on one plot. Each clone was planted on an area of 36.3 $m^2$, on a 6.6 × 5.5 m block. The poplar cuttings in this pilot experiment were planted at a high density of 24,000 $ha^{-1}$. Manual weeding was performed in the first (2007) and second (2008) year of growth; no plant protection procedures were conducted in the other years. No mineral fertilisers were applied in the year of setting up the plantation. Fertilisers at the following rates were sown in the second (2008) and fifth (2011) years of the experiment: 90 kg $ha^{-1}$ N, 13 kg $ha^{-1}$ P and 49.8 kg $ha^{-1}$ K. Poplar was harvested in two consecutive 4-year harvest rotations. The first rotation covered the years 2007–2010, the second—the years 2011–2014. The poplar was harvested in winter, i.e., in February/March 2011 and 2015.

### 2.2. Determination of the Biomass Yield, Energy Value of Yield and Biomass Quality

For the calculation of the biomass yield, all plants from each field were cut manually using a chainsaw. The plants were then all weighed to determine the biomass yield per plot and per 1 ha. While harvesting, all plants (main stem and branches) were cut with a chopper into wood chips and from this biomass blend, representative collective biomass samples (approx. 3 kg) were taken for each clone and placed in plastic bags and transported to a laboratory. In the laboratory, laboratory samples were taken for further analyses. The dry matter yield in two consecutive 4-year harvest rotations was calculated after the moisture content was determined. The moisture content in biomass was determined by drying and weighing, as per EN ISO 18134-1:2015. To this end, biomass was dried at 105 °C until a constant weight was achieved, using a laboratory dryer (FD BINDER, Tuttlingen) and precision scales of 1 mg graduation (Radwag). Subsequently, the dry biomass was ground in an analytic mill, with a 1-mm mesh sieve (Retsch SM 200, Haan). The prepared samples were used for determination of ash at 550 °C, volatile matter at 650 °C and fixed carbon in an ELTRA TGA-THERMOSTEP automatic thermogravimetric analyser as per PN-EN ISO 18122:2016-01 and PN-EN ISO 18123:2016-01. The higher heating value (HHV) of the poplar biomass was determined by the dynamic method in an IKA C2000 calorimeter. Subsequently, the HHV and the moisture content were used to calculate the lower heating value (LHV) for each poplar clone from each harvest rotation (PN-EN ISO 18125:2017-07). The contents of carbon (C), hydrogen (H) and sulphur (S) were determined in poplar biomass with an automatic ELTRA CHS 500 analyser (PN-EN ISO 16948:2015-07 and PN-EN ISO 16994:2016-10). A nitrogen assay was conducted using Kjeldahl's method on a K-435 mineraliser and a B-324 BUCHI distilling device. The chlorine content was determined with an Eschka mixture.

The yield energy value of the poplar biomass was calculated as the product of the mean yield of fresh biomass (f.m.) for each clone from two consecutive 4-year rotations and the biomass LHV – from formula 1. Moreover, the biomass yield energy value was also converted to one year of plantation use.

$$Y_{ev} = Y_b \times LHV^{wb} \quad (1)$$

where:

- $Y_{ev}$—biomass yield energy value (GJ ha$^{-1}$),
- $Y_b$—biomass yield (Mg ha$^{-1}$ f.m.),
- $LHV^{wb}$—biomass lower heating value (wb—wet basis) (GJ Mg$^{-1}$).

### 2.3. Statistical Analysis

The variance analysis model with repeated measures was used, in which the clone was used as the constant and grouping factor, while subsequent harvest rotations were the factor of repeated measures. The level of significance of the analysis was established at $P < 0.05$. The arithmetic mean and standard deviation were calculated for each of the analysed features. Homogeneous groups were identified with the Tukey significance test (HSD). Significantly different values were denoted with letters in the following manner: A.B.C . . . denote homogenous groups for clone; ***a.b*** . . . denote homogenous groups for rotation; a.b.c . . . denote homogenous groups for clone x rotation interaction. Moreover, Pearson's r correlation coefficients between the features under study were also determined. All statistical analyses were done with the STATISTICA software (version 13.3).

## 3. Results and Discussion

### 3.1. Biomass Yield and its Energy Value

Both the poplar biomass yield and its energy value were significantly differentiated by the clone, harvest rotation and the interaction of these attributes (Table 1). The significantly largest fresh and dry biomass yields were obtained from the UWM 2 clone—89.5 Mg ha$^{-1}$ and 40.0 Mg ha$^{-1}$ from the two 4-year rotations, respectively (Table 2). These figures for the UWM 3 and UWM 1 clones were lower by ca. 30% and 40%, respectively, and the yield from the UWM 4 clone was more than twice smaller than that of UWM 2. The average yields of fresh (87.4 Mg ha$^{-1}$) and dry biomass (40.6 Mg ha$^{-1}$ DM—dry matter) of poplar in the second 4-year rotation were significantly higher (by 260% and 278%, respectively) compared to the average yield from the first harvest rotation. The significantly largest average yields of fresh (119.7 Mg ha$^{-1}$) and dry biomass (54.5 Mg ha$^{-1}$ DM) were obtained from the UWM 2 clone in the second 4-year harvest rotation. Expressed per 1 year of the plantation use, they were 29.9 Mg ha$^{-1}$ year$^{-1}$ and 13.6 Mg ha$^{-1}$ year$^{-1}$ DM, respectively. However, the average dry biomass yield for the four poplar clones under study was lower in the second rotation: 10.1 Mg ha$^{-1}$ year$^{-1}$ DM, and it was very low in the first rotation: merely 3.6 Mg ha$^{-1}$ year$^{-1}$ DM

**Table 1.** Analysis of variance repeated measure for the analysed features *.

| Source of Variation | Degrees of Freedom | *P* Value for | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Fresh Biomass Yield | Dry Biomass Yield | Yield Energy Value | Moisture | Fixed Carbon | Volatile Matter | Ash | HHV | LHV | C | H | S | N | Cl |
| Clone | 3 | <0.001 * | <0.001 * | <0.001 * | <0.001 * | 0.679 | 0.679 | 0.566 | 0.183 | <0.001 * | 0.075 | 0.132 | 0.948 | 0.783 | 0.218 |
| Error(1) | 12 | | | | | | | | | | | | | | |
| Rotation | 1 | <0.001 * | <0.001* | <0.001 * | <0.001 * | <0.001 * | 0.915 | 0.005 * | 0.014 * | <0.001 * | 0.001 * | 0.706 | 0.740 | 0.940 | <0.001 * |
| Rotation x Clone | 3 | 0.020 * | 0.015 * | 0.013 * | 0.086 | 0.847 | 0.848 | 0.001 * | 0.356 | 0.116 | 0.324 | 0.976 | 0.952 | 0.830 | 0.118 |
| Error(2) | 12 | | | | | | | | | | | | | | |

* asterisk indicatesstatistically significant values at $P < 0.05$.

**Table 2.** Yield and yield energy value of four poplar clones in two consecutive 4-year harvest rotations.

| Clone | Fresh Biomass Yield (Mg ha$^{-1}$) | | | Dry Biomass Yyield (Mg ha$^{-1}$) | | | Yield Energy Value (GJ ha$^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|---|
| | First Rotation | Second Rotation | Mean | First Rotation | Second Rotation | Mean | First Rotation | Second Rotation | Mean |
| UWM 1 | 20.0 ± 5.3d | 83.0 ± 6.8b | 51.5 ± 34.1B | 9.1 ± 2.4d | 39.4 ± 3.2b | 24.2 ± 16.4B | 148.3 ± 39.1d | 663.6 ± 54.6b | 405.9 ± 278.9B |
| UWM 2 | 59.3 ± 10.9c | 119.7 ± 5.1a | 89.5 ± 33.2A | 25.6 ± 4.7c | 54.5 ± 2.3a | 40.0 ± 15.8A | 421.4 ± 77.7c | 922.6 ± 39.2a | 672.0 ± 273.9A |
| UWM 3 | 37.6 ± 8.9cd | 87.1 ± 3.4b | 62.3 ± 27.2B | 15.7 ± 3.7d | 40.0 ± 1.6b | 27.8 ± 13.3B | 254.2 ± 60.2d | 671.2 ± 26.3b | 462.7 ± 227.1B |
| UWM 4 | 17.6±10.3d | 59.7 ± 3.7c | 38.7 ± 23.6C | 8.0 ± 4.7d | 28.4 ± 1.8c | 18.2 ± 11.4C | 133.2 ± 78.1d | 484.6 ± 30.1c | 308.9 ± 195.6C |
| Mean | 33.6±19.1*b* | 87.4 ± 22.5*a* | 60.5 ± 34.2 | 14.6 ± 8.1*b* | 40.6 ± 9.8*a* | 27.6 ± 15.9 | 239.3 ± 132.5*b* | 685.5 ± 164.8*a* | 462.4 ± 270.2 |

± standard deviations; A.B.C … homogenous groups for clone; ***a.b*** … homogenous groups for rotation; a.b.c … homogenous groups for clone x rotation interaction.

In a different study conducted in Poland, the yield of poplar *Populus nigra* × *P. Maximowiczii* Henry cv. Max-5 in a 4-year harvest rotation was 8.2 Mg ha$^{-1}$ year$^{-1}$ DM [11]. The experiment cited above demonstrates the significant effect of different methods of soil enrichment on poplar yield; it was the highest on a plot in which lignin was applied in combination with mineral fertilisers (10.5 Mg ha$^{-1}$ year$^{-1}$ DM). The poplar yield on a control plot, with no soil enrichment, was lower by 48%. A higher yield from a poplar plantation was obtained in Italy [32]. A clone of *Populus deltoides* L. in a 2-year harvest rotation gave a yield of 11.7 Mg ha$^{-1}$ year$^{-1}$ DM. Moreover, extending the harvest rotation to three and four years had a significant positive effect on the poplar yield, causing it to increase to 15.0 and 18.4 Mg ha$^{-1}$ year$^{-1}$ DM. A similarly high yield of poplar in a 4-year harvest rotation (18.0 Mg ha$^{-1}$ year$^{-1}$ DM) was found for the clone *Populus maximowiczii* × *P. nigra* (NM6) in Canada [20]. A very high yield of six genotypes of poplar in three consecutive two-year harvest rotations was obtained in Italy by Sabatti et al. [33]. In that experiment, poplar was grown at an agricultural site with highly productive soil and a large amount of nitrogen fertilisation. Biomass production differed significantly among rotations starting from 16 Mg ha$^{-1}$ year$^{-1}$ DM in the first, peaking at 20 Mg ha$^{-1}$ year$^{-1}$ DM in the second, and decreasing to 17 Mg ha$^{-1}$ year$^{-1}$ DM in the third rotation. However, other authors have reported that seven clones of poplar of the *Populus* × *canadensis* and seven of the *Populus deltoides* species grown in Italy did not give such a high yield [34]. It was found after nine years of poplar cultivation and four harvest rotations that the average yield of biomass of the *Populus deltoides* species was 9.7 Mg ha$^{-1}$ year$^{-1}$ DM, and it was lower for clones of the *Populus* x *canadensis* species—5.6 Mg ha$^{-1}$ year$^{-1}$ DM. It was shown in the study cited above that the average yield for 14 poplar clones was 8.34 Mg ha$^{-1}$ year$^{-1}$ DM. The yield of poplar obtained in other studies also varied (1.6–28 Mg ha$^{-1}$ year$^{-1}$ DM) depending on the climatic conditions, the type of soil, species and clone, harvest rotation, age of the plantation, level of fertilisation and other agricultural procedures [35–39]. It was also demonstrated that the annual yield of poplar biomass increased with the age of plants up to a maximum between the third and fourth growing seasons [40]. In a study in Belgium, the average dry biomass yield of poplar established on degraded land and maintained as a low-energy input system during the fourth rotation was 4.3±3.4 Mg ha$^{-1}$ year$^{-1}$ DM across all clones, but the most productive clones yielded up to 10.5 Mg ha$^{-1}$ year$^{-1}$ DM [41]. Therefore, it can be claimed that the yield was very similar to that obtained in the current study.

The energy value of poplar yield (calculated as the product of fresh biomass yield and its LHV) harvested in two consecutive 4-year rotations was 462 GJ ha$^{-1}$, with a high standard deviation of 270 GJ ha$^{-1}$, which showed a high differentiation of this parameter between clones and harvest rotations (Table 2). The significantly largest yield energy value was obtained from the UWM 2 clone—672 GJ ha$^{-1}$ on average from the two 4-year rotations (Table 2). The mean value of this attribute for the UWM 3, UWM 1 and UWM 4 clones was lower by ca. 31%, 40% and 54%, respectively. The mean biomass yield energy value for the second 4-year rotation was higher by as much as 290% compared to the value from the first harvest rotation. The significantly highest yield energy value was found in the UWM 2 clone in the second harvest rotation: 230.6 GJ ha$^{-1}$ year$^{-1}$ (Figure 1). The energy value of UWM 1 and UWM 3 clones in the second rotation was nearly 170 GJ ha$^{-1}$ year$^{-1}$ (homogeneous group b). Meanwhile, the attribute value for the UWM 4 clone was approx. 120 GJ ha$^{-1}$ year$^{-1}$ (homogeneous group c). Furthermore, in the first rotation, only the yield energy value of the UWM 2 clone exceeded 100 GJ ha$^{-1}$ year$^{-1}$ (homogeneous group c), and the other clones were in the last (homogeneous group d). Different results of yield energy value resulted mainly from different yields and biomass LHV, both between the clones and the rotations, since the yield energy value was calculated based on these two parameters. In the first rotation, the yield and biomass LHV were significantly lower than those obtained in the second rotation. The higher biomass yield in the second rotation resulted from the fact that poplar plants developed a considerably more developed root system compared with the plants of the first rotation when the root system underwent systematic expansion. It should be concluded that the differences in yield energy value between the studied clones were of genetic background since poplars were cultivated in analogous climatic and soil conditions.

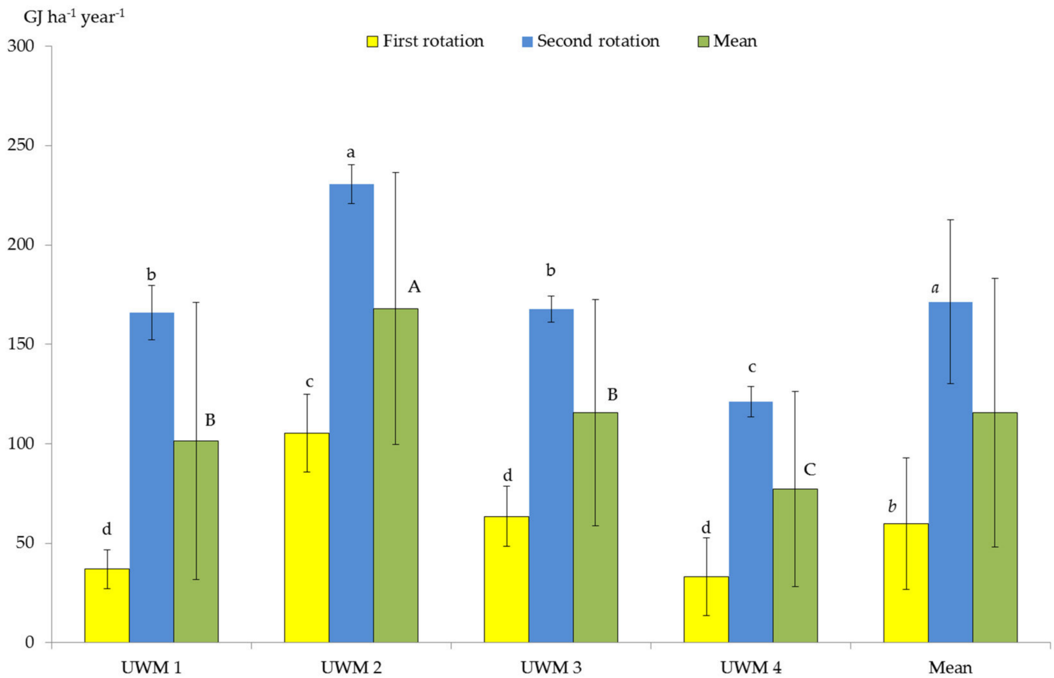


**Figure 1.** Yield energy value of four poplar clones in two consecutive 4-year harvest rotations converted to one year of the plantation use. A.B.C ... homogenous groups for clone; *a.b* ... homogenous groups for rotation; a.b.c ... homogenous groups for clone x rotation interaction; error bars represent standard deviations.

The highest yield energy value for *Populus nigra* × *P. Maximowiczii* Henry cv. Max-5 (177 GJ ha$^{-1}$ year$^{-1}$) in the authors' other study was achieved on soil enriched with lignin and mineral fertilisers. The value of the attribute with other soil enrichment combinations was lower by 11–48% [11]. A similar energy value of poplar yield of 188 GJ ha$^{-1}$ year$^{-1}$ was achieved in its production in a two-year harvest cycle [42]. In other studies conducted in Italy, the energy value of poplar biomass grown in different harvest cycles, with mineral fertilisation and irrigation, was much higher—257 GJ ha$^{-1}$ year$^{-1}$ [43] and 270 GJ ha$^{-1}$ year$^{-1}$ [15]. Nassi o Di Nasso et al. [44] analysed the effect of harvest rotation cycles (annual, biannual, triennial) on the energy balance of a 12-year-old short-rotation coppice poplar with mineral fertilization and obtained an even higher energy value of biomass of 450 GJ ha$^{-1}$ year$^{-1}$ after the first triennial cutting cycle. However, the energy value of the yield decreased to 350, 289 and 127 GJ ha$^{-1}$ year$^{-1}$ in the second, third and last triennial cutting cycle, respectively, which resulted in an average of 304 GJ ha$^{-1}$ year$^{-1}$ during the whole period of the plantation use. On the other hand, the energy value of poplar yield obtained in extensive cultivation in a 4-year harvest rotation was much lower (70.9 GJ ha$^{-1}$ year$^{-1}$) [45]. This was confirmed by a study conducted by Dillen et al. [41], which showed that the energy value of the yield of poplar grown on degraded land was about 92 GJ ha$^{-1}$ year$^{-1}$. However, when poplar was grown in Sweden (long harvest cycle), the gross energy yields over the plantation live cycle (24 years) were 4710 and 4430 GJ ha$^{-1}$, for fertilized and unfertilized poplar, respectively, which corresponded to 196 and 185 GJ ha$^{-1}$ year$^{-1}$, respectively [26]. Therefore, the mean yield energy value obtained in the current study in north-eastern Poland for the UWM 2 clone (168 GJ ha$^{-1}$ year$^{-1}$) and, especially, the much higher value in the second 4-year harvest rotation (231 GJ ha$^{-1}$ year$^{-1}$), should be seen as high and satisfactory.

### 3.2. Thermophysical Properties and Elemental Composition of Biomass

The poplar biomass moisture content was significantly differentiated by the clone and harvest rotation, while the fixed carbon content was only significantly differentiated by the harvest rotation (Table 1). The average poplar biomass moisture content in the experiment was 54.8% wb (Table 3). The UWM 3 and UWM 2 clones contained significantly more moisture compared to the other two clones. Moreover, the moisture content in the first 4-year harvest rotation (56.2%) was significantly (by 2.8 p.p.) higher compared to the mean moisture content in the second harvest rotation. The average content of fixed carbon and volatile matter in 4-year poplar shoots was 18.6% DM and 79.4% DM, respectively. In another study by the authors, the fixed carbon and volatile matter content in 4-year old shoots of *Populus nigra* × *P. Maximowiczii* Henry cv. Max-5 was 20.8% d.m and 77.4% DM, respectively, and the moisture content was 55.7% [46]. Other studies have also confirmed that the moisture content in poplar upon harvest is high and exceeds 50%; sometimes even exceeding 60% [33,47–50].

**Table 3.** Moisture content, fixed carbon and volatile matter content in the biomass of four poplar clones in two consecutive 4-year harvest rotations.

| Clone | Moisture Content (%) | | | Fixed Carbon (% DM) | | | Volatile Matter (% DM) | | |
|---|---|---|---|---|---|---|---|---|---|
| | First Rotation | Second Rotation | Mean | First Rotation | Second Rotation | Mean | First Rotation | Second Rotation | Mean |
| UWM 1 | 54.7 ± 0.1 | 52.6 ± 1.2 | 53.7 ± 1.4B | 18.7 ± 0.2 | 18.1 ± 0.6 | 18.4 ± 0.6 | 79.5 ± 0.5 | 79.4 ± 1.1 | 79.4 ± 0.7 |
| UWM 2 | 56.9 ± 1.0 | 54.5 ± 0.2 | 55.7 ± 1.5A | 19.0 ± 0.7 | 18.2 ± 0.7 | 18.6 ± 0.8 | 79.5 ± 1.0 | 79.4 ± 0.9 | 79.5 ± 0.9 |
| UWM 3 | 58.3 ± 0.7 | 54.1 ± 0.2 | 56.2 ± 2.4A | 18.9 ± 0.4 | 17.9 ± 0.3 | 18.4 ± 0.6 | 79.7 ± 0.6 | 79.6 ± 0.5 | 79.7 ± 0.5 |
| UWM 4 | 54.7 ± 0.2 | 52.3 ± 1.0 | 53.5 ± 1.4B | 19.2 ± 0.2 | 18.4 ± 0.7 | 18.8 ± 0.6 | 78.8 ± 0.8 | 79.1 ± 1.1 | 78.9 ± 0.9 |
| Mean | 56.2 ± 1.7***a*** | 53.4 ± 1.2***b*** | 54.8 ± 2.0 | 19.0 ± 0.4***a*** | 18.2 ± 0. ***b*** | 18.6 ± 0.6 | 79.4 ± 0.7 | 79.4 ± 0.8 | 79.4 ± 0.8 |

± standard deviations; A.B.C . . . homogenous groups for clone; ***a.b*** . . . homogenous groups for rotation; a.b.c . . . homogenous groups for clone × rotation interaction.

The ash content in poplar biomass was significantly differentiated by harvest rotations and the interactions between the harvest rotation and the clone and was 1.4% DM on average (Tables 1 and 4). The ash content in 4-year old poplar trees throughout the experiment ranged from 1.0 to 1.8% DM. On the other hand, HHV was significantly differentiated by the harvest rotation, and LHV was significantly differentiated by the clone and harvest rotation (Table 1). LHV of poplar biomass as measured in this experiment was 7.5 MJ $kg^{-1}$ (Table 4). The LHV values of UWM 4 and UWM 1 clones (homogeneous group A) were significantly higher compared to the other two clones (homogeneous group B). The LHV of poplar obtained in the second 4-year harvest rotation was significantly higher compared to the first harvest rotation. In another study, the average ash content in 4-year old shoots of *Populus nigra* × *P. Maximowiczii* Henry cv. Max-5 was slightly higher (1.8% DM), and the LHV was very similar (7.5 MJ $kg^{-1}$) [46]. Different LHV results in our study were determined by different moisture content and biomass HHV between the rotations since LHV was calculated based on these two parameters. In the second rotation, biomass moisture content was lower while HHV was higher, which resulted in a higher LHV when compared with those values obtained in the first rotation. Other studies have also shown that the ash content in poplar biomass may vary (0.98–3.12% DM) depending on the cultivar/clone, harvest rotation and other factors [33,47–49].

**Table 4.** Ash content, higher and lower heating value of biomass of four poplar clones in two consecutive 4-year harvest rotations.

| Clone | Ash Content (% DM) | | | Higher Heating Value (MJ kg−1 DM) | | | Lower Heating Value (MJ kg−1) | | |
|---|---|---|---|---|---|---|---|---|---|
| | First Rotation | Second Rotation | Mean | First Rotation | Second Rotation | Mean | First Rotation | Second Rotation | Mean |
| UWM 1 | 1.5 ± 0.4a | 1.6 ± 0.4a | 1.6 ± 0.4 | 19.3 ± 0.1 | 19.6 ± 0.2 | 19.4 ± 0.2 | 7.4 ± 0.1 | 8.0 ± 0.2 | 7.7 ± 0.3A |
| UWM 2 | 1.2 ± 0.3b | 1.5 ± 0.4a | 1.3 ± 0.3 | 19.7 ± 0.2 | 19.9 ± 0.2 | 19.8 ± 0.2 | 7.1 ± 0.1 | 7.7 ± 0.0 | 7.4 ± 0.3B |
| UWM 3 | 1.0 ± 0.2b | 1.5 ± 0.2a | 1.2 ± 0.3 | 19.6 ± 0.1 | 19.7 ± 0.3 | 19.6 ± 0.2 | 6.8 ± 0.1 | 7.7 ± 0.1 | 7.2 ± 0.5B |
| UWM 4 | 1.8 ± 0.6a | 1.5 ± 0.4a | 1.6 ± 0.5 | 19.6 ± 0.1 | 19.7 ± 0.2 | 19.7 ± 0.2 | 7.6 ± 0.1 | 8.1 ± 0.2 | 7.8 ± 0.3A |
| Mean | 1.4 ± 0.4***b*** | 1.5 ± 0.3***a*** | 1.4 ± 0.4 | 19.6 ± 0.2***b*** | 19.7 ± 0.2***a*** | 19.6 ± 0.2 | 7.2 ± 0.3***b*** | 7.9 ± 0.2***a*** | 7.5 ± 0.4 |

± standard deviation; A.B.C ... homogenous groups for clone; ***a.b*** ... homogenous groups for rotation; a.b.c ... homogenous groups for clone x rotation interaction.

An assessment of the content of selected elements found that only the harvest rotation affected the C and Cl content (Table 1). Significantly higher carbon content (average 51.5% DM) and lower chlorine content (average 0.009% DM) were found in the second 4-year harvest rotation (Tables 5 and 6). The mean content of C, H, S, N and Cl in 4-year old poplar shoots was 51.1, 6.0, 0.028, 0.41 and 0.013% DM, respectively. A significant positive correlation was found between the S and N content (0.91) and between the ash content and N content (0.67) and S content (0.63) (Table 7). Moreover, a positive correlation was found between the fixed carbon content and the S, N and Cl content. The C, H, S and N content as determined in the authors' earlier examinations of 4-year old shoots of *Populus nigra* × *P. Maximowiczii* Henry cv. Max-5 was similar: 51.0, 5.8, 0.024, 0.44% DM [46]. The C, H, S and N content in other studies was also similar: 50.3, 6.1, 0.03 and 0.42% DM [50]. A slightly higher content of C, H, S (51.8, 6.4, 0.04% DM, respectively) and a lower content of N (0.16% DM) in biomass of *Populus* x *euroamericana* (Dode) Guinier (AF2) was found by Monedero et al. 2017 [49]. Considering the above, it could be concluded that poplar biomass may serve as fuel with potentially low $SO_2$ and particulate emission due to the low content of sulphur and ash. Moreover, the type of biomass conversion technology and equipment (e.g., boilers) used are of great importance here as well. It should be stressed that burning poplar biomass in small boilers with manual fuel feeding (old type) and stove, like any other solid fuel, may pose problems with black carbon, polycyclic aromatic hydrocarbons and volatile organic compounds emissions. Therefore, the use of modern automatic boilers for home heating and fluidal boilers in power plants and heat power plants is recommended. Such combustion technologies ensure low emissions of atmospheric pollutants [51–53]. Combustion of the studied poplar biomass should not cause any significant corrosion of boiler elements since this biomass contains low amounts of chlorine and the S/Cl ratio based on the current study averaged 2.2. It is accepted that high-temperature corrosion occurs intensively when the fuel chloride contents are over 0.2%, and the S/Cl ratio is below 2.2 [54,55].

**Table 5.** Content of carbon (C), hydrogen (H) and sulphur (S) in biomass of four poplar clones in two consecutive 4-year harvest rotations.

| Clone | C (% DM) | | | H (% DM) | | | S (% DM) | | |
|---|---|---|---|---|---|---|---|---|---|
| | First Rotation | Second Rotation | Mean | First Rotation | Second Rotation | Mean | First Rotation | Second Rotation | Mean |
| UWM 1 | 50.1 ± 0.2 | 51.1 ± 0.5 | 50.6 ± 0.6 | 5.9 ± 0.1 | 5.9 ± 0.1 | 5.9 ± 0.1 | 0.030 ± 0.002 | 0.028 ± 0.013 | 0.029 ± 0.008 |
| UWM 2 | 50.5 ± 0.9 | 52.0 ± 0.0 | 51.2 ± 1.0 | 6.0 ± 0.1 | 6.0 ± 0.1 | 6.0 ± 0.1 | 0.028 ± 0.004 | 0.024 ± 0.015 | 0.026 ± 0.010 |
| UWM 3 | 50.7 ± 0.4 | 51.4 ± 0.5 | 51.0 ± 0.5 | 6.0 ± 0.1 | 5.9 ± 0.1 | 5.9 ± 0.1 | 0.026 ± 0.004 | 0.026 ± 0.013 | 0.026 ± 0.009 |
| UWM 4 | 51.4 ± 0.6 | 51.8 ± 0.6 | 51.6 ± 0.6 | 5.9 ± 0.0 | 6.0 ± 0.1 | 6.0 ± 0.0 | 0.029 ± 0.005 | 0.030 ± 0.022 | 0.029 ± 0.014 |
| Mean | 50.7 ± 0.7*b* | 51.5 ± 0.5*a* | 51.1 ± 0.7 | 5.9 ± 0.1 | 6.0 ± 0.1 | 6.0 ± 0.1 | 0.028 ± 0.004 | 0.027 ± 0.014 | 0.028 ± 0.010 |

± standard deviations; A.B.C … homogenous groups for clone; ***a.b*** … homogenous groups for rotation; a.b.c … homogenous groups for clone x rotation interaction.

**Table 6.** Content of nitrogen (N) and chlorine (Cl) in biomass of four poplar clones in two consecutive 4-year harvest rotations.

| Clone | N (% DM) | | | Cl (% DM) | | |
|---|---|---|---|---|---|---|
| | First Rotation | Second Rotation | Mean | First Rotation | Second Rotation | Mean |
| UWM 1 | 0.46 ± 0.1 | 0.51 ± 0.3 | 0.48 ± 0.2 | 0.011 ± 0.003 | 0.009 ± 0.004 | 0.010 ± 0.003 |
| UWM 2 | 0.40 ± 0.1 | 0.34 ± 0.2 | 0.37 ± 0.1 | 0.018 ± 0.004 | 0.009 ± 0.003 | 0.014 ± 0.006 |
| UWM 3 | 0.39 ± 0.1 | 0.33 ± 0.2 | 0.36 ± 0.1 | 0.017 ± 0.004 | 0.009 ± 0.005 | 0.013 ± 0.006 |
| UWM 4 | 0.41 ± 0.1 | 0.47 ± 0.3 | 0.44 ± 0.2 | 0.024 ± 0.001 | 0.009 ± 0.008 | 0.017 ± 0.010 |
| Mean | 0.42 ± 0.1 | 0.41 ± 0.2 | 0.41 ± 0.2 | 0.018 ± 0.005*a* | 0.009 ± 0.004*b* | 0.013 ± 0.007 |

± standard deviations; A.B.C … homogenous groups for clone; ***a.b*** … homogenous groups for rotation; a.b.c … homogenous groups for clone x rotation interaction.

**Table 7.** Simple correlation coefficient between the analyzed features*.

| Item | Moisture | Fixed Carbon | Volatile Matter | Ash | HHV | LHV | C | H | S | N | Cl |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Moisture | 1.00 | | | | | | | | | | |
| Fixed Carbon | 0.58 * | 1.00 | | | | | | | | | |
| Volatile Matter | −0.04 | −0.72 * | 1.00 | | | | | | | | |
| Ash | −0.30 | 0.34 | −0.79 * | 1.00 | | | | | | | |
| HHV | 0.15 | 0.32 | −0.54 * | 0.36 | 1.00 | | | | | | |
| LHV | −0.97 * | −0.52 * | −0.08 | 0.38 | 0.07 | 1.00 | | | | | |
| C | −0.41 * | −0.25 | −0.19 | 0.15 | 0.51 * | 0.53 * | 1.00 | | | | |
| H | 0.11 | −0.08 | 0.07 | −0.16 | 0.15 | −0.08 | 0.36 | 1.00 | | | |
| S | 0.15 | 0.64 * | −0.79 * | 0.63 * | 0.50 * | −0.04 | −0.04 | −0.26 | 1.00 | | |
| N | 0.09 | 0.60 * | −0.81 * | 0.67* | 0.40 | 0.00 | −0.07 | −0.20 | 0.91 * | 1.00 | |
| Cl | 0.50* | 0.65 * | −0.29 | 0.06 | 0.11 | −0.48 * | −0.11 | 0.10 | 0.00 | 0.04 | 1.00 |

* asterisk indicatesstatistically significant values at $P < 0.05$.

## 4. Conclusions

This study found that the biomass yield, energy value and wood quality of *Populus balsamifera* grown in the north-east of Poland as energy feedstock was differentiated by both the clone of the *Populus balsamifera* species and by the harvest rotation and by the interaction of these factors. Both the biomass yield and its energy value in the first 4-year harvest rotation were found to be relatively low. A distinct 260–290% increase in these attributes was observed in the second 4-year rotation. Among the clones under study, the highest yield energy value was determined in the UWM 2 clone in the second harvest rotation. The values of this parameter for the other clones were 27–47% lower. Such large differences in the yield energy value resulted from varied yields and biomass LHV between harvest rotations and clones. The plants produced considerably higher yields in the second 4-year rotation, thus ensuring a higher yield energy value. An analysis of the biomass quality showed that poplar wood contained high levels of moisture and low levels of ash, sulphur, nitrogen and chlorine. This may be indicative of a good quality fuel with potentially low $SO_2$ and particulate emissions. Moreover, due to the low chlorine content and advantageous S/Cl ratio, poplar biomass combustion should not pose problems with corrosion of boiler elements. Based on the results of this study it can be concluded that poplar can be grown in the north-east of Poland and that it gives a yield with a high energy value and beneficial biomass properties from the energy generation perspective. However, further studies are necessary, both on experimental and commercial scales to perform a comprehensive assessment of economic, energy-related and environmental assessment of poplar biomass production in the SRWC system, which will be the object of future studies.

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## Nomenclature

| | |
|---|---|
| DM | dry matter |
| f.m. | fresh biomass |
| HHV | higher heating value (GJ $Mg^{-1}$ DM) |
| $LHV^{wb}$ | biomass lower heating value (wet basis) (GJ $Mg^{-1}$) |
| RES | renewable energy sources |
| SRWC | short rotation woody crops |
| wb | wet basis |
| Yb | biomass yield (Mg $ha^{-1}$ f.m.) |
| Yev | biomass yield energy value (GJ $ha^{-1}$) |

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