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Willow, Poplar, and Black Locust Debarked Wood as Feedstock for Energy and Other Purposes

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Abstract: Solid biomass can be used for energy generation and the production of various renewable bioproducts. The aim of this study was to determine the yield and characteristics of wood obtained as debarking residue from 14 genotypes of short-rotation woody crops (SRWCs). These included five *Populus* genotypes, one *Robinia* genotype, and eight *Salix* genotypes, harvested in both annual and quadrennial cycles. The results showed that the highest dry wood yield (12.42 Mg ha^{-1} y^{-1} DM) and yield energy value (244.34 GJ ha^{-1} y^{-1}) were obtained from willow (cultivar Żubr) harvested in a quadrennial cycle. The best effect among the poplar genotypes was achieved for the Hybryda275, and it was particularly marked in the quadrennial harvest cycle. The poorest results were determined for black locust. The *Robinia* characteristics included the significantly lowest moisture content (31.6%), which was a positive attribute from the energy point of view, but, on the other hand, it had some adverse characteristics—the highest levels of sulfur (0.033% DM), nitrogen (0.38% DM), and ash (0.69% DM). More beneficial properties in this respect were determined for willow and poplar wood. Moreover, willow and poplar wood contained more cellulose—51.8 and 50.0% DM, respectively—compared with black locust. Extending the SRWC shoot harvest cycle from annual to quadrennial resulted in an increase in cellulose, lignin, and carbon, higher heating value, and a decrease in nitrogen, sulfur, ash, and moisture content. Therefore, extending the harvest cycle improved the parameters of SRWC wood as an energy feedstock.

Keywords: *Populus*; *Robinia*; *Salix*; short-rotation coppice; wood; solid biofuel; higher heating value; ash; sulfur; nitrogen; chlorine; cellulose; lignin

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1. Introduction

Solid biomass can be used for energy generation and the production of various renewable bioproducts. Plant biomass is primarily derived from agriculture, forestry, and the processing of materials derived from these industries [1]. Agricultural land can be used to grow perennial industrial crops (PICs), which are a type of lignocellulosic biomass source [2–6]. PICs include a group of short-rotation woody crops (SRWCs) of genera *Eucalyptus*, *Salix*, *Populus*, and *Robinia*, which are sources of woody biomass [7,8]. The production and use of SRWCs are seen as bringing environmental, social, and economic benefits [9–12]. According to the biobased economy concept, biomass use should be diverse, and it should include generating various renewable food bioproducts and others, as well as energy generation [13–17].

Therefore, it is proposed that bark should be separated from wood so that these two materials of different quality can be used in different ways. This approach can result in the valuation and cascaded use of these two materials (wood and bark) obtained from SRWC shoots. Valuable secondary metabolites containing phenolic compounds are obtained from the bark of willow, poplar, and black locust [18–22]. Phenolic glucosides, also known as salicylic glucosides, and salicylic acid (found in willow bark) possess anti-inflammatory, antipyretic, antirheumatic, analgesic, and anticoagulant properties [20,23,24]. Therefore, bark produced as a raw material for manufacturing high-added-value bioproducts will be accompanied by generating wood as SRWC shoot debarking residue. Owing to its properties, such wood can be a valuable material for use in biorefineries and as energy feedstock [16]. However, due to the high diversity among SRWC species, only those that are the most suitable for cultivation from the yield and biomass quality perspective, including the quality of wood as debarking residue, should be selected. It should also be added that, most often, studies in this field cover one type of SRWC, i.e., willow, poplar, or black locust. Therefore, the novelty of this study was the comparison of these three types of SRWC, grown simultaneously under the same environmental (climatic and soil) conditions, at the same time and in two different harvesting cycles. The present study hypothesized that the wood, as a residue from the debarking of SRWC shoots, has interesting and practically important properties. This study seeks to evaluate the quality of wood residue from 14 different genotypes of short-rotation woody crops (SRWCs), both those harvested annually and those harvested every four years, after debarking. The specific objectives included the determination of (i) wood yield and energy value, (ii) thermophysical properties, (iii) elemental composition, and (iv) lignocellulosic composition.

2. Materials and Methods

2.1. Field Experiment

In April 2009, the University of Warmia and Mazury in Olsztyn (UWM) founded a plantation for the purpose of growing short-rotation woody crops (SRWC) in northeast Poland. The field experiment was conducted by the Department of Genetics, Plant Breeding and Bioresource Engineering of the UWM. A two-factorial experiment was conducted, with the first factor being fourteen SRWC genotypes of three different genera, including [25]: one genotype of genus *Robinia*: *Robinia pseudoacacia* L.; five genotypes of genus *Populus*: *P. balsamifera* L., UWM2; *P. balsamifera* L., UWM3; *P. nigra* × *P. maximowiczii* (L.) Henry, Max-5; *P. maximowiczii* × *P. trichocarpa* (Henry) Torr. and A. Gray, Androscoggin; *P. maximowiczii* × *P. trichocarpa* (Henry) Torr. and A. Gray, Hybryda275; eight genotypes of genus *Salix*: *S. alba* L., UWM200; *S. alba* L., UWM095; *S. dasyclados* Willd., UWM155; *S. fragilis* L., UWM195; *S. pentandra* L., UWM035; *S. triandra* L., UWM198; *S. viminalis* × *S. purpurea* L., UWM033; and *S. viminalis* L., cultivar Żubr. Two shoot harvest cycles were studied: annual and quadrennial.

The planting process consisted of 20 cm long willow and poplar cuttings, along with black locust seedlings, which were planted at a density of 18,000 plants per hectare. After every harvest, mineral fertilizers were applied to the crops, which included 90 kg ha^{-1} of ammonium nitrate for N, 30 kg ha^{-1} of triple superphosphate for P_2O_5, and 60 kg ha^{-1} of potassium salt for K_2O. The yield potential and biomass samples for further analysis were obtained by selecting three plots of 45 m^2 each for each SRWC genotype. The aboveground shoots of all SRWC genotypes were harvested three times in an annual cycle from 2018 to 2020, in late March of each year, and once in the quadrennial cycle. During the harvest period, the shoots of all SRWC genotypes were harvested in the dormant state and without leaves to ensure consistency. The shoots were cut into fragments from all sections along the shoots, packed in PE bags, and transported to the laboratory. Quadrennial leafless shoots (approx. 7 m high, approx. 5 cm in diameter) from each plot were harvested manually with a chainsaw, while annual shoots (approx. 3 m high, approx. 2 cm in diameter) were harvested with a petrol brush cutter. All shoots were electronically weighed immediately after the harvest. The result was used to calculate the yield of shoots, which was then referred to as a unit area (Mg ha^{-1}).

2.2. Separation of SRWC Shoots into Wood and Bark Fractions and Determination of Wood Yield

The SRWC shoot sections sent to the laboratory were separated into bark and wood using a sharp knife. The bark was used to analyze the concentration of bioactive substances in it and, subsequently, the potential yield of bioactive substances [26]. The wood was analyzed for its potential use in industry and in energy generation. Therefore, the biomass was dried at 105 °C until the sample weight was constant according to PN-EN ISO 18134-2 [27]. The result was used to calculate the wood content of the shoots and their percentage share in the whole dendromass (bark + wood). To ensure accuracy, annual shoots of each genotype were harvested three times, and each year, the analyses were carried out in triplicate. This means that nine analyses were conducted for annual shoots of each genotype. However, for this manuscript, only the mean data from three years for annual shoots are presented. On the other hand, quadrennial shoots of each genotype were harvested only once, and the analyses were carried out in triplicate. The shoot yield (Mg ha^{-1}), percentage share (%) of wood in it, and the dry matter content (%) were used to assess the dry wood yield (Mg ha^{-1} y^{-1}).

2.3. Laboratory Analyses

After performing the measurements and calculations, the wood samples were ground using a Retsch SM 200 laboratory mill (Retsch, Haan, Germany) and a 1 mm mesh sieve. The ground wood samples were then stored in plastic bags at room temperature. All the analyses were performed at the Energy Feedstock Assessment Laboratory at the Department of Genetics, Plant Breeding and Bioresource Engineering of the UWM. The dynamic method was used to determine the higher heating value (HHV) in an IKA calorimeter C2000 (IKA, Taufen, Germany) according to PN-EN ISO 18125:2017-07 [28]. The weighed portion of approx. 0.5 g was used to determine the HHV. An Eltra Tga Thermostep automatic thermogravimetric analyzer (ELTRA, Neuss, Germany) was used to determine the total ash content, fixed carbon (FC), and volatile matter (VM) content at 550 °C, following the standards PN-EN ISO 18122:2016-01 [29] and PN-EN ISO 18123:2016-01 [30]. The weighed portion of ground wood for an individual analysis was approx. 1.5 g. An Eltra CHS 500 automatic analyzer (ELTRA, Neuss, Germany) was used to determine the total carbon (C), hydrogen (H), and sulfur (S) contents of wood via high-temperature combustion (1350 °C), in accordance with PN-EN ISO 16948:2015-07 [31] and PN-EN ISO 16994:2016-10 [32] standards. The weighed portion for the analyses was approx. 0.15 g. The Kjeldahl method with a K-435 analyzer and a BUCHI B-324 (BUCHI, Flawil, Switzerland) distiller were used to determine the total nitrogen (N) content. The total chlorine (Cl) was determined using the Eschka mixture in accordance with the PN-ISO 587:2000 standard [33]. The weighed portion of wood for N and Cl analyses was approx. 1 g each.

The cold water extract (CWE) content was determined by comparing the sample weight before and after extraction. Distilled water (20–25 °C) was used for the sample extraction for 48 h using F57 filtration bags from ANKOM Technology. The samples were washed twice in an Ankom A200 (NY, USA) apparatus and then dried at 105 °C before being weighed. These weighed samples were then used for further analyses. To determine the hot water extract (HWE) content, the samples were extracted for 3 h at 100 °C, dried, and then weighed again at 105 °C. After extracting the hot water, further analyses were carried out to determine the NDF (neutral detergent fiber) according to PN-EN ISO 16472:2007 [34], ADF (acid detergent fiber), and ADL (acid detergent lignin) according to PN-EN ISO 13906:2009 [35] fractions in the wood using an Ankom A200 extraction system. These differences in the results were used to calculate the lignin (Lig), cellulose (Cel), and hemicellulose (Hem) content of the SRWC wood samples. The HWE and NDF contents were used to calculate the content of other soluble substances (OSSs). Each sample was subjected to laboratory analysis three times.

2.4. Energy Value of the Wood

The energy value of wood from a unit area (GJ ha^{-1} y^{-1}) was obtained by multiplying the dry wood's HHV (GJ Mg^{-1} DM) by its yield (Mg ha^{-1} y^{-1} DM). Subsequently, the wood yield energy value was expressed as the carbon equivalent (Mg ha^{-1}), assuming that medium-quality hard coal has a calorific value of 25 GJ Mg^{-1}.

2.5. Statistical Analysis

A set of averaged three-year data for annual and one-year harvest data for quadrennial shoots was used in this study. Before any statistical analysis was performed, the normality of the attributes under study was verified using the Shapiro–Wilk test. For statistical analyses, a two-factorial ANOVA was used, with genotype (14 different SRWCs) as the first factor and harvest cycle (annual and quadrennial) as the second factor. Homogeneous groups were determined by applying Tukey's honest significant difference (HSD) test at the significance level of $p < 0.05$. The study results were presented by calculating the arithmetic mean, the standard error of the mean, and the coefficient of variance for each analyzed attribute of each SRWC genotype. Additionally, the Pearson correlation coefficient between the attributes was also determined. Descriptive statistics were calculated for all SRWC genotypes, including mean, median, minimum and maximum values, lower and upper quartiles, standard deviation, and coefficient of variation. Moreover, two similarity analyses were performed for the 14 SRWC genotypes under study and for the determined wood attributes. In order to analyze the similarities between different genotypes and their wood attributes, a multivariate cluster analysis was conducted. The Ward method was used for agglomeration, while Euclidean distances were utilized to measure the distance between the clusters. Sneath's criterion was used to identify the clusters. Two cut-off lines were applied, the first at 2/3 D_{max}, and the second at 1/3 D_{max}, where Dmax is the maximum measure of distance. The results of the cluster analysis were displayed in a dendrogram. All statistical analyses were carried out using STATISTICA 13 software (TIBCO Software Inc., Palo Alto, CA, USA).

3. Results

3.1. SRWC Wood Yield and Its Energy Value

The wood yield and energy value varied significantly depending on the SRWC genotype, as well as the plant harvest cycle and the interaction between these two factors (Table 1). Among the 14 SRWC genotypes studied, the highest wood yield was obtained from the *S. viminalis* Żubr cultivar, with a yield of 10.65 Mg ha^{-1} y^{-1} DM. This was classified as homogeneous group "A" (Figure 1). A second homogeneous group "B" included poplar *P. maximowiczii* × *P. trichocarpa*, Hybryda275, and willow *S. alba* UWM095 as well as, indirectly, another two willow genotypes, *S. fragilis* UWM195 and *S. triandra* UWM198. The wood yield for the four genotypes exceeded 8 Mg ha^{-1} y^{-1} DM and was lower by 20–29% compared with the wood yield of the willow Żubr cultivar. *R. pseudoacacia* gave the lowest dry wood yield (3.86 Mg ha^{-1} y^{-1} DM), which was lower by 64%. The study found that the plant harvest cycle had a significant impact on the dry wood yield. The quadrennial cycle resulted in a higher yield of dry wood (8.25 Mg ha^{-1} y^{-1} DM) compared with the annual cycle, with an increase of almost 37%. The highest dry wood yield in the entire experiment (12.42 Mg ha^{-1} y^{-1} DM) was obtained from *S. viminalis* of the Żubr cultivar harvested in the quadrennial cycle (Figure 1, Table A1). The intermediate homogeneous group "ab" included the yield of *P. maximowiczii* × *P. trichocarpa*, Hybryda275 wood, whose yield in the quadrennial cycle was lower by 10%. The lowest dry wood yield was obtained from the *P. balsamifera* UWM3 harvested in the annual cycle, which was lower by as much as 78%. In general, *R. pseudoacacia* and *P. balsamifera* UWM3 gave the lowest wood yields, both in the annual and the quadrennial harvest cycles.

Table 1. Analysis of variance (*p* values) for the analyzed features.

Source of Variation	Degrees of Freedom	Dry Wood Yield	MC	VM	H	S	Cl	For the Rest Features [1]
Genotype	13	<0.001 *	<0.001 *	<0.001 *	0.058	<0.001 *	<0.001 *	<0.001 *
Harvest cycle	1	<0.001 *	<0.001 *	<0.001 *	0.007 *	<0.001 *	0.008 *	<0.001 *
Genotype × Harvest cycle	13	<0.001 *	<0.001 *	0.001 *	0.056	0.078	0.010 *	<0.001 *
Error	56							

[1] energy value of wood yield; coal equivalent, higher heating value; ash; FC; C; N; cold water extracts; hot water extracts; other soluble substances; hemicellulose; cellulose; lignin; * significant values ($p < 0.05$).

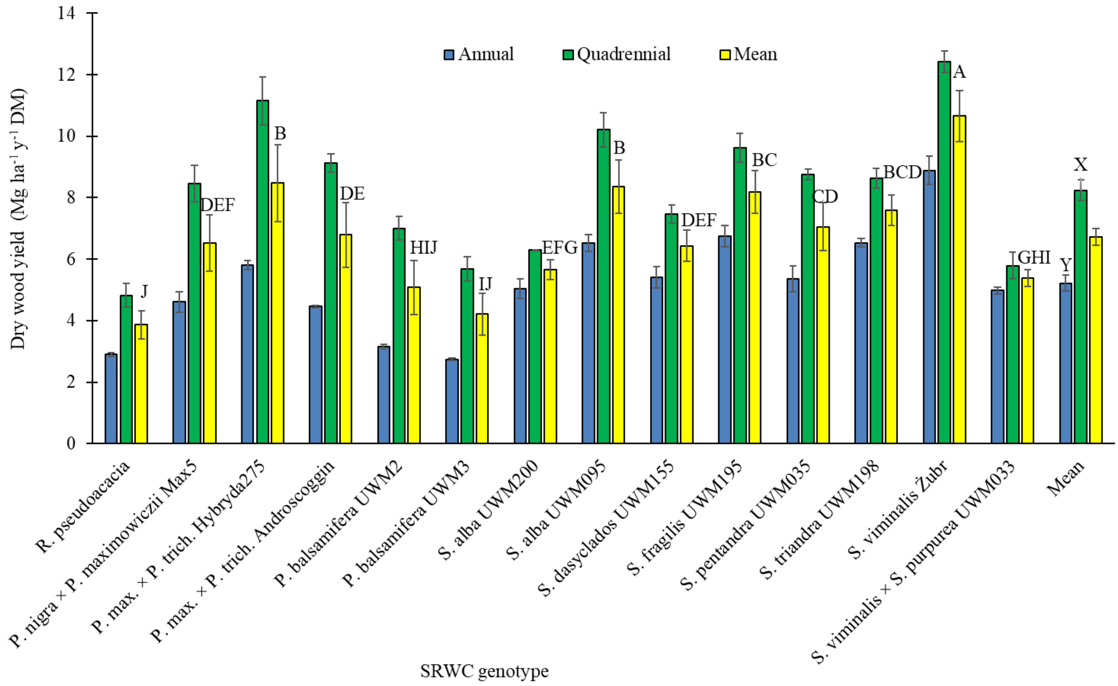

Figure 1. Dry wood yield for SRWC genotypes and harvest cycles (Mg ha^{-1} y^{-1} DM). A, B, C, etc.—genotype homogeneous groups; X, Y—harvest cycle homogeneous groups; genotype × harvest cycle interaction homogeneous groups (see Table A1); error bars—standard error of mean.

The energy value of wood from 1 ha was calculated by multiplying the dry wood yield by its higher heating value (HHV). Obviously, in general, genotypes that give higher wood yields had a higher energy value per unit area. This is why the relationship between the genotypes under study was nearly the same as that of the dry wood yield. The significantly highest wood energy value among the 14 SRWC genotypes under study was calculated for willow of the Żubr cultivar—208.88 GJ ha^{-1} y^{-1} DM (Figure 2). A second homogeneous group "B" included the Hybryda275 poplar and *S. alba* UWM095 willow, and their wood energy value was lower by approx. 21%. The mean energy value of the *R. pseudoacacia* was lower by as much as 64%. During the quadrennial cycle, the dry wood yield had a higher energy value of nearly 162 GJ ha^{-1} y^{-1}, which was 37% higher than the annual cycle. The significantly highest wood energy value in the entire experiment (244.34 GJ ha^{-1} y^{-1}) was calculated for *S. viminalis* (Żubr cultivar) in the quadrennial harvest cycle (Figure 2, Table A2). It was equivalent to nearly 10 Mg ha^{-1} y^{-1} of hard coal (Table A3). The intermediate homogeneous group "ab" included the Hybryda275 poplar wood in the quadrennial harvest cycle, and the wood energy value was lower by 12% compared with the highest value in this experiment (Figure 2, Table A2). Over 200 GJ ha^{-1} y^{-1} was also found for the *S. alba* UWM095, but the value was lower by 17%. The lowest wood energy value (mere 53 GJ ha^{-1} y^{-1}) was achieved for *P. balsamifera* UWM3, harvested in the annual cycle. In the annual harvest cycle, the wood energy value did not exceed

100 GJ ha^{-1} y^{-1} for seven SRWC genotypes. *R. pseudoacacia* and *P. balsamifera* UWM3 had the lowest energy values in both the annual and quadrennial harvest cycles. The wood energy value, expressed as the coal equivalent, ranged from 2 to 10 Mg ha^{-1} throughout the experiment (Table A3).

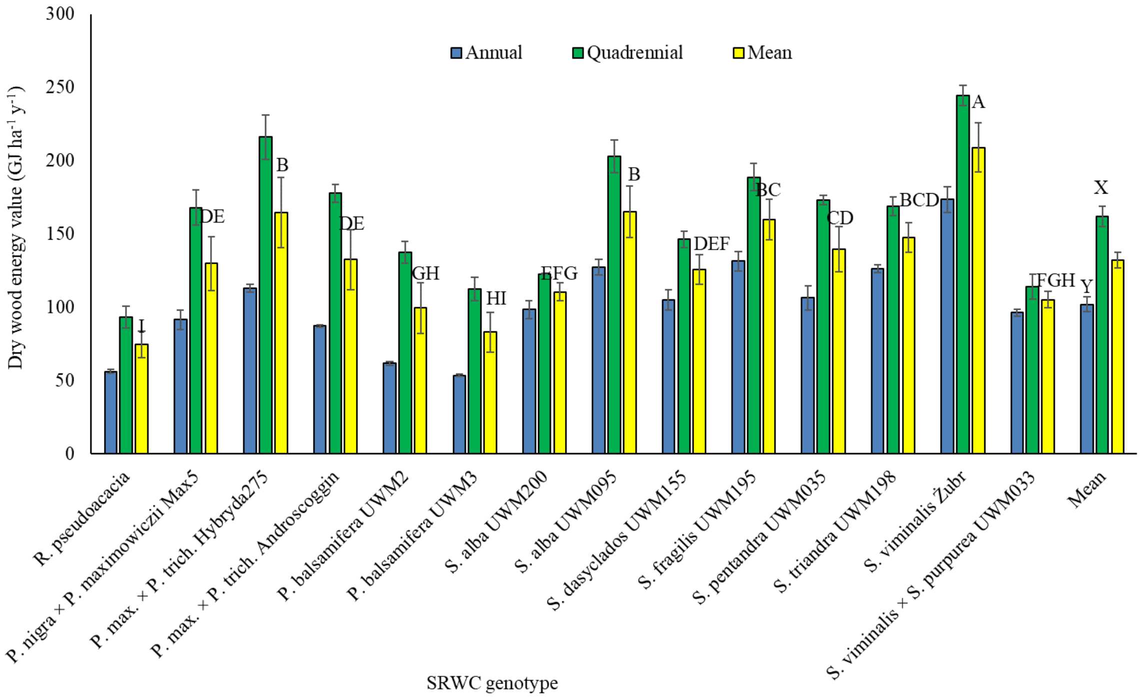

Figure 2. Dry wood energy value for SRWC genotypes and harvest cycles (GJ ha^{-1} y^{-1}). A, B, C, etc.—genotype homogeneous groups; X, Y—harvest cycle homogeneous groups; genotype × harvest cycle interaction homogeneous groups (see Table A2); error bars—standard error of mean.

3.2. Thermophysical Characteristics of SRWC Wood

The thermophysical characteristics of SRWC wood varied significantly based on genotype, plant harvest cycle, and their interaction (Table 1). The highest mean moisture content (56.01%) was determined in the *P. nigra* × *P. maximowiczii* Max-5 wood (Table 2). The mean moisture content of the other poplar genotype wood was also high and ranged from 53.5% to 55.8%. The willow wood moisture content was lower, and it lay within a range between 43.3% and 51.41% for the *S. pentandra* UWM035 and *S. dasyclados* UWM155 genotypes, respectively. The significantly lowest moisture content of the wood (31.61%) was determined in *R. pseudoacacia*, the homogeneous group "H". The moisture content of wood at the level of the second experiment factor was significantly differentiated because the annual shoot moisture content was higher by 2.13 pp than that of wood from the quadrennial shoots. The largest disproportion of the attribute (nearly 27 pp.) was observed for the moisture content between the wood obtained from the quadrennial shoots of the Max-5 poplar (57.31%) and *R. pseudoacacia* (Table 2).

The significantly highest HHV (19.85 GJ Mg^{-1} DM) was determined for the wood of the Max-5 poplar (Table 3). The mean HHV for other poplar and willow genotypes ranged from 18.81 to 19.43 GJ Mg^{-1} DM for Hybryda275 poplar and *S. pentandra* UWM035. On the other hand, *R. pseudoacacia* was characterized by the significantly lowest value of this attribute—19.36 GJ Mg^{-1} DM. The HHV for the wood in the quadrennial harvest cycle was slightly (but statistically significantly) higher than that calculated for the annual harvest cycle. The highest HHV (19.87 GJ Mg^{-1} DM) in the entire study was determined for the wood obtained from quadrennial shoots of the *S. alba* UWM095, while the lowest was for *R. pseudoacacia* (19.33 GJ Mg^{-1} DM) in the quadrennial harvest cycle (Table 3). The results showed a significant positive correlation between HHV and the carbon, lignin, and cellulose content, as presented in Table A4.

Table 2. Moisture content of wood for SRWC genotypes and harvest cycles (%).

Genotype	Harvest Cycle		Mean
	Annual	Quadrennial	
R. pseudoacacia	32.61 ± 1.13 m	30.6 ± 0.16 m	31.61 ± 0.68 H
P. nigra × *P. maximowiczii* Max-5	54.71 ± 0.39 abc	57.31 ± 0.11 a	56.01 ± 0.61 A
P. max. × *P. trich.* Hybryda275	53.67 ± 1.56 bc	53.37 ± 0.18 cd	53.52 ± 0.71 BC
P. max. × *P. trich.* Androscoggin	55.13 ± 1.25 abc	53.22 ± 0.30 cde	54.17 ± 0.72 AB
P. balsamifera UWM2	56.97 ± 0.99 ab	54.72 ± 0.08 abc	55.84 ± 0.67 A
P. balsamifera UWM3	54.58 ± 0.53 abc	55.43 ± 0.94 abc	55.00 ± 0.52 AB
S. alba UWM200	49.08 ± 0.29 ghi	49.41 ± 0.42 fghi	49.24 ± 0.24 DEF
S. alba UWM095	48.57 ± 0.60 hi	46.37 ± 0.13 ijk	47.47 ± 0.57 F
S. dasyclados UWM155	53.07 ± 0.36 cde	49.75 ± 0.37 efghi	51.41 ± 0.78 CD
S. fragilis UWM195	52.48 ± 0.39 cdefg	49.58 ± 0.48 fghi	51.03 ± 0.71 D
S. pentandra UWM035	44.04 ± 0.51 jkl	42.60 ± 0.16 l	43.32 ± 0.40 G
S. triandra UWM198	52.66 ± 0.79 cdef	43.87 ± 0.52 kl	48.27 ± 2.01 F
S. viminalis Żubr	49.99 ± 0.78 defgh	47.46 ± 0.03 hij	48.73 ± 0.66 EF
S. viminalis × *S. purpurea* UWM033	53.86 ± 0.54 abc	47.93 ± 0.19 hi	50.89 ± 1.35 DE
Mean	50.82 ± 0.95 X	48.69 ± 1.02 Y	49.75 ± 0.70

A, B, C, etc.—genotype homogeneous groups; X, Y—harvest cycle homogeneous groups; a, b, c, etc.—genotype × harvest cycle interaction homogeneous groups; ±—standard error of mean.

Table 3. Higher heating value of wood for SRWC genotypes and harvest cycles (GJ Mg^{-1} DM).

Genotype	Harvest Cycle		Mean
	Annual	Quadrennial	
R. pseudoacacia	19.38 ± 0.08 fg	19.33 ± 0.01 g	19.36 ± 0.04 F
P. nigra × *P. maximowiczii* Max-5	19.84 ± 0.06 abc	19.86 ± 0.05 a	19.85 ± 0.04 A
P. max. × *P. trich.* Hybryda275	19.48 ± 0.05 defg	19.37 ± 0.02 fg	19.43 ± 0.03 EF
P. max. × *P. trich.* Androscoggin	19.55 ± 0.04 cdefg	19.46 ± 0.02 defg	19.50 ± 0.03 CDEF
P. balsamifera UWM2	19.54 ± 0.10 cdefg	19.60 ± 0.01 abcdef	19.57 ± 0.05 CDE
P. balsamifera UWM3	19.50 ± 0.08 defg	19.78 ± 0.02 abcd	19.64 ± 0.07 BCD
S. alba UWM200	19.55 ± 0.09 bcdef	19.50 ± 0.03 defg	19.53 ± 0.04 CDE
S. alba UWM095	19.51 ± 0.06 defg	19.87 ± 0.01 a	19.69 ± 0.09 ABC
S. dasyclados UWM155	19.38 ± 0.08 fg	19.58 ± 0.01 abcdef	19.48 ± 0.06 DEF
S. fragilis UWM195	19.47 ± 0.04 defg	19.61 ± 0.01 abcdef	19.54 ± 0.04 CDE
S. pentandra UWM035	19.87 ± 0.06 a	19.75 ± 0.02 abcde	19.81 ± 0.04 AB
S. triandra UWM198	19.35 ± 0.04 g	19.53 ± 0.01 defg	19.44 ± 0.04 EF
S. viminalis Żubr	19.52 ± 0.07 defg	19.67 ± 0.02 abcdef	19.59 ± 0.05 CDE
S. viminalis × *S. purpurea* UWM033	19.34 ± 0.16 g	19.67 ± 0.01 abcdef	19.50 ± 0.10 CDEF
Mean	19.52 ± 0.03 Y	19.61 ± 0.03 X	19.57 ± 0.02

A, B, C, etc.—genotype homogeneous groups; X, Y—harvest cycle homogeneous groups; a, b, c, etc.—genotype × harvest cycle interaction homogeneous groups; ±—standard error of mean.

The significantly highest mean ash content (0.69% DM) was found for the *R. pseudoacacia* wood, homogeneous group "A" (Table 4). The intermediate group "AB" included the wood of two poplar genotypes and two willow ones, and the value of this attribute was lower by 3–4%. The wood of *S. alba* UWM095 had a significantly lower ash content of 0.52% DM, which was 24% lower than *R. pseudoacacia*. The ash content of the wood was significantly affected by the plant harvest cycle. As the harvest cycle became longer, the ash content decreased. Throughout the experiment, the highest ash content (0.81% DM) was found in the wood of annual shoots of *R. pseudoacacia*, homogeneous group "a". On the other hand, the lowest values of the attribute (0.48% DM) were determined in the wood of quadrennial shoots of *S. pentandra* UWM035.

Table 4. Ash content in wood for SRWC genotypes and harvest cycles (% DM).

Genotype	Harvest Cycle		Mean
	Annual	Quadrennial	
R. pseudoacacia	0.81 ± 0.04 a	0.57 ± 0.01 efghijk	0.69 ± 0.06 A
P. nigra × *P. maximowiczii* Max-5	0.73 ± 0.02 ab	0.61 ± 0.02 cdefghi	0.67 ± 0.03 AB
P. max. × *P. trich.* Hybryda275	0.62 ± 0.03 bcdefg	0.49 ± 0.01 ijk	0.56 ± 0.03 CDE
P. max. × *P. trich.* Androscoggin	0.64 ± 0.02 bcdefg	0.51 ± 0.02 hijk	0.57 ± 0.03 CDE
P. balsamifera UWM2	0.65 ± 0.02 bcdef	0.59 ± 0.01 defghij	0.62 ± 0.02 ABC
P. balsamifera UWM3	0.65 ± 0.02 bcdef	0.69 ± 0.01 bcde	0.67 ± 0.01 AB
S. alba UWM200	0.64 ± 0.02 bcdefg	0.58 ± 0.01 efghijk	0.61 ± 0.02 BCD
S. alba UWM095	0.55 ± 0.01 fghijk	0.49 ± 0.01 jk	0.52 ± 0.01 E
S. dasyclados UWM155	0.56 ± 0.02 fghijk	0.52 ± 0.01 ghijk	0.54 ± 0.01 DE
S. fragilis UWM195	0.63 ± 0.03 bcdefg	0.57 ± 0.01 fghijk	0.60 ± 0.02 BCD
S. pentandra UWM035	0.64 ± 0.02 bcdefg	0.48 ± 0.01 k	0.56 ± 0.04 CDE
S. triandra UWM198	0.70 ± 0.03 abcd	0.63 ± 0.02 bcdefg	0.67 ± 0.02 AB
S. viminalis Żubr	0.64 ± 0.04 bcdefg	0.58 ± 0.01 efghijk	0.61 ± 0.02 BCD
S. viminalis × *S. purpurea* UWM033	0.71 ± 0.05 abc	0.60 ± 0.02 cdefghi	0.66 ± 0.03 AB
Mean	0.65 ± 0.01 X	0.56 ± 0.01 Y	0.61 ± 0.01

A, B, C, etc.—genotype homogeneous groups; X, Y—harvest cycle homogeneous groups; a, b, c, etc.—genotype × harvest cycle interaction homogeneous groups; ±—standard error of mean.

The significantly highest mean fixed carbon content (19.96% DM) and the lowest volatile matter content (79.37% DM) were determined for the wood of *R. pseudoacacia* from homogeneous groups "A" and "D", respectively (Tables A5 and A6). Further, it was the opposite for the *S. triandra* UWM198 genotype, as the mean fixed carbon content was the lowest (17.67% DM), and the volatile matter was the highest (81.70% DM). The fixed carbon content ranged from 17.67 to 20.01% DM throughout the experiment (Table A5). The volatile matter content ranged from 79.22 to 81.70% DM (Table A6).

3.3. Elemental Composition of SRWC Wood

The content of C, N, Cl, and S elements in SRWC wood was significantly affected by the SRWC genotype, plant harvest cycle, and their interaction. Specifically, the C, N, and Cl contents were differentiated by both factors, while the S content was only affected by the main factors. The harvest cycle, on the other hand, only significantly differentiated the H content (Table 1). The mean carbon content of the genotypes under study lay within a narrow range between 55.03% DM for the Androscoggin poplar and 55.96% DM for *P. balsamifera* UWM3, and homogeneous groups "A" and "B", respectively (Table 5). The wood harvested in the quadrennial cycle contained significantly more carbon (55.86% DM) compared with its annual harvest, although the difference was only 0.7 pp. During the experiment, the wood of quadrennial shoots of *P. balsamifera* UWM3, homogeneous group "a", had the highest carbon content of 56.65% DM. On the other hand, the wood of annual shoots of *R. pseudoacacia*, the homogeneous group "g", had the lowest carbon content of 54.36% DM.

The hydrogen content of the wood of all the genotypes exceeded 6% DM and ranged from 6.34 to 6.54% DM (Table A7). Wood harvested in the annual cycle contained slightly yet significantly more hydrogen (6.47% DM) compared with its quadrennial harvest. The wood of *R. pseudoacacia* contained the highest N level (0.38% DM), group "A" (Table 6). The second homogeneous group, "B", included wood of the poplar Max5, and its content of this element was lower by approx. 23% compared with *R. pseudoacacia*. The lowest mean N content (0.17% DM) was found in the wood *S. pentandra* UWM035, which was lower by approx. 57% compared with *R. pseudoacacia*. The mean N content of the wood obtained in the annual cycle (0.30% DM) was higher by 46% compared with its quadrennial cycle. Throughout the experiment, the highest nitrogen content (0.45% DM) was found in the wood of annual shoots of *R. pseudoacacia*, homogeneous group "a". On the other hand, the lowest values of nitrogen content (0.12% DM) were determined in the wood of quadrennial shoots of three willow genotypes: *S. pentandra*, *S. triandra*, and *S. viminalis*, homogeneous group "k". The nitrogen content was significantly and positively correlated with the fixed carbon, ash, sulfur, soluble substance, and hemicellulose content (Table A4).

Table 5. Carbon content in wood for SRWC genotypes and harvest cycles (% DM).

Genotype	Harvest Cycle		Mean
	Annual	Quadrennial	
R. pseudoacacia	54.36 ± 0.21 g	56.10 ± 0.09 abcd	55.23 ± 0.40 AB
P. nigra × *P. maximowiczii* Max-5	55.56 ± 0.09 abcdef	56.26 ± 0.09 ab	55.91 ± 0.17 A
P. max. × *P. trich.* Hybryda275	55.11 ± 0.12 cdefg	55.37 ± 0.05 bcdefg	55.24 ± 0.08 AB
P. max. × *P. trich.* Androscoggin	55.42 ± 0.23 bcdefg	54.65 ± 0.01 fg	55.03 ± 0.20 B
P. balsamifera UWM2	54.84 ± 0.30 efg	56.14 ± 0.05 ab	55.49 ± 0.32 AB
P. balsamifera UWM3	55.28 ± 0.38 cdefg	56.65 ± 0.13 a	55.96 ± 0.35 A
S. alba UWM200	55.22 ± 0.13 cdefg	56.55 ± 0.09 ab	55.88 ± 0.31 A
S. alba UWM095	55.59 ± 0.22 abcdef	56.25 ± 0.12 ab	55.92 ± 0.18 A
S. dasyclados UWM155	55.37 ± 0.29 bcdefg	56.16 ± 0.15 ab	55.76 ± 0.23 AB
S. fragilis UWM195	54.87 ± 0.45 efg	55.54 ± 0.23 abcdefg	55.20 ± 0.27 AB
S. pentandra UWM035	55.91 ± 0.19 abcde	55.61 ± 0.06 abcdef	55.76 ± 0.11 AB
S. triandra UWM198	54.76 ± 0.40 efg	55.46 ± 0.12 abcdefg	55.11 ± 0.24 B
S. viminalis Żubr	54.89 ± 0.18 defg	55.59 ± 0.14 abcdef	55.24 ± 0.19 AB
S. viminalis × *S. purpurea* UWM033	55.05 ± 0.45 cdefg	55.69 ± 0.22 abcdef	55.37 ± 0.27 AB
Mean	55.16 ± 0.09 Y	55.86 ± 0.09 X	55.51 ± 0.07

A, B—genotype homogeneous groups; X, Y—harvest cycle homogeneous groups; a, b, c, etc.—genotype × harvest cycle interaction homogeneous groups; ±—standard error of mean.

Table 6. Nitrogen content in wood for SRWC genotypes and harvest cycles (% DM).

Genotype	Harvest Cycle		Mean
	Annual	Quadrennial	
R. pseudoacacia	0.45 ± 0.01 a	0.31 ± 0.01 cd	0.38 ± 0.03 A
P. nigra × *P. maximowiczii* Max-5	0.43 ± 0.01 ab	0.16 ± 0.02 ijk	0.29 ± 0.06 B
P. max. × *P. trich.* Hybryda275	0.29 ± 0.02 de	0.17 ± 0.01 hijk	0.23 ± 0.03 CDE
P. max. × *P. trich.* Androscoggin	0.29 ± 0.03 de	0.18 ± 0.01 hijk	0.24 ± 0.03 CDE
P. balsamifera UWM2	0.32 ± 0.01 cd	0.13 ± 0,01 jk	0.23 ± 0.04 CDE
P. balsamifera UWM3	0.38 ± 0.02 bc	0.16 ± 0.02 ijk	0.27 ± 0.05 BC
S. alba UWM200	0.24 ± 0.01 efgh	0.19 ± 0.02 ghij	0.21 ± 0.01 DEF
S. alba UWM095	0.31 ± 0.01 cd	0.20 ± 0.02 fghi	0.26 ± 0.03 BCD
S. dasyclados UWM155	0.29 ± 0.02 de	0.16 ± 0.01 ijk	0.23 ± 0.03 CDE
S. fragilis UWM195	0.26 ± 0.03 def	0.14 ± 0.02 ijk	0.20 ± 0.03 EFG
S. pentandra UWM035	0.21 ± 0.01 fghi	0.12 ± 0.02 k	0.17 ± 0.02 G
S. triandra UWM198	0.26 ± 0.03 def	0.12 ± 0.01 k	0.19 ± 0.03 EFG
S. viminalis Żubr	0.23 ± 0.01 efgh	0.12 ± 0.01 k	0.18 ± 0.03 FG
S. viminalis × *S. purpurea* UWM033	0.26 ± 0.01 def	0.13 ± 0.01 jk	0.19 ± 0.03 EFG
Mean	0.30 ± 0.01 X	0.16 ± 0.01 Y	0.23 ± 0.01

A, B, C, etc.—genotype homogeneous groups; X, Y—harvest cycle homogeneous groups; a, b, c, etc.—genotype × harvest cycle interaction homogeneous groups; ±—standard error of mean.

The wood of *R. pseudoacacia* also contained the significantly largest amount of sulfur (0.033% DM), homogeneous group "A" (Table 7). The second group "B" included the wood of *P. balsamifera* UWM3, and its sulfur level was lower by approx. 20% compared with *R. pseudoacacia*. Further, the lowest S content (0.020% DM) was found in the wood of *S. pentandra* UWM035 and three hybrid poplar genotypes in the homogeneous group "D". The other genotypes were grouped together in the intermediate homogeneous groups. The mean sulfur content of wood obtained during the annual harvest cycle was 0.027% dry matter, which was significantly higher (by 23%) compared to the quadrennial cycle. Throughout the experiment, the wood of annual shoots of *R. pseudoacacia* had the highest sulfur content (0.038% dry matter), while the lowest values of this attribute (0.013% dry matter) were found in the wood of quadrennial shoots of the Max5 poplar. The sulfur content was significantly and positively correlated with the ash, nitrogen, soluble substance, and hemicellulose content (Table A4).

Table 7. Sulfur content in wood for SRWC genotypes and harvest cycles (% DM).

Genotype	Harvest Cycle		Mean
	Annual	Quadrennial	
R. pseudoacacia	0.038 ± 0.002	0.029 ± 0.001	0.033 ± 0.002 A
P. nigra × *P. maximowiczii* Max-5	0.026 ± 0.001	0.013 ± 0.001	0.020 ± 0.003 D
P. max. × *P. trich.* Hybryda275	0.024 ± 0.002	0.016 ± 0.002	0.020 ± 0.002 D
P. max. × *P. trich.* Androscoggin	0.023 ± 0.001	0.017 ± 0.001	0.020 ± 0.001 D
P. balsamifera UWM2	0.025 ± 0.001	0.017 ± 0.001	0.021 ± 0.002 CD
P. balsamifera UWM3	0.029 ± 0.002	0.025 ± 0.001	0.027 ± 0.001 B
S. alba UWM200	0.029 ± 0.001	0.023 ± 0.001	0.026 ± 0.002 BC
S. alba UWM095	0.026 ± 0.001	0.024 ± 0.002	0.025 ± 0.001 BCD
S. dasyclados UWM155	0.026 ± 0.001	0.023 ± 0.001	0.024 ± 0.001 BCD
S. fragilis UWM195	0.025 ± 0.003	0.021 ± 0.002	0.023 ± 0.002 BCD
S. pentandra UWM035	0.025 ± 0.004	0.015 ± 0.001	0.020 ± 0.003 D
S. triandra UWM198	0.028 ± 0.006	0.024 ± 0.001	0.026 ± 0.003 BC
S. viminalis Żubr	0.026 ± 0.002	0.024 ± 0.001	0.025 ± 0.001 BCD
S. viminalis × *S. purpurea* UWM033	0.027 ± 0.003	0.020 ± 0.001	0.024 ± 0.002 BCD
Mean	0.027 ± 0.001 X	0.021 ± 0.001 Y	0.024 ± 0.001

A, B, C, etc.—genotype homogeneous groups; X, Y—harvest cycle homogeneous groups; no letter indicates no significant differences, ±—standard error of mean.

The highest mean chlorine content (0.019% DM) was found in the wood of two willow genotypes: *S. fragilis* UWM195 and *S. viminalis* × *S. purpurea* UWM033, group "A" (Table A8). The wood of *P. balsamifera* UWM2, which belonged to the homogeneous group "C", had the lowest Cl content (0.013% DM) among all the species tested. The other genotypes were grouped in intermediate homogeneous groups. The mean Cl content of the wood obtained in the annual harvest cycle (0.017% DM) was significantly higher (by 8%) than the content obtained in the quadrennial cycle. The highest Cl content throughout the experiment (0.020% DM) was found in the wood of annual shoots of *S. triandra* and *S. viminalis* × *S. purpurea*. On the other hand, the lowest values of the attribute (0.012% DM) were found in the wood of annual shoots of *P. balsamifera* UWM2.

3.4. Lignocellulosic Composition of SRWC Wood

The SRWC genotype, plant harvest cycle, and their interaction significantly differentiated cold and hot water extracts, other soluble substances, and the hemicellulose, cellulose, and lignin content (Table 1). *P. balsamifera* UWM3 had the highest cold water extract content (4.62% DM) among all the woods (Table A9). The wood of *R. pseudoacacia* belonged to the second homogeneous group, "B". On the other hand, the wood of *S. pentandra* UWM035 had the lowest cold water extract content (2.54% DM). The amount of cold water extract content in wood is affected by the plant harvest cycle. As the harvest cycle becomes longer, the content decreases by approximately 41%. The wood from annual shoots of *P. balsamifera* UWM3 had the highest cold water extract content (5.73% DM), while the wood from quadrennial shoots of willow, cultivar Żubr, had the lowest (1.44% DM).

The significantly highest hot water extract content (7.80% DM) was found in the wood of *R. pseudoacacia* (Table A10). The second homogeneous group, "B", included the wood of *P. balsamifera* UWM2. The lowest hot water extract content (4.73% DM) was found in the wood of *P. max.* × *P. trich.* Androscoggin. The plant harvest cycle also significantly affected the hot water extract content of the wood. As the harvest cycle became longer, there was an approximate 30% decrease in the cold water extract content. The wood from annual shoots of *P. balsamifera* UWM3 had the highest cold water extract content, which was 9.42% DM.

On the other hand, the wood of quadrennial shoots of *P. max.* × *P. trich.* Androscoggin had the lowest cold water extract content, which was 3.69% DM.

The wood of *S. fragilis* UWM195 had the highest content of other soluble substances (6.39% DM) compared to other woods (Table A11). However, the wood of willow, cultivar Żubr, had the lowest level of other soluble substances (3.53% DM). The content of other soluble substances in wood was also affected by the plant harvest cycle. As the harvest cycle became longer, the content decreased by approximately 15%. The wood from annual shoots of *S. fragilis* UWM195 had the highest content of other soluble substances (7.48% DM), while the wood of annual shoots of willow, cultivar Żubr, had the lowest content (3.35% DM).

The significantly highest mean hemicellulose content (27.30% DM) was found in the *R. pseudoacacia* wood (Table 8). The second group, "B", included the wood of *P. balsamifera* UWM2, and the biopolymer content of it was lower by approx. 6% compared with *R. pseudoacacia*. In this study, it was found that the wood of two willow genotypes, *S. pentandra* UWM035 and *S. alba* UWM095, belonging to the homogeneous group "I", had the lowest hemicellulose content, which was 25% less than the highest content. The mean hemicellulose content of wood obtained in the annual harvest cycle was 24.77% DM, which was significantly higher (by 14%) than that of the quadrennial harvest cycle. The significantly highest hemicellulose content throughout the experiment (28.32% DM) was found in the *R. pseudoacacia* wood from annual shoots, and the lowest (18.45% DM) was in the *S. pentandra* UWM 035 wood from quadrennial shoots. The ash, nitrogen, hot water extract, and cold water extract contents showed a significant positive correlation with the hemicellulose content (Table A4).

Table 8. Hemicellulose content in wood for SRWC genotypes and harvest cycles (% DM).

Genotype	Harvest Cycle		Mean
	Annual	Quadrennial	
R. pseudoacacia	28.32 ± 0.20 a	26.27 ± 0.09 cd	27.30 ± 0.47 A
P. nigra × *P. maximowiczii* Max-5	24.62 ± 0.29 ef	19.80 ± 0.05 l	22.21 ± 1.09 G
P. max. × *P. trich.* Hybryda275	27.10 ± 0.05 bc	22.48 ± 0.11 hi	24.79 ± 1.03 C
P. max. × *P. trich.* Androscoggin	26.90 ± 0.24 bc	21.47 ± 0.21 jk	24.18 ± 1.22 D
P. balsamifera UWM2	27.36 ± 0.09 b	23.94 ± 0.01 fg	25.65 ± 0.76 B
P. balsamifera UWM3	25.43 ± 0.08 de	20.94 ± 0.14 k	23.18 ± 1.01 E
S. alba UWM200	23.71 ± 0.26 fg	19.29 ± 0.13 lm	21.50 ± 1.01 H
S. alba UWM095	21.88 ± 0.13 ij	19.07 ± 0.14 lm	20.47 ± 0.63 I
S. dasyclados UWM155	24.51 ± 0.07 ef	22.07 ± 0.40 ij	23.29 ± 0.57 E
S. fragilis UWM195	23.42 ± 0.02 g	19.01 ± 0.14 lm	21.21 ± 0.99 H
S. pentandra UWM035	22.41 ± 0.13 hi	18.45 ± 0.26 m	20.43 ± 0.90 I
S. triandra UWM198	23.20 ± 0.06 gh	21.23 ± 0.12 jk	22.22 ± 0.44 G
S. viminalis Żubr	24.11 ± 0.04 fg	21.69 ± 0.14 ijk	22.90 ± 0.54 EF
S. viminalis × *S. purpurea* UWM033	23.88 ± 0.19 fg	20.85 ± 0.20 k	22.36 ± 0.69 FG
Mean	24.77 ± 0.30 X	21.18 ± 0.32 Y	22.98 ± 0.29

A, B, C, etc.—genotype homogeneous groups; X, Y—harvest cycle homogeneous groups; a, b, c, etc.—genotype × harvest cycle interaction homogeneous groups; ±—standard error of mean.

The wood of *S. pentandra* UWM035 had the highest mean cellulose content (52.81% DM) (Table 9). This biopolymer content also exceeded 52% DM in three other willow genotypes. However, the cellulose content of poplar wood ranged from 49.24 to 50.85% DM for *P. nigra* × *P. maximowiczii* Max5 and Hybryda275 poplar. Further, the lowest cellulose content (45.26% DM) was found in the *R. pseudoacacia* wood, homogeneous group "I", which meant that it was lower by 14% than the highest mean value for *S. pentandra* UWM035. The mean cellulose content of wood obtained in the quadrennial harvest cycle (53.71% DM) was higher (by 11%) compared with its annual harvest cycle. The significantly highest cellulose content throughout the experiment (56.97% DM) was found in the wood of the quadrennial shoots of willow *S. triandra* UWM198, and the lowest (43.69% DM) was in the wood of the annual shoots of *R. pseudoacacia*.

Table 9. Cellulose content in wood for SRWC genotypes and harvest cycles (% DM).

Genotype	Harvest Cycle		Mean
	Annual	Quadrennial	
R. pseudoacacia	43.69 ± 0.03 l	46.83 ± 0.06 j	45.26 ± 0.7 G
P. nigra × *P. maximowiczii* Max-5	45.16 ± 0.22 k	53.32 ± 0.02 ef	49.24 ± 1.83 F
P. max. × *P. trich.* Hybryda275	48.08 ± 0.20 i	53.62 ± 0.18 de	50.85 ± 1.24 E
P. max. × *P. trich.* Androscoggin	47.74 ± 0.19 i	53.53 ± 0.10 de	50.63 ± 1.30 E
P. balsamifera UWM2	45.23 ± 0.16 k	54.25 ± 0.09 cd	49.74 ± 2.02 F
P. balsamifera UWM3	46.38 ± 0.01 j	52.96 ± 0.15 ef	49.67 ± 1.47 F
S. alba UWM200	50.58 ± 0.13 g	53.27 ± 0.21 ef	51.93 ± 0.61 CD
S. alba UWM095	48.51 ± 0.12 i	52.64 ± 0.21 f	50.58 ± 0.93 E
S. dasyclados UWM155	49.76 ± 0.14 gh	54.80 ± 0.15 bc	52.28 ± 1.13 ABC
S. fragilis UWM195	46.00 ± 0.21 jk	54.64 ± 0.27 bc	50.32 ± 1.94 E
S. pentandra UWM035	50.60 ± 0.03 g	55.03 ± 0.17 bc	52.81 ± 0.99 A
S. triandra UWM198	46.01 ± 0.14 jk	56.97 ± 0.09 a	51.49 ± 2.45 D
S. viminalis Żubr	50.18 ± 0.15 gh	55.26 ± 0.01 b	52.72 ± 1.14 AB
S. viminalis × *S. purpurea* UWM033	49.57 ± 0.05 h	54.80 ± 0.3 bc	52.18 ± 1.18 BC
Mean	47.68 ± 0.34 Y	53.71 ± 0.35 X	50.69 ± 0.41

A, B, C, etc.—genotype homogeneous groups; X, Y—harvest cycle homogeneous groups; a, b, c, etc.—genotype × harvest cycle interaction homogeneous groups; ±—standard error of mean.

The significantly highest mean lignin content (17.86% DM) was found in the wood of poplar *P. nigra* × *P. maximowiczii* Max5 (Table 10). The lignin content was significantly lower in the other poplar genotypes, and it was the significantly lowest in the wood of *P. balsamifera* UWM2—13.44% DM, homogeneous group "I". The lignin content of the wood of willow genotypes lay within the range of 14.07 to 17.12% DM for *S. triandra* UWM198 and *S. alba* UWM200, respectively. The wood of *R. pseudoacacia* had a lignin content of nearly 15% DM. The quadrennial harvest cycle produced wood with a mean lignin content of 15.88% DM, which was 3% higher than that of the annual cycle. The significantly highest lignin content throughout the experiment (18.33% DM) was found in the wood from quadrennial shoots of poplar, genotype Max5, and the lowest (13.04% DM) was in the wood from quadrennial shoots of *P. balsamifera* UWM2. The lignin content was correlated significantly positively with HHV as well as fixed and elemental carbon content (Table A4).

Table 10. Lignin content in wood for SRWC genotypes and harvest cycles (% DM).

Genotype	Harvest Cycle		Mean
	Annual	Quadrennial	
R. pseudoacacia	14.23 ± 0.13 klmn	15.73 ± 0.07 efg	14.98 ± 0.34 FG
P. nigra × *P. maximowiczii* Max-5	17.39 ± 0.25 b	18.33 ± 0.13 a	17.86 ± 0.24 A
P. max. × *P. trich.* Hybryda275	15.22 ± 0.02 ghij	16.05 ± 0.13 def	15.64 ± 0.20 E
P. max. × *P. trich.* Androscoggin	15.20 ± 0.10 ghij	17.42 ± 0.09 b	16.31 ± 0.50 CD
P. balsamifera UWM2	13.84 ± 0.14 lmno	13.04 ± 0.12 o	13.44 ± 0.20 I
P. balsamifera UWM3	13.77 ± 0.01 mno	15.50 ± 0.10 ghi	14.64 ± 0.39 G
S. alba UWM200	17.02 ± 0.16 bc	17.21 ± 0.24 bc	17.12 ± 0.14 B
S. alba UWM095	16.50 ± 0.29 cde	16.79 ± 0.07 bcd	16.64 ± 0.15 BC
S. dasyclados UWM155	14.60 ± 0.15 jklm	14.60 ± 0.15 jklm	14.60 ± 0.09 GH
S. fragilis UWM195	14.95 ± 0.12 hijk	16.02 ± 0.19 def	15.49 ± 0.26 EF
S. pentandra UWM035	17.17 ± 0.11 bc	17.04 ± 0.17 bc	17.10 ± 0.10 B
S. triandra UWM198	14.69 ± 0.10 ijkl	13.46 ± 0.13 no	14.07 ± 0.28 H
S. viminalis Żubr	15.71 ± 0.29 efg	15.21 ± 0.07 ghij	15.46 ± 0.17 EF
S. viminalis × *S. purpurea* UWM033	15.90 ± 0.15 ef	15.95 ± 0.25 def	15.93 ± 0.13 DE
Mean	15.44 ± 0.19 Y	15.88 ± 0.23 X	15.66 ± 0.15

A, B, C, etc.—genotype homogeneous groups; X, Y—harvest cycle homogeneous groups; a, b, c, etc.—genotype × harvest cycle interaction homogeneous groups; ±—standard error of mean.

3.5. General Characteristics of SRWC Wood

Table 11 presents statistics for the data on wood characteristics for all of the 14 SRWC genotypes harvested in the two harvest cycles. These results show the lowest variation (coefficient of variation < 5%) for the following attributes: VM (0.8%), HHV (0.9%), C (1.2%), H (1.4%), and FC (3.4%). The mean values for these parameters were the following: 80.46% DM, 19.57 GJ Mg^{-1} DM, 50.51% DM, 6.45% DM, and 18.96% DM. The variation of cellulose and lignin content was also low (coefficient of variation < 10%), given the fact that the experiment dealt with the wood of several different SRWC genotypes in two different harvest cycles. The range (minimum–maximum) within which those practically important attributes lay was large: 43.6–57.1% DM for cellulose and 12.8–18.5% DM for lignin. The mean values for these attributes were 50.7 and 15.7% DM, respectively. The highest variability (40.3%) was observed for the N content, which ranged between 0.11 and 0.47% DM. High variability was also observed in cold water extracts (coefficient of variation 35.3%), dry wood yield (36.9%), and the energy value of wood (37.1%). The high variability of dry wood yield shows how important it is to select the right SRWC genotype and the right plant harvest cycle, as it is essential for achieving a satisfying dendromass yield, especially since the minimum dry wood yield was barely 2.7 Mg ha^{-1} y^{-1}, and the maximum was 13.1 Mg ha^{-1} y^{-1}. In consequence, the energy value of wood was highly diverse and ranged from 52.5 to 256.8 GJ ha^{-1} y^{-1}.

Table 11. Selected statistical analysis indicators for all features of the SRWC wood (N Valid = 84).

Feature	Mean	Minimum Value	Maximum Value	Lower Quartile	Upper Quartile	Standard Deviation	Coefficient of Variation (%)
Dry wood yield (Mg ha^{-1} y^{-1} DM)	6.73	2.69	13.06	4.93	8.54	2.48	36.89
Dry wood energy value (GJ ha^{-1} y^{-1})	131.83	52.52	256.85	97.57	166.92	48.87	37.07
Coal equivalent (Mg ha^{-1} y^{-1})	5.27	2.10	10.27	3.90	6.68	1.95	37.07
Moisture content (%)	49.75	30.43	58.77	47.53	54.05	6.45	12.96
Higher heating value (MJ kg^{-1} DM)	19.57	19.08	19.97	19.44	19.69	0.18	0.94
Ash content (% DM)	0.61	0.47	0.86	0.57	0.65	0.08	13.52
Fixed carbon (% DM)	18.96	17.63	20.39	18.50	19.33	0.65	3.43
Volatile matter (% DM)	80.46	79.04	81.81	80.06	80.94	0.67	0.83
C (% DM)	55.51	53.98	56.87	55.16	56.00	0.66	1.19
H (% DM)	6.45	6.30	6.70	6.37	6.50	0.09	1.41
N (% DM)	0.23	0.11	0.47	0.16	0.31	0.09	40.29
S (% DM)	0.024	0.012	0.041	0.020	0.027	0.006	23.68
Cl (% DM)	0.017	0.010	0.023	0.014	0.019	0.003	17.35
Cold water extracts (% DM)	3.31	1.25	5.82	2.33	4.13	1.17	35.33
Hot water extracts (% DM)	6.16	3.62	9.76	4.87	7.30	1.67	27.10
Other soluble substances (% DM)	4.51	3.27	7.50	3.86	5.03	0.98	21.73
Hemicellulose (% DM)	22.98	17.98	28.67	21.14	24.55	2.69	11.72
Cellulose (% DM)	50.69	43.64	57.12	47.17	54.01	3.76	7.42
Lignin (% DM)	15.66	12.82	18.54	14.71	16.78	1.35	8.62

A cluster analysis based on the values of all the attributes of the wood from the 14 SRWC genotypes harvested in two different harvest cycles at the cut-off point of 2/3 D_{max} allowed grouping them into four main clusters (Figure 3a). *R. pseudoacacia* made its own cluster. Two genotypes of poplar *P. balsamifera,* UWM2 and UWM3, made a second cluster. Two genotypes of willow, *S. fragilis* UWM195 and *S. triandra* UWM198, made a third cluster. The remaining three genotypes of poplar and six genotypes of willow made a fourth joint cluster. When the analysis accuracy increased, nine clusters were identified at 1/3 D_{max}. The first three clusters remained unchanged, as with the cut-off at 2/3 D_{max}. The fourth cluster was broken down into six smaller ones. The four genotypes *P. nigra* × *P. maximowiczii* Max5, *S. alba* UWM095, *S. pentandra* UWM035, and *S. viminalis* cultivar Żubr made four independent clusters. The other two poplar hybrids and *S. dasyclados* UWM155 made another cluster. The last cluster included two further willow genotypes: *S. alba* UWM200 and *S. viminalis* × *S. purpurea* UWM033. In addition, the analysis of SRWC wood characteristics revealed the presence of two distinct clusters when the cut-off was set at 2/3 D_{max} (as shown in Figure 3b). One of these clusters contained eight attributes, namely ash, sulfur, nitrogen, fixed carbon content, cold water extracts, hot water extracts, other soluble substances, and hemicellulose. A second cluster included the other 11 analyzed parameters: dry wood yield, energy value of wood yield, coal equivalent, moisture, HHV, volatile matter content, C, H, Cl, cellulose, and lignin. When the analysis accuracy increased, five clusters were identified at 1/3 D_{max}.

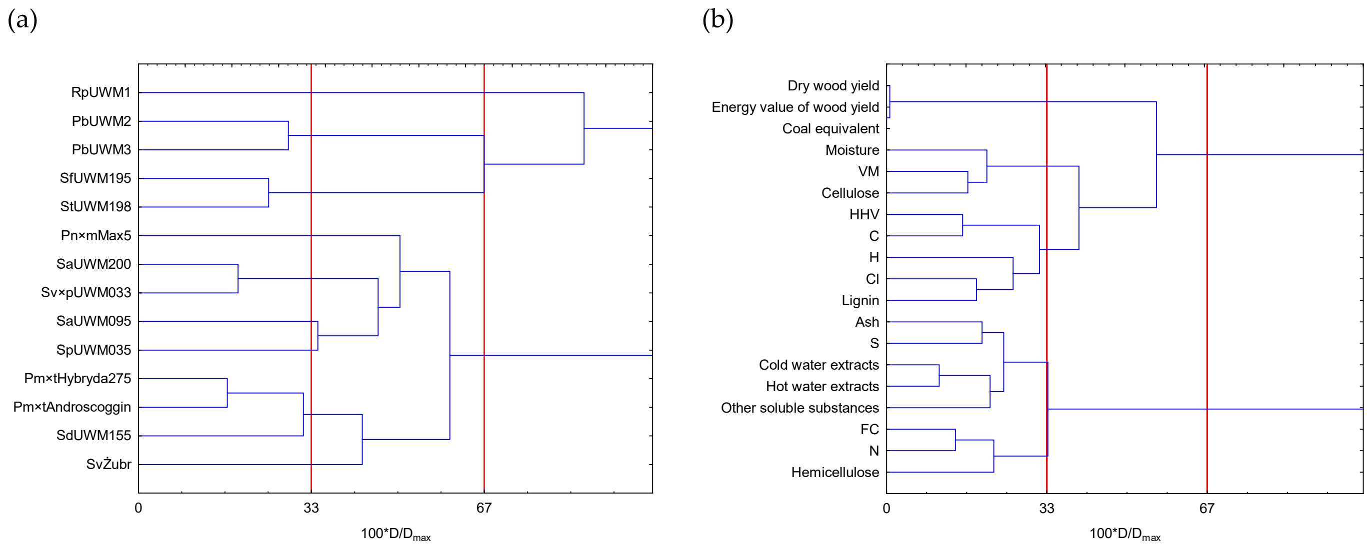

Figure 3. Dendrogram of a hierarchical cluster analysis showing the similarities of SRWC genotypes (**a**) and their wood characteristics (**b**). The red vertical line marks the Sneath criterion (2/3 D_{max}) and (1/3 D_{max}). D—linage distance; D_{max}—maximum linage distance. *Robinia pseudoacacia* (RpUWM1); *P. nigra* × *P. maximowiczii* Max-5 (Pn × mMax5); *P. maximowiczii* × *P. trichocarpa* Hybryda275 (Pm × tHybryda275); *P. maximowiczii* × *P. trichocarpa*, Androscoggin (Pm × tAndroscoggin); *P. balsamifera* UWM2 (PbUWM2); *P. balsamifera* UWM3 (PbUWM3); *S. alba* UWM200 (SaUWM200); *S. alba* UWM095 (SaUWM095); *S. dasyclados* UWM155 (SdUWM155); *S. fragilis* UWM195 (SfUWM195); *S. pentandra* UWM035 (SpUWM035); *S. triandra* UWM198 (StUWM198); *S. viminalis* × *S. purpurea* UWM033 (Sv × pUWM033); *S. viminalis* cultivar Żubr (SvŻubr).

4. Discussion

4.1. Wood Yield and Its Energy Value

Wood is the major component of SRWC shoot lignocellulosic biomass, whose share can vary depending on many factors, including species, genotype, and harvest cycle. The dry wood content of the dry biomass yield, obtained from an annual cycle in the current experiment, was 62.8% DM, and ranged from 52.0 to 72.8% DM for *P. nigra* × *P. maximowiczii* Henry Max-5 and *S. triandra* UWM198, respectively. These values were higher in the quadrennial harvest cycle, with the mean wood content being 79.3% DM and ranging from 73.5 to 84.8% DM for *P. balsamifera* UWM3 and *S. triandra* UWM198, respectively. The wood content of annual willow shoots, in another study, was 71.9% DM, and ranged from 62.3 to 74.9% DM [36]. This means that these levels were close to those found in the current study. Therefore, one should note that when bark is obtained from SRWC shoots, large amounts of pure wood are left as residues after shoot debarking, which can be used in a variety of ways in biorefineries, the paper industry, or for energy generation. Obviously, the wood yield in the current experiment was strongly determined by the genotype and harvest cycle. Nevertheless, it was high in the case of most genotypes, especially in the quadrennial harvest cycle, with a mean level of 8.3 Mg ha^{-1} y^{-1} DM, ranging from nearly 5 to over 12 Mg ha^{-1} y^{-1} DM, for *R. pseudoacacia* and *S. viminalis* cultivar Żubr, respectively. For the annual harvest cycle, the values ranged from 3 to nearly 9 Mg ha^{-1} y^{-1} DM for these genotypes. Moreover, the willow genotypes gave a higher yield in the annual harvest cycle than the poplar or *R. pseudoacacia* genotypes. However, the difference in the wood yield between willow and poplar was not so great in the longer harvest cycle. In the quadrennial cycle, the highest yield may have been given by *S. viminalis*, cultivar Żubr, but the yield from *P. max.* × *P. trich.* Hybryda275 was practically the same. A high yield from annual willow shoots was also found in a different study [36]. The highest wood yield (over 9 Mg ha^{-1} y^{-1} DM) in that experiment was for *S. purpurea* × *S. daphnoides* hybrids. The dry biomass yield of *S. alba* and *S. viminalis* was high (over 13 Mg ha^{-1} y^{-1} DM) [37], whereas for *S. dasyclados* it was 11 Mg ha^{-1} y^{-1} DM [38]. If the wood content of those annual shoots was taken to be approx. 63%, its yield would be 7–8 Mg ha^{-1} y^{-1} DM. The biomass yield from poplar, willow, and black locust from three quadrennial consecutive harvest cycles, depending on the various soil enriching options, was 9.1, 8.5, and 4.8 Mg ha^{-1} y^{-1} DM [8]. If the wood content of those quadrennial SRWC shoots was taken to be approx. 79%, its yield would be 7.2, 6.7, and 3.8 Mg ha^{-1} y^{-1} DM, respectively. With a similar assumption of the wood content of the SRWC biomass, the wood yield from four clones of *P. balsamifera* from two quadrennial harvest cycles would be 5.5 Mg ha^{-1} y^{-1} DM, with it being significantly higher in the second harvest cycle—8.0 Mg ha^{-1} y^{-1} DM [39]. Therefore, the cited potential levels of the wood yield were similar to those in the current study for the poplar genotypes of the same species. Further, other data show that the potential wood yield from various poplar species harvested in various cycles would be approx. 12–15 Mg ha^{-1} y^{-1} DM [40]; 9–14 Mg ha^{-1} y^{-1} DM [41,42]. Lower levels of a potential poplar wood yield (4–8 Mg ha^{-1} y^{-1} DM) were achieved in different studies [7,43]. In North America, the potential wood yield of different willow species harvested in different cycles varied within a range of 8 to 11 Mg ha^{-1} y^{-1} DM [44–46], and within a potentially wide range of 2 to 18 Mg ha^{-1} y^{-1} DM in Europe [47–49]. The potential wood yield from black locust would range from 2 to 8 Mg ha^{-1} y^{-1} DM [50–53]. Therefore, although the SRWC wood yield obtained in this study was not the highest, it was satisfactory and comparable to the literature reports.

The energy value of SRWC wood, as determined in this study, is primarily dependent on the wood yield. This is why the energy value ranges from 53 to 244 GJ ha^{-1} y^{-1} for *P. balsamifera* UWM3 in the annual harvest cycle and *S. viminalis*, cultivar Żubr, in the quadrennial harvest cycle. In general, higher values were found for all the SRWC genotypes in the quadrennial (mean: 162 GJ ha^{-1} y^{-1}) than in the annual cycle (102 GJ ha^{-1} y^{-1}). The energy value of willow wood in annual cycles was 136 GJ ha^{-1} y^{-1} and ranged from 93 to 200 GJ ha^{-1} y^{-1} depending on the genotype [36]. The cited range was close to that found in this study for willow genotypes harvested in the annual cycles (96 to 173 GJ ha^{-1} y^{-1}). These values apply to the energy value of wood alone (without bark), which is why they should be regarded as satisfactory and high. The research in this regard usually provides the energy value of the whole SRWC biomass (wood + bark). This shows that when biomass is harvested as an energy feedstock, it is obtained as a whole, without being separated into fractions, i.e., bark and wood. For example, the whole poplar, willow, and black locust biomass energy values from three consecutive quadrennial harvest cycles were 142, 137, and 81 GJ ha^{-1} y^{-1}, respectively [8]. If the wood content of biomass of the four-year SRWC shoots was taken to be 79%, then its potential energy value would be 112 GJ ha^{-1} y^{-1} for poplar, 108 GJ ha^{-1} y^{-1} for willow, and 64 GJ ha^{-1} y^{-1} for black locust. Considering this percentage share of wood in poplar biomass, the energy value of the four clones of *P. balsamifera* in two quadrennial harvest cycles would be 91 GJ ha^{-1} y^{-1}, and it would be 135 GJ ha^{-1} y^{-1} in the second harvest cycle [39]. Assuming similar wood content, poplar biomass in a quadrennial cycle has an energy value nearly half as low [54]. Further, a potentially higher wood energy value (202–213 GJ ha^{-1} y^{-1}) was achieved by growing poplar in various harvest cycles, with fertilization and watering [55,56]. A high energy value of black locust biomass (190 GJ ha^{-1} y^{-1}), which would be equivalent to approx. 150 GJ ha^{-1} y^{-1} of the energy value of wood alone, was achieved in the six-year harvest cycle [57]. This would be potentially twice as high compared with the mean value for *R. pseudoacacia* in our experiment. The significant variations in energy values of SRWC wood and the entire biomass (wood + bark) are due to several factors, such as the selection of species and genotypes, the harvest cycle, soil and climate conditions, and the agrotechnical procedures used in the production process. These factors affect the biomass yield and the energy stored in it.

4.2. SRWC Wood Characteristics

Considering SRWC wood as a potential energy feedstock, one should note its thermophysical characteristics and elemental composition. The moisture content is a basic parameter that immediately impacts the calorific value. In general, *R. pseudoacacia* contained the significantly lowest amounts of moisture (a mean of 31.6%) compared with willow (a mean of 48.8%) and poplar, which contained the highest amounts of moisture (a mean of 54.9%). The moisture content of the whole biomass (wood + bark), as measured in a different study in three consecutive quadrennial harvest cycles (depending on various soil enrichment options), was also the significantly lowest (a mean of 38.9%) [58]. The willow and poplar biomass moisture content was also higher (49.8% and 56.5%, respectively). A lower moisture content (approx. 40%) of *R. pseudoacacia* was also found in a different study [59], compared with willow biomass (approx. 50%) [60,61] and poplar (50–60%) [39,40,62].

Therefore, the low moisture content of black locust wood was a positive characteristic. However, this wood's characteristics were worse in terms of the content of sulfur (0.033% DM), nitrogen (0.38% DM), and ash (0.69% DM) compared with the values for poplar and willow wood, for which these values were lower. It should be emphasized that nitrogen and sulfur in solid biofuel are not desirable, as they cause higher NOx and SO_2 emissions during combustion, and the ash can cause technological problems. Low levels of sulfur (0.031% DM), nitrogen (0.32% DM), and ash (0.59% DM) were also found in the wood of ten genotypes of willow harvested in annual cycles [36]. However, the nitrogen and sulfur content of willow was even lower in this study. Moreover, willow wood contained the lowest levels of nitrogen and ash in this study. The biomass of willow exhibited the lowest ash content with 1.25% dry matter, and the values were higher by 12% and 34%, respectively, for black locust and poplar in a different study in which the whole biomass (wood + bark) was analyzed [58]. These ash content levels were much higher compared with those in pure wood, as determined in whole SRWC biomass (wood + bark). The bark is known to contain more ash than wood, not only in SRWC but also in forest dendromass [63]. The ash content of biomass can vary considerably (1–3% DM), depending on the genotype and soil [62,64,65]. It is similar to poplar (0.98–3.12% DM) [40,61,62] and black locust (0.17–3.3% DM) [66]. Despite the large fluctuations in SRWC biomass ash content, it is typically lower than that of straw, semi-woody, or palm kernel shell biomass [67,68]. It is important to note that less ash in solid biofuel is more energy-efficient. However, different installations (e.g., depending on power output and technology used) have different expectations regarding ash content. For example, for small automatic pellet-fueled boilers (up to 10–30 kW) that generate heat for single-family homes, the ash content is expected to be below 1% DM. On the other hand, in the ISO standard for wood pellets of the highest class A1, the ash content should be $\leq$0.7% DM, and in class A2 it should be $\leq$1.2% DM. However, larger local woodchip-fueled installations have a considerably higher tolerance for ash content. For the use of woody biomass for energy purposes under Polish conditions, when ordering woodchip supplies, the ash content is expected to be below 3% DM and sometimes below 5% DM. Thus, the results of the present study showed that the debarked wood of all SRWC genotypes met the highest expectations in terms of ash content.

The lignocellulosic composition of SRWC wood should be noted when analyzing its potential usability as a raw material for integrated biorefineries or for the paper industry. Cellulose is widely used, and its highest level in this study was found in willow wood (51.8% DM), followed by poplar (50.0% DM), and the lowest levels of this biopolymer were found in wood of *R. pseudoacacia* (45.3% DM). Moreover, it was found in other studies [16] that willow wood contained higher levels of cellulose (56.0% DM) compared with poplar (51.0% DM) and black locust (52.0% DM). This biopolymer content of the SRWC species, as reported in that study, was higher by several pp compared with the mean values determined in this study, and this was particularly visible in *R. pseudoacacia*. Moreover, the cellulose content of pure SRWC wood was higher by several pp compared with its content of whole biomass (wood + bark). This is also reflected in the cellulose content of triennial willow shoots, whose mean level was 44.4% DM [69]. A study by Przybysz et al. [70] found that 'Hybryda275' poplar had a higher cellulose content (52.4% DM) in older wood, which is consistent with the levels found in this study for this genotype during the quadrennial harvest cycle. Quite diverse, but also often very high cellulose content (54–59%) and low lignin content (17–22%) in willow biomass were reported by Baker et al. [71]. A similar lignin content (16–22%) in S. *viminalis* biomass was also determined by Gao et al. [72]. In contrast, a significantly higher lignin content (27–32% DM) in SRWC biomass was found in studies conducted in Northern Ireland and Canada [73]. However, in the present study, SRWC wood was characterized by significantly lower lignin contents. Of these, willow wood had the highest average lignin content, but it averaged only 15.8% DM, and its lowest amounts (15.0% DM) were found in wood of *R. pseudoacacia*. Lignin content was also determined, where a higher level was found in the wood of black locust (17.0% DM) than in willow (16.3% DM) and the highest in poplar wood (18.3% DM) [16]. Moreover, those values were higher by several pp than those determined in this study. A similar lignin content (18.0% DM) was found in the wood of the Hybryda275 poplar [70]. It was much higher in triennial willow shoots (25% DM) [69]. The *R. pseudoacacia* wood analyzed in the current study contained the highest mean level of hemicellulose (27.3% DM), and its lowest amounts (21.8% DM) were found in the wood of the willow genotypes. In a separate study conducted by Stolarski et al. [16], hemicellulose content was analyzed in various types of wood. The cited study found that black locust had the highest hemicellulose content (23.5% DM) compared to poplar (20.1% DM) and willow (19.2% DM). However, these values were still lower than the hemicellulose content found in the wood analyzed in the current study. The hemicellulose content of pure SRWC wood, as determined in that study, was higher by several pp compared with its content of whole biomass (wood + bark). A higher hemicellulose content (over 26% DM) was found in triennial willow biomass [69], as well as in poplar [70]. This value was similar to the annual harvest cycle of black locust, certain poplar genotypes, and some willow genotypes in the current study.

Both this study and the literature reports on SRWC biomass yield and quality show that most of the species and genotypes under study can find diverse applications because of varied amounts and quality of the biofeedstock (wood, bark, or wood and bark together) and because of the requirements and expectations of a specific industry branch. Willow biomass, including mainly *S. viminalis* genotypes harvested in longer (e.g., quadrennial) harvest cycles, seems to be an interesting feedstock for the energy industry because of the biomass quality, yield, and energy value. Meanwhile, the bark of *P. balsamifera* UWM2 proved to be an interesting source of bioactive substances, containing their highest total concentration [26]. The current study has shown that willow and poplar wood could be interesting for the energy and paper industry and integrated biorefineries because of their high cellulose content. The black locust contained the highest hemicellulose level, but the wood yield from this genotype was much lower than from most willow and poplar genotypes. However, it should also be noted that the choice of debarked wood as feedstock may also depend on the processing techniques employed. Different genotypes may respond differently to conversion processes such as combustion, pyrolysis, or gasification.

5. Conclusions

The current study has found that the wood yield and its energy value were significantly influenced by the genotype, even within the same SRWC genus. The harvest cycle also played an important role, with longer cycles resulting in higher values for these parameters. The *Salix* genus had the highest dry wood yield and energy value, with *S. viminalis*, cultivar Żubr, producing the most in both the annual and quadrennial harvest cycles. The best effect for genus *Populus* was achieved for *P. maximowiczii* × *P. trichocarpa* Hybryda275, and it was particularly marked in the quadrennial harvest cycle. The poorest results were determined for *R. pseudoacacia.* When it comes to the energy-related characteristics, those of *R. pseudoacacia* included the significantly lowest moisture content, which was a positive attribute, but, on the other hand, it had some adverse characteristics—the highest levels of nitrogen, sulfur, and ash. More beneficial properties in this respect were determined for willow and poplar wood. Moreover, willow and poplar wood contained more cellulose compared with black locust. However, it is important to conduct more research in order to assess the economic and environmental viability of producing bioenergy and different bioproducts using SRWC wood, bark, or a combination of both as feedstock. This will provide a complete evaluation of the practical usability of these materials for various purposes. It is also worth noting that the production of SRWC biomass in a quadrennial harvest cycle can be challenging for farmers, as the waiting time for the first revenues from this type of production is much longer compared with the production of annual crops. Therefore, in order to make this kind of SRWC biomass production viable, long-term contracts must be signed between farmers and bioenergy facilities that use this solid biofuel for energy purposes. Such contracts serve as a guarantee for the farmer that their investment in SRWC biomass production will bring the intended benefits. Additionally, bioenergy facilities would have a stable supply of good-quality energy feedstock.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Dry wood yield for SRWC genotypes and harvest cycles (Mg ha^{-1} y^{-1} DM).

Genotype	Harvest Cycle		Mean
	Annual	Quadrennial	
R. pseudoacacia	2.90 ± 0.06 mn	4.82 ± 0.38 hijklm	3.86 ± 0.46 J
P. nigra × *P. maximowiczii* Max-5	4.61 ± 0.33 ijklmn	8.46 ± 0.60 cdefg	6.53 ± 0.91 DEF
P. max. × *P. trich.* Hybryda275	5.80 ± 0.14 ghijk	11.15 ± 0.78 ab	8.48 ± 1.25 B
P. max. × *P. trich.* Androscoggin	4.46 ± 0.04 jklmn	9.13 ± 0.30 cd	6.79 ± 1.05 DE
P. balsamifera UWM2	3.15 ± 0.07 lmn	7.01 ± 0.38 efghi	5.08 ± 0.88 HIJ
P. balsamifera UWM3	2.74 ± 0.04 n	5.68 ± 0.39 ghijk	4.21 ± 0.68 IJ
S. alba UWM200	5.03 ± 0.32 hijkl	6.29 ± 0.02 ghijk	5.66 ± 0.32 EFG
S. alba UWM095	6.53 ± 0.28 fghij	10.21 ± 0.55 bc	8.37 ± 0.87 B
S. dasyclados UWM155	5.40 ± 0.35 hijk	7.47 ± 0.29 defgh	6.44 ± 0.51 DEF
S. fragilis UWM195	6.74 ± 0.35 fghij	9.62 ± 0.47 bc	8.18 ± 0.69 BC
S. pentandra UWM035	5.35 ± 0.42 hijk	8.76 ± 0.17 cde	7.06 ± 0.79 CD
S. triandra UWM198	6.53 ± 0.14 fghij	8.63 ± 0.33 cdef	7.58 ± 0.50 BCD
S. viminalis Żubr	8.89 ± 0.45 cde	12.42 ± 0.34 a	10.65 ± 0.83 A
S. viminalis × *S. purpurea* UWM033	4.98 ± 0.12 hijkl	5.79 ± 0.43 ghijk	5.38 ± 0.27 GHI
Mean	5.22 ± 0.26 Y	8.25 ± 0.34 X	6.73 ± 0.27

A, B, C, etc.—genotype homogeneous groups; X, Y—harvest cycle homogeneous groups; a, b, c, etc.—genotype × harvest cycle interaction homogeneous groups; ±—standard error of mean.

Table A2. Dry wood energy value for SRWC genotypes and harvest cycles (GJ ha^{-1} y^{-1}).

Genotype	Harvest Cycle		Mean
	Annual	Quadrennial	
R. pseudoacacia	56.19 ± 1.25 no	93.19 ± 7.31 jklmn	74.69 ± 8.91 I
P. nigra × *P. maximowiczii* Max-5	91.41 ± 6.50 klmno	167.97 ± 11.87 cdef	129.69 ± 18.16 DE
P. max. × *P. trich.* Hybryda275	113.06 ± 2.71 hijkl	216.05 ± 15.20 ab	164.56 ± 24.04 B
P. max. × *P. trich.* Androscoggin	87.11 ± 0.79 lmno	177.59 ± 5.88 bcd	132.35 ± 20.41 DE
P. balsamifera UWM2	61.54 ± 1.37 mno	137.37 ± 7.47 efgh	99.46 ± 17.29 GH
P. balsamifera UWM3	53.38 ± 0.80 o	112.33 ± 7.79 hijkl	82.85 ± 13.64 HI
S. alba UWM200	98.28 ± 6.29 jklm	122.69 ± 0.34 hijkl	110.49 ± 6.14 EFG
S. alba UWM095	127.28 ± 5.52 hijk	202.88 ± 11.03 bc	165.08 ± 17.78 B
S. dasyclados UWM155	104.75 ± 6.83 ijkl	146.26 ± 5.74 defg	125.51 ± 10.10 DEF
S. fragilis UWM195	131.28 ± 6.84 ghji	188.57 ± 9.26 bc	159.92 ± 13.81 BC
S. pentandra UWM035	106.32 ± 8.29 ijkl	172.99 ± 3.39 cde	139.65 ± 15.44 CD
S. triandra UWM198	126.37 ± 2.71 hijk	168.60 ± 6.45 cdef	147.48 ± 9.95 BCD
S. viminalis Żubr	173.43 ± 8.82 cde	244.34 ± 6.78 a	208.88 ± 16.62 A
S. viminalis × *S. purpurea* UWM033	96.22 ± 2.39 jklm	113.89 ± 8.55 hijkl	105.06 ± 5.6 FGH
Mean	101.9 ± 5.04 Y	161.77 ± 6.78 X	131.83 ± 5.33

A, B, C, etc.—genotype homogeneous groups; X, Y—harvest cycle homogeneous groups; a, b, c, etc.—genotype × harvest cycle interaction homogeneous groups; ±—standard error of mean.

Table A3. Coal equivalent of wood energy value for SRWC genotypes and harvest cycles (Mg ha^{-1} y^{-1}).

Genotype	Harvest Cycle		Mean
	Annual	Quadrennial	
R. pseudoacacia	2.25 ± 0.05	3.73 ± 0.29	2.99 ± 0.36
P. nigra × *P. maximowiczii* Max-5	3.66 ± 0.26	6.72 ± 0.47	5.19 ± 0.73
P. max. × *P. trich.* Hybryda275	4.52 ± 0.11	8.64 ± 0.61	6.58 ± 0.96
P. max. × *P. trich.* Androscoggin	3.48 ± 0.03	7.10 ± 0.24	5.29 ± 0.82
P. balsamifera UWM2	2.46 ± 0.05	5.49 ± 0.30	3.98 ± 0.69
P. balsamifera UWM3	2.14 ± 0.03	4.49 ± 0.31	3.31 ± 0.55
S. alba UWM200	3.93 ± 0.25	4.91 ± 0.01	4.42 ± 0.25
S. alba UWM095	5.09 ± 0.22	8.12 ± 0.44	6.60 ± 0.71
S. dasyclados UWM155	4.19 ± 0.27	5.85 ± 0.23	5.02 ± 0.40
S. fragilis UWM195	5.25 ± 0.27	7.54 ± 0.37	6.40 ± 0.55
S. pentandra UWM035	4.25 ± 0.33	6.92 ± 0.14	5.59 ± 0.62
S. triandra UWM198	5.05 ± 0.11	6.74 ± 0.26	5.90 ± 0.40
S. viminalis Żubr	6.94 ± 0.35	9.77 ± 0.27	8.36 ± 0.66
S. viminalis × *S. purpurea* UWM033	3.85 ± 0.10	4.56 ± 0.34	4.20 ± 0.22
Mean	4.08 ± 0.2	6.47 ± 0.27	5.27 ± 0.21

Table A4. The Pearson correlation coefficients for the analyzed features in the SRWC wood.

Item	Dry Wood Yield	Dry Wood Energy Value	Coal Equivalent	Moisture	HHV	Ash	FC	VM	C	H	N	S	Cl	Cold Water Extracts	Hot Water Extracts	Other Soluble Substances	Hemicellulose	Cellulose	Lignin
Dry wood yield	1.00	1.00 *	1.00 *	0.03	0.20	−0.57 *	−0.38 *	0.41 *	0.18	−0.09	−0.70 *	−0.55 *	0.06	−0.72 *	−0.61 *	−0.21	−0.65 *	0.70 *	0.24 *
Dry wood energy value		1.00	1.00 *	0.03	0.22 *	−0.57 *	−0.37 *	0.41 *	0.19	−0.10	−0.70 *	−0.55 *	0.06	−0.73 *	−0.61 *	−0.21	−0.66 *	0.71 *	0.25 *
Coal equivalent			1.00	0.03	0.22 *	−0.57 *	−0.37 *	0.41 *	0.19	−0.10	−0.70 *	−0.55 *	0.06	−0.73 *	−0.61 *	−0.21	−0.66 *	0.71 *	0.25 *
Moisture				1.00	0.11	0.01	−0.19	0.20	−0.01	0.03	−0.10	−0.36 *	−0.03	0.13	−0.05	0.07	−0.05	0.04	0.00
HHV					1.00	−0.09	0.03	0.04	0.49 *	−0.13	−0.26 *	−0.28 *	−0.24 *	−0.34 *	−0.26 *	−0.08	−0.45 *	0.32 *	0.41 *
Ash						1.00	0.33 *	−0.39 *	−0.24 *	−0.14	0.54 *	0.51 *	0.17	0.52 *	0.48 *	0.28 *	0.52 *	−0.57 *	−0.26 *
FC							1.00	−0.96 *	0.02	−0.02	0.57 *	0.22 *	0.17	0.36 *	0.38 *	0.14	0.32 *	−0.53 *	0.27 *
VM								1.00	0.00	0.05	−0.55 *	−0.25 *	−0.24 *	−0.39 *	−0.39 *	−0.17	−0.35 *	0.54 *	−0.20
C									1.00	−0.05	−0.43 *	−0.40 *	−0.20	−0.28 *	−0.33 *	−0.20	−0.48 *	0.46 *	0.23 *
H										1.00	0.12	0.18	0.01	0.09	0.08	−0.08	0.07	−0.13	0.18
N											1.00	0.69 *	0.05	0.78 *	0.76 *	0.35 *	0.75 *	−0.91 *	−0.14
S												1.00	0.05	0.55 *	0.58 *	0.29 *	0.54 *	−0.62 *	−0.27 *
Cl													1.00	−0.02	0.05	0.20	−0.02	−0.13	0.19
Cold water extracts														1.00	0.89 *	0.48 *	0.66 *	−0.85 *	−0.39 *
Hot water extracts															1.00	0.59 *	0.53 *	−0.85 *	−0.35 *
Other soluble substances																1.00	0.02	−0.51 *	−0.08
Hemicellulose																	1.00	−0.78 *	−0.50 *
Cellulose																		1.00	0.18
Lignin																			1.00

* Significant values ($p < 0.05$).

Table A5. Fixed carbon content in wood for SRWC genotypes and harvest cycles (% DM).

Genotype	Harvest Cycle		Mean
	Annual	**Quadrennial**	
R. pseudoacacia	20.01 ± 0.07 a	19.91 ± 0.28 ab	19.96 ± 0.13 A
P. nigra × *P. maximowiczii* Max-5	19.92 ± 0.27 ab	19.89 ± 0.03 ab	19.90 ± 0.12 A
P. max. × *P. trich.* Hybryda275	19.22 ± 0.17 abcde	17.96 ± 0.15 fg	18.59 ± 0.30 CDE
P. max. × *P. trich.* Androscoggin	19.13 ± 0.23 abcde	18.54 ± 0.01 cdefg	18.84 ± 0.17 BCDE
P. balsamifera UWM2	18.98 ± 0.29 abcdef	18.39 ± 0.05 defg	18.68 ± 0.19 BCDE
P. balsamifera UWM3	18.89 ± 0.15 bcdef	18.48 ± 0.05 cdefg	18.68 ± 0.12 BCDE
S. alba UWM200	18.74 ± 0.08 cdefg	19.14 ± 0.03 abcde	18.94 ± 0.10 BCD
S. alba UWM095	19.54 ± 0.38 abc	19.02 ± 0.21 abcdef	19.28 ± 0.23 AB
S. dasyclados UWM155	19.38 ± 0.44 abcd	18.34 ± 0.04 defg	18.86 ± 0.30 BCDE
S. fragilis UWM195	18.69 ± 0.23 cdefg	18.22 ± 0.15 efg	18.46 ± 0.16 DE
S. pentandra UWM035	18.50 ± 0.37 cdefg	19.17 ± 0.07 abcde	18.84 ± 0.23 BCDE
S. triandra UWM198	18.80 ± 0.21 cdef	17.67 ± 0.02 g	18.24 ± 0.27 D
S. viminalis Żubr	19.19 ± 0.11 abcde	18.68 ± 0.03 cdefg	18.94 ± 0.13 BCD
S. viminalis × *S. purpurea* UWM033	19.49 ± 0.16 abc	18.85 ± 0.08 bcdef	19.17 ± 0.16 BC
Mean	19.18 ± 0.09 X	18.73 ± 0.10 Y	18.96 ± 0.07

A, B, C, etc.—genotype homogeneous groups; X, Y—harvest cycle homogeneous groups; a, b, c, etc.—genotype × harvest cycle interaction homogeneous groups; ±—standard error of mean.

Table A6. Volatile matter content in wood for SRWC genotypes and harvest cycles (% DM).

Genotype	Harvest Cycle		Mean
	Annual	**Quadrennial**	
R. pseudoacacia	79.22 ± 0.06 h	79.52 ± 0.28 efgh	79.37 ± 0.14 D
P. nigra × *P. maximowiczii* Max-5	79.92 ± 0.52 defgh	79.50 ± 0.01 gh	79.71 ± 0.25 CD
P. max. × *P. trich.* Hybryda275	80.16 ± 0.20 cdefgh	81.55 ± 0.15 ab	80.85 ± 0.33 AB
P. max. × *P. trich.* Androscoggin	80.23 ± 0.25 cdefgh	80.95 ± 0.01 abcdef	80.59 ± 0.20 AB
P. balsamifera UWM2	80.37 ± 0.30 bcdefgh	81.02 ± 0.05 abcde	80.70 ± 0.20 AB
P. balsamifera UWM3	80.46 ± 0.14 bcdefgh	80.84 ± 0.06 abcdef	80.65 ± 0.11 AB
S. alba UWM200	80.65 ± 0.10 abcdefg	80.28 ± 0.03 cdefgh	80.47 ± 0.10 ABC
S. alba UWM095	79.91 ± 0.38 defgh	80.49 ± 0.21 abcdefg	80.20 ± 0.23 BC
S. dasyclados UWM155	80.06 ± 0.46 cdefgh	81.14 ± 0.04 abcd	80.60 ± 0.32 AB
S. fragilis UWM195	80.67 ± 0.24 abcdefg	81.21 ± 0.15 abc	80.94 ± 0.18 AB
S. pentandra UWM035	80.86 ± 0.39 abcdef	80.35 ± 0.07 bcdefgh	80.61 ± 0.21 AB
S. triandra UWM198	80.50 ± 0.24 abcdefg	81.70 ± 0.02 a	81.10 ± 0.29 A
S. viminalis Żubr	80.17 ± 0.15 cdefgh	80.74 ± 0.03 abcdefg	80.45 ± 0.14 ABC
S. viminalis × *S. purpurea* UWM033	79.80 ± 0.19 efgh	80.55 ± 0.08 abcdefg	80.17 ± 0.19 BC
Mean	80.21 ± 0.09 Y	80.70 ± 0.10 X	80.46 ± 0.07

A, B, C, etc.—genotype homogeneous groups; X, Y—harvest cycle homogeneous groups; a, b, c, etc.—genotype × harvest cycle interaction homogeneous groups; ±—standard error of mean.

Table A7. Hydrogen content in wood for SRWC genotypes and harvest cycles (% DM).

Genotype	Harvest Cycle		Mean
	Annual	**Quadrennial**	
R. pseudoacacia	6.42 ± 0.04	6.44 ± 0.01	6.43 ± 0.02
P. nigra × *P. maximowiczii* Max-5	6.37 ± 0.06	6.40 ± 0.02	6.39 ± 0.03
P. max. × *P. trich.* Hybryda275	6.41 ± 0.03	6.54 ± 0.02	6.48 ± 0.03
P. max. × *P. trich.* Androscoggin	6.44 ± 0.04	6.51 ± 0.01	6.47 ± 0.02
P. balsamifera UWM2	6.47 ± 0.01	6.36 ± 0.01	6.41 ± 0.03
P. balsamifera UWM3	6.51 ± 0.10	6.34 ± 0.01	6.42 ± 0.06
S. alba UWM200	6.52 ± 0.10	6.49 ± 0.02	6.50 ± 0.04
S. alba UWM095	6.53 ± 0.03	6.52 ± 0.01	6.52 ± 0.01
S. dasyclados UWM155	6.52 ± 0.04	6.50 ± 0.02	6.51 ± 0.02
S. fragilis UWM195	6.41 ± 0.05	6.36 ± 0.02	6.38 ± 0.03
S. pentandra UWM035	6.57 ± 0.09	6.35 ± 0.03	6.46 ± 0.06
S. triandra UWM198	6.46 ± 0.04	6.34 ± 0.01	6.40 ± 0.03
S. viminalis Żubr	6.47 ± 0.04	6.42 ± 0.02	6.45 ± 0.02
S. viminalis × *S. purpurea* UWM033	6.54 ± 0.09	6.43 ± 0.01	6.48 ± 0.05
Mean	6.47 ± 0.02 X	6.43 ± 0.01 Y	6.45 ± 0.01

X, Y—harvest cycle homogeneous groups; no letter indicates no significant differences, ±—standard error of mean.

Table A8. Chlorine content in wood for SRWC genotypes and harvest cycles (% DM).

Genotype	Harvest Cycle		Mean
	Annual	Quadrennial	
R. pseudoacacia	0.017 ± 0.003 abc	0.016 ± 0.002 abc	0.017 ± 0.001 ABC
P. nigra × *P. maximowiczii* Max-5	0.015 ± 0.002 abc	0.019 ± 0.001 ab	0.017 ± 0.001 ABC
P. max. × *P. trich.* Hybryda275	0.018 ± 0.001 abc	0.016 ± 0.002 abc	0.017 ± 0.001 ABC
P. max. × *P. trich.* Androscoggin	0.018 ± 0.001 abc	0.014 ± 0.002 abc	0.016 ± 0.001 ABC
P. balsamifera UWM2	0.012 ± 0.001 c	0.014 ± 0.001 abc	0.013 ± 0.001 C
P. balsamifera UWM3	0.015 ± 0.002 abc	0.013 ± 0.001 bc	0.014 ± 0.001 BC
S. alba UWM200	0.018 ± 0.001 abc	0.018 ± 0.001 abc	0.018 ± 0.001 A
S. alba UWM095	0.017 ± 0.002 abc	0.015 ± 0.002 abc	0.016 ± 0.002 ABC
S. dasyclados UWM155	0.017 ± 0.001 abc	0.014 ± 0.002 abc	0.015 ± 0.001 ABC
S. fragilis UWM195	0.019 ± 0.001 ab	0.019 ± 0.001 abc	0.019 ± 0.001 A
S. pentandra UWM035	0.016 ± 0.001 abc	0.017 ± 0.001 abc	0.017 ± 0.001 ABC
S. triandra UWM198	0.020 ± 0.001 a	0.013 ± 0.002 bc	0.017 ± 0.002 ABC
S. viminalis Żubr	0.018 ± 0.002 abc	0.018 ± 0.001 abc	0.018 ± 0.001 AB
S. viminalis × *S. purpurea* UWM033	0.020 ± 0.001 a	0.018 ± 0.001 abc	0.019 ± 0.001 A
Mean	0.017 ± 0.001 X	0.016 ± 0.001 Y	0.017 ± 0.001

A, B, C—genotype homogeneous groups; X, Y—harvest cycle homogeneous groups; a, b, c—genotype × harvest cycle interaction homogeneous groups; ±—standard error of mean.

Table A9. Cold water extract content in wood for SRWC genotypes and harvest cycles (% DM).

Genotype	Harvest Cycle		Mean
	Annual	Quadrennial	
R. pseudoacacia	4.03 ± 0.24 cdef	4.04 ± 0.11 cdef	4.03 ± 0.12 B
P. nigra × *P. maximowiczii* Max-5	4.78 ± 0.14 bc	1.64 ± 0.07 mn	3.21 ± 0.71 DE
P. max. × *P. trich.* Hybryda275	3.79 ± 0.01 def	1.94 ± 0.23 lmn	2.86 ± 0.43 EF
P. max. × *P. trich.* Androscoggin	3.98 ± 0.01 cdef	1.92 ± 0.02 lmn	2.95 ± 0.46 EF
P. balsamifera UWM2	5.28 ± 0.17 ab	2.69 ± 0.17 ijkl	3.99 ± 0.59 BC
P. balsamifera UWM3	5.73 ± 0.05 a	3.51 ± 0.02 efgh	4.62 ± 0.50 A
S. alba UWM200	2.50 ± 0.04 ijkl	3.27 ± 0.01 fghi	2.89 ± 0.17 EF
S. alba UWM095	4.14 ± 0.13 cde	2.50 ± 0.12 ijkl	3.32 ± 0.38 DE
S. dasyclados UWM155	4.11 ± 0.09 cde	2.87 ± 0.07 hijk	3.49 ± 0.28 CD
S. fragilis UWM195	4.38 ± 0.04 cd	2.31 ± 0.06 jklm	3.34 ± 0.46 DE
S. pentandra UWM035	3.08 ± 0.03 ghij	2.00 ± 0.04 lmn	2.54 ± 0.24 F
S. triandra UWM198	4.77 ± 0.10 bc	2.24 ± 0.09 klmn	3.51 ± 0.57 CD
S. viminalis Żubr	3.81 ± 0.51 def	1.44 ± 0.12 n	2.62 ± 0.58 F
S. viminalis × *S. purpurea* UWM033	3.91 ± 0.08 def	1.98 ± 0.22 lmn	2.94 ± 0.45 EF
Mean	4.16 ± 0.13 X	2.45 ± 0.12 Y	3.31 ± 0.13

A, B, C, etc.—genotype homogeneous groups; X, Y—harvest cycle homogeneous groups; a, b, c, etc.—genotype × harvest cycle interaction homogeneous groups; ±—standard error of mean.

Table A10. Hot water extract content in wood for SRWC genotypes and harvest cycles (% DM).

Genotype	Harvest Cycle		Mean
	Annual	Quadrennial	
R. pseudoacacia	8.32 ± 0.22 bc	7.29 ± 0.06 de	7.80 ± 0.25 A
P. nigra × *P. maximowiczii* Max-5	8.04 ± 0.16 cd	4.11 ± 0.02 no	6.08 ± 0.88 DE
P. max. × *P. trich.* Hybryda275	5.46 ± 0.03 ijk	4.38 ± 0.05 mno	4.92 ± 0.24 GH
P. max. × *P. trich.* Androscoggin	5.78 ± 0.13 hij	3.69 ± 0.04 o	4.73 ± 0.47 H
P. balsamifera UWM2	9.04 ± 0.16 ab	5.38 ± 0.02 ijk	7.21 ± 0.82 B
P. balsamifera UWM3	9.42 ± 0.21 a	5.21 ± 0.11 klm	7.31 ± 0.95 AB
S. alba UWM200	4.93 ± 0.04 lmn	6.15 ± 0.21 ghi	5.54 ± 0.29 EF
S. alba UWM095	7.27 ± 0.12 def	6.43 ± 0.06 fgh	6.85 ± 0.20 BC
S. dasyclados UWM155	6.72 ± 0.34 efg	4.69 ± 0.44 lmn	5.70 ± 0.52 EF
S. fragilis UWM195	8.16 ± 0.09 c	5.02 ± 0.02 klm	6.59 ± 0.70 CD
S. pentandra UWM035	5.80 ± 0.08 hij	5.10 ± 0.17 klm	5.45 ± 0.18 FG
S. triandra UWM198	9.49 ± 0.11 a	4.62 ± 0.15 lmn	7.06 ± 1.09 BC
S. viminalis Żubr	6.65 ± 0.16 efg	4.11 ± 0.03 no	5.38 ± 0.57 FG
S. viminalis × *S. purpurea* UWM033	6.32 ± 0.01 gh	4.78 ± 0.05 lmn	5.55 ± 0.35 EF
Mean	7.24 ± 0.23 X	5.07 ± 0.15 Y	6.16 ± 0.18

A, B, C, etc.—genotype homogeneous groups; X, Y—harvest cycle homogeneous groups; a, b, c, etc.—genotype × harvest cycle interaction homogeneous groups; ±—standard error of mean.

Table A11. Other soluble substance content in wood for SRWC genotypes and harvest cycles (% DM).

Genotype	Harvest Cycle		Mean
	Annual	Quadrennial	
R. pseudoacacia	5.44 ± 0.12 cd	3.88 ± 0.02 ijklm	4.66 ± 0.35 C
P. nigra × *P. maximowiczii* Max-5	4.79 ± 0.01 efg	4.43 ± 0.05 gh	4.61 ± 0.08 C
P. max. × *P. trich.* Hybryda275	4.14 ± 0.10 hijk	3.47 ± 0.11 lmn	3.81 ± 0.17 EF
P. max. × *P. trich.* Androscoggin	4.38 ± 0.08 ghi	3.90 ± 0.02 ijklm	4.14 ± 0.11 D
P. balsamifera UWM2	4.52 ± 0.05 fgh	3.39 ± 0.02 mn	3.96 ± 0.25 DE
P. balsamifera UWM3	5.01 ± 0.11 def	5.39 ± 0.08 cd	5.20 ± 0.11 B
S. alba UWM200	3.76 ± 0.06 jklmn	4.06 ± 0.11 hijkl	3.91 ± 0.09 DE
S. alba UWM095	5.84 ± 0.16 c	5.07 ± 0.06 de	5.45 ± 0.19 B
S. dasyclados UWM155	4.41 ± 0.13 gh	3.84 ± 0.04 jklmn	4.12 ± 0.14 DE
S. fragilis UWM195	7.48 ± 0.01 a	5.30 ± 0.05 d	6.39 ± 0.49 A
S. pentandra UWM035	4.03 ± 0.03 hijkl	4.38 ± 0.10 ghi	4.21 ± 0.09 D
S. triandra UWM198	6.61 ± 0.19 b	3.71 ± 0.19 jklmn	5.16 ± 0.66 B
S. viminalis Żubr	3.35 ± 0.02 n	3.72 ± 0.09 jklmn	3.53 ± 0.09 F
S. viminalis × *S. purpurea* UWM033	4.33 ± 0.02 hgij	3.62 ± 0.11 klmn	3.98 ± 0.17 DE
Mean	4.86 ± 0.17 X	4.15 ± 0.10 Y	4.51 ± 0.11

A, B, C, etc.—genotype homogeneous groups; X, Y—harvest cycle homogeneous groups; a, b, c, etc.—genotype × harvest cycle interaction homogeneous groups; ±—standard error of mean.

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