Yield of Pulp, Dimensional Properties of Fibers, and Properties of Paper Produced from Fast Growing Trees and Grasses

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Paper is produced mainly from wood fibrous pulps, which has been increasingly replaced by pulps from fast growing plants due to limited wood resources. In this work, properties of cellulosic pulps produced by the sulfate method from four fast growing grasses, poplar cultivar 'Hybrid 275', and European larch, as well as pine and birch wood chips, were compared. In addition, the cellulosic pulp yield, dimensions of fibers contained in the pulps and mechanical and optical characteristics of paper sheets produced from the pulps were compared. The pulp yield of the poplar cultivar 'Hybrid 275' (51.6%) was almost 5% higher than birch pulp (47.0%). Moreover, all of the investigated tensile properties of paper made from 'Hybrid 275' pulp were higher than for paper produced from birch pulp. Fast growing grasses, despite lower pulp yield (34.0 to 47.1%), showed comparable tensile properties to birch. Therefore, these pulps are promising raw materials for papermaking.

Keywords: Format; Poplar cultivar 'Hybrid275'; European larch; Fast growing grasses; Papermaking

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INTRODUCTION

Paper is used in many branches of industry and almost every aspect of our daily lives. Global paper production has reached 400 MM tons annually. In the future (by 2050), paper production is expected to increase in the world to approximately 700 MM tons (low estimate) and 900 MM tons (high estimate) (Bajpai 2016). Currently paper is manufactured mostly from wood cellulosic pulps (Fornalski 2015). One ton of paper is produced from around 2.5 tons of wood. Because of the limited wood resources that have been increasingly used not only for papermaking but also for production of furniture, plywood and many other goods, it is necessary also to consider other sorts of fibrous biomass for paper manufacturing. One of most attractive renewable fiber resources is the biomass of fast-growing perennials and annual plants (Saikia *et al.* 1997; Boruszewski *et al.* 2017; Mirski *et al.* 2017).

Fast-growing trees such as eucalyptus (Almeida *et al.* 2007) and poplar hybrids (Christersson 2008) as well as fast growing grasses such as *Miscanthus giganteus*

(Milovanovic *et al.* 2012) are particularly promising plants for the paper industry. Production of paper commodities from these resources has been growing (Zalesny *et al.* 2011).

The annual global increase in the area of fast-growing high-yield plantations has reached 3 million hectares, which is a small share of total forest area (Del Lungo *et al.* 2006), since 30% of the land on the Earth is covered by forests and only 5% of that area are plantations. Those plantations are capable of supplying more than 800 MM tons of lignocellulosic biomass (Carle and Holmogren 2009). So far, the largest plantations have been established in China, USA, and India (West 2006).

Currently, a large portion of harvested wood is incinerated to produce energy. This biomass is derived mainly from natural forests and managed plantations of fast growing tree species (Del Lungo *et al.* 2006; Carle and Holmgren 2009). However, because of the regulations leading to reduction of energy production from forest resources, it has become necessary to search for novel sorts of fibrous plant biomass (Tilman *et al.* 2006; Arias *et al.* 2011). This biomass may be derived from plantations of perennial grasses (Muylle *et al.* 2015).

Particularly attractive are fast growing grasses adapted to the European moderate climate, such as tall wheatgrass, smooth bromegrass, tall fescue, and switchgrass. All these species are inexpensive sources of lignocellulosic biomass (Aase and Siddoway 1974; Kai-yun *et al.* 2015). Their seeding provides productive crops for a few or even more than 10 years (80 to 150 tons/ha) at relatively low costs (Coffey *et al.* 1997). Plantations of such plants may be located in areas that cannot be used for production of food because of ecological (*e.g.* soils that need recultivation) and economic reasons (*e.g.* class V - VI soils) (Martyniak and Żurek 2014).

Non-wood biomass such as grass biomass outperforms other materials, *e.g.* wood from forests, because it can be harvested every year and used for papermaking; this makes it possible to reduce the demand for wood and prevent devastation of forests (Leblois *et al.* 2017). Neither cultivation nor harvesting of grasses requires application of expensive machines that are necessary for cutting and chopping of trees.

The objective of this work was to assess the potential of two fast growing trees, poplar cultivar 'Hybrid 275' and European larch (*Larix decidua* Mill.), and four grasses, tall wheatgrass (*Agropyron elongatum* (Host). Beauv.), smooth brome (*Bromus inermis* Leyss.), tall fescue (*Festuca arundinacea* Schreb.), and switchgrass (*Panicum virgatum* L.) as materials for papermaking. Properties of pulps derived from these six plants were compared with properties of pulps obtained from three materials that are used in papermaking such as pine (*Pinus sylvestris* L.) wood, birch (*Betula pendula* Roth) wood and miscanthus (*Miscanthus giganteus* J. M. Greef & Deuter ex Hodk. & Renvoize) biomass.

The main aim of this work was to investigate susceptibility of investigated fast-growing grasses and trees for production of paper. Comprehensive analysis of pulp and paper properties is performed in order to verify if these raw materials can be a substitute for commonly used birch and pine wood used by pulp and paper industry.

EXPERIMENTAL

Raw Materials

The biomass of the grasses tested (*Miscanthus giganteus* J. M. Greef & Deuter ex Hodk. & Renvoize, *Agropyron elongatum* (Host). Beauv., *Festuca arundinacea* Schreb., *Bromus inermis* Leyss., and *Panicum virgatum* L.) were harvested using a reel lawn mower ALKO 5001 R-II (ALKO, Germany), in the generative (blooming) phase when the contents of cellulose and other fibrous polymers were the highest. The biomass was dried to the humidity of 10% and chopped to 1.5-2.0 cm chaff using a MTD 475 (Briggs & Stratton, Germany) petrol powered shredder, dedicated for disintegration of tree branches.

Woodchips of poplar cultivar 'Hybrid 275', European larch (*Larix decidua* Mill.), pine (*Pinus sylvestris* L.), and birch (*Betula pendula* Roth) were obtained from trunks with a diameter of around 25 cm. Material used in the tests was obtained from plantations managed by the State Forests National Forest Holding.

Before pulping, wood (poplar cultivar 'Hybrid 275', larch, pine, and birch) was manually debarked and deprived of knots. Wood logs were sawn using an electric Milwakee MD 304 saw (Milwakee Corp, Germany) to 25 mm slices and chopped manually to 25 x16 x 8 mm chips.

Chemical Composition of Raw Material

Raw materials were disintegrated in laboratory mill Retsch SM 100. Materials were screened through 0.63mm wire and retained on 0.5 mm wire using custom designed vibration screener (CBKO-Hydrolab, Poland) and then prepared lignocellulosic materials were subjected to analysis.

Analysis of chemical composition of raw materials included quantification of extractives, lignin, cellulose, hemicelluloses, and ash. The content of lignin was determined by a gravimetric method in compliance with the TAPPI T222 standard after the removal of extractives according to the TAPPI T204 standard. The content of holocellulose was determined according to the TAPPI T249 standard. Cellulose was quantified as alpha cellulose, according to the TAPPI T203 standard. The content of hemicelluloses was calculated as the difference between the holocellulose and cellulose contents. Ash content was determined by gravimetric method in compliance with TAPPI T211 standard. All these assays were performed in triplicate for each raw material.

Cellulosic Pulps

Cellulosic pulps were prepared as described by Modrzejewski *et al.* (1969). Pulping conditions were as follows: active alkali 26% (to b.d. lignocellulosic material), sulfidity 30%, liquid module 4.0 for wood and 10 for grasses, maximal digestion temperature 165 °C (for pine and European larch wood 172 °C), heating up-time 2 h, digestion time in maximal temperature 2 h, cooling time to ambient temperature 15 min. It should be noted that pulping conditions were optimized within the scope of our previous (unpublished) research activities. The pulps obtained were used to produce paper. Paper was also produced from the pulps subjected to refining to the freeness of 30°SR, to determine the impact of the latter process on paper characteristics.

Pulping was carried out using a 15 L laboratory heated digester PD-114 (Danex, Poland) with agitation (3 swings per minute, swinging angle of 60°). The temperature was controlled using a dedicated ESM-4950 driver governed by a computer program that enabled recording of the data.

Dry weight of all materials was determined before pulping. Wood samples (1000 g d.w.) were suspended in 4 dm^3 of alkaline sulfate solution and heated as described in Table 1. Grass biomass (500 g d.w.) was suspended in 5 dm^3 of alkaline sulfate solution and treated as described above.

At the end of cooking, the content of the digester was cooled with 240 dm^3 of cold water (to decrease the temperature), and a sample of residual base (0.5 dm^3) was withdrawn. Then the pulp was washed with 50 dm^3 of water and soaked overnight in 10 dm^3 of water to remove base residues. Then the fibrous biomass was disintegrated using a laboratory JAC SHPD28D propeller pulp disintegrator (Danex, Poland) at 10000 rpm, and screened using a PS-114 membrane screener (Danex, Poland) (0.2 mm gap). After screening, the pulps and shives were dried at room temperature (20 to 22 °C) for 48 h, and weighted to determine the yield of pulps and shives contents. The dry pulps were stored in hermetically closed vials before further experiments.

The pulps and samples of base residues from the digester were characterized. The pulps were characterized in terms of the yield from the digester, the yield after screening, the contents of shives, and the residual lignin content, expressed as the Kappa number. The average polymerization degree of cellulose contained in the pulps was determined by the viscometric method (ISO 5351 (2010)). The consumption of bases was expressed as the percentage of bases that underwent reaction with the fibrous materials.

Sheets of paper were produced under laboratory conditions from rewetted pulp samples (22.5 g d.w. samples were soaked in water for 24 h) that were subjected to disintegration using the laboratory JAC SHPD28D propeller pulp disintegrator (Danex, Poland) at 23000 rpm, according to ISO 5263-1 (2004). The disintegrated pulps were concentrated to the dry weigh content of 10% and refined in a PFI mill under standard conditions (ISO 5264-2 (2011)). The ultimate standard freeness of the pulps was around 30°SR. This parameter was determined according to ISO 5267-1 (2000). Values of WRV were determined according to ISO 23714 (2014). Dimensions of fibers were measured according to ISO 16065-2 (2016) using a Morfi Compact Black Edition apparatus (Techpap, France). Paper sheets (the grammage of around 75 g/m^2) were produced from the refined and not refined pulps using a Rapid-Koethen apparatus (according to ISO 5269-2 (2004)). Mechanical properties of paper were determined only for the sheets with the grammage of 74 to 76 g/m^2. The sheets were stored for 24 h at the relative humidity of 50 ± 2% and temperature of 23 ± 1 °C (ISO 187 (1990)) before determination of mechanical properties such as tensile index, stretch, TEA (ISO 1924-2 (2008)), burst index (ISO 1974 (2012)), and tear index (ISO 2758 (2014)). The other parameters measured were the bulk (ISO 534 (2011)), brightness (TAPPI T452), and opacity (TAPPI T519).

Paper sheets were also characterized using an electron microscope SEM/EDS Hitachi S-4700 after coating with carbon.

RESULTS AND DISCUSSION

The results of analyses of chemical composition of tested raw materials – (Table 1), are presented as means and standard deviations of triplicate assays. These results demonstrate that chemical composition of these materials was different. The highest content of cellulose (52.4% d.w.) was observed in the biomass of poplar cultivar 'Hybrid

275'. Among the grasses, the richest source of cellulose was the biomass of miscanthus (47.2% d.w.).

Table 1. Chemical Composition of the Tested Fibrous Materials

Material	Cellulose [% d.w.]	Hemicelluloses [% d.w.]	Lignin [% d.w.]	Extractives [% d.w.]	Ash [% d.w.]
Poplar cultivar 'Hybrid 275'	52.4 (0.8)	26.2 (0.8)	18.0 (0.6)	2.2 (0.6)	1.2 (0.2)
European larch	45.5 (0.4)	20.1 (0.4)	31.2 (0.7)	2.6 (0.8)	0.6 (0.1)
Tall wheatgrass	44.0 (0.6)	33.4 (0.8)	13.6 (0.2)	3.2 (0.4)	5.8 (0.2)
Smooth bromegrass	35.4 (0.1)	40.2 (0.4)	13.7 (0.5)	4.2 (0.5)	6.5 (0.2)
Tall fescue	34.4 (0.3)	40.9 (0.3)	14.0 (0.8)	3.8 (0.6)	6.9 (0.3)
Switchgrass	40.7 (0.7)	30.4 (0.6)	17.4 (0.9)	4.1 (0.4)	7.4 (0.3)
Miscanthus giganteus	47.2 (0.1)	25.9 (0.8)	17.8 (0.8)	2.6 (0.6)	6.5 (0.2)
Birch	49.5 (0.6)	20,6 (0.8)	26.6 (0.8)	2.8 (0.8)	0.5 (0.2)
Pine	45.3 (0.6)	25.1 (0.6)	26.4 (0.7)	2.6 (0.9)	0.6 (0.2)

The other grasses contained more hemicelluloses than the biomass of miscanthus, hardwoods, and softwoods that may positively affect the properties of paper because hemicelluloses promote swelling of fibers (Spiegelberg 1966).

All the fibrous materials were subjected to pulping by the sulfate method. The results were collected in Table 2.

Table 2. Yields and Characteristics of Cellulosic Pulps Obtained by the Sulfate Method

Material	Consumption of bases [%]	Yield of pulp from the digester [%]	Yield of pulp after screening [%]	Shives [%]	Kappa number [-]	DP [-]
Poplar cultivar 'Hybrid 275'	97.25 (0.04)	52.52 (0.42)	51.60 (0.38)	1.75 (0.15)	20.63 (0.21)	1500 (30)
European larch	98.80 (0.02)	46.70 (0.38)	36.60 (0.64)	21.63 (0.98)	56.83 (0.40)	1235 (14)
Tall wheatgrass	99.25 (0.03)	40.82 (0.31)	40.20 (0.38)	1.53 (0.11)	12.25 (0.11)	1910 (28)
Smooth bromegrass	98.64 (0.03)	34.67 (0.28)	34.58 (0.16)	0.27 (0.02)	14.42 (0.16)	1623 (16)
Tall fescue	98.84 (0.04)	34.08 (0.29)	34.02 (0.23)	0.18 (0.02)	12.71 (0.24)	1663 (18)
Switchgrass	99.35 (0.06)	34.47 (0.31)	34.09 (0.22)	1.11 (0.04)	13.71 (0.12)	1640 (22)
Miscanthus giganteus	99.32 (0.03)	47.82 (0.46)	47.12 (0.31)	1.47 (0.18)	14.31 (0.16)	1649 (19)
Birch	97.36 (0.04)	48.91 (0.39)	46.99 (0.20)	3.92 (0.22)	23.38 (0.23)	1294 (11)
Pine	97.22 (0.05)	43.89 (0.28)	40.66 (0.28)	7.35 (0.42)	42.22 (0.26)	1068 (19)

These results demonstrate that the consumption of bases was above 97% in all the cases. The highest pulp yield (before and after screening) was obtained from the poplar cultivar 'Hybrid 275' (52.5 and 51.6%, respectively). Among the grasses, the highest pulp yields were obtained from miscanthus (above 47%) while for the other grasses these yields ranged from 34 to 40%.

All of the fibrous materials were converted to cellulosic pulps at the same concentration of bases (of 26% on a wood dry weight). Therefore, the value of kappa number, corresponding to the residual lignin content, reflects their susceptibility to pulping. The pulps derived from the grasses were characterized by the significantly lower values of kappa number compared to the pulps from the hardwoods and softwoods. The European larch wood was the least susceptible to pulping. The kappa number of the pulp derived from the larch wood was the highest, of 56.8 (by 14 units higher compared to the pine pulp). Moreover, the larch pulp was rich in shives that also provided evidence of the low susceptibility of larch wood to kraft pulping.

After screening the pulps were characterized in terms of the freeness, water retention value (WRV), fiber dimensions and fines contents. The results of these measurements are presented in Table 3.

Table 3. Characteristics of the Kraft Pulps before Refining

Material	Free-ness [°SR]	WRV [%]	Mean fibre arithmetic length [µm]	Mean weighted fibre length [µm]	Mean fibre width [µm]	Mean fibre coarseness [mg/m]	Kinked fibre content [%]	Fine content [% in length]
Poplar cultivar 'Hybrid 275'	14	147.4 (0.6)	696 (7)	819 (8)	23.4 (0.2)	0.093 (0.004)	37.5	12.2 (0.4)
European larch	11	122.1 (0.8)	1409 (12)	2190 (9)	34.3 (0.2)	0.233 (0.009)	32.8	5.4 (0.2)
Tall wheatgrass	15	141.8 (0.3)	599 (5)	929 (8)	26.0 (0.2)	0.116 (0.006)	18.4	27.7 (0.6)
Smooth bromegrass	22	174.3 (0.7)	538 (3)	840 (7)	18.6 (0.1)	0.066 (0.003)	15.1	41.4 (0.9)
Tall fescue	25	140.6 (1.1)	555 (5)	854 (5)	20.1 (0.1)	0.076 (0.004)	20.1	36.9 (0.8)
Switchgrass	15	139.3 (0.4)	584 (5)	854 (6)	21.0 (0.1)	0.096 (0.006)	17.3	39.4 (1.2)
Miscanthus giganteus	16	142.8 (0.8)	585 (4)	899 (7)	20.9 (0.1)	0.088 (0.009)	20.6	30.7 (0.9)
Birch	12	126.1 (0.3)	807 (6)	923 (8)	19.2 (0.1)	0.071 (0.004)	25.2	7.6 (0.3)
Pine	12	126.4 (0.4)	1627 (8)	2256 (11)	30.6 (0.2)	0.148 (0.008)	25.1	6.1 (0.4)

Then the pulps were subjected to refining in a PFI mill until their freeness reached the value of around 30°SR. Properties of the refined pulps are presented in Table 4. The refined pulps were used to produce sheets of paper under laboratory conditions. Their grammage was 75 g/m^2. Mechanical and optical properties of these sheets are shown in Table 5.

Table 4. Characteristics of the Refined Pulps (freeness around 30°SR +/- 1°SR)

Material	Freeness [°SR]	WRV [%]	Mean fibre arithmetic length [µm]	Mean weighted fibre length [µm]	Mean fibre width [µm]	Mean fibre coarseness [mg/m]	Kinked fibre content [%]	Fine content [% in length]
Poplar cultivar 'Hybrid 275'	31	263.1 (0.9)	687 (8)	815 (8)	24.0 (0.1)	0.090 (0.006)	21.4 (1.1)	12.8 (0.8)
European larch	29	226.5 (1.8)	975 (6)	1645 (6)	34.1 (0.2)	0.244 (0.012)	30.8 (0.6)	29.2 (0.9)
Tall wheatgrass	30	196.4 (0.8)	579 (5)	886 (6)	25.3 (0.2)	0.118 (0.004)	20.1 (1.8)	31.7 (1.3)
Smooth bromegrass	31	221.5 (1.2)	513 (11)	803 (8)	17.7 (0.1)	0.056 (0.005)	19.9 (1.6)	38.3 (1.4)
Tall fescue	31	238.0 (1.6)	519 (4)	804 (4)	18.4 (0.1)	0.061 (0.002)	20.2 (1.1)	42.3 (0.6)
Switchgrass	31	209.7 (0.9)	538 (6)	780 (7)	19.5 (0.1)	0.082 (0.004)	17.8 (1.2)	45.2 (0.8)
Miscanthus giganteus	30	202.4 (1.2)	574 (5)	867 (5)	21.8 (0.2)	0.088 (0.011)	18.8 (1.0)	30.0 (1.0)
Birch	31	246.4 (1.6)	803 (9)	924 (9)	20.3 (0.2)	0.084 (0.003)	22.7 (0.8)	12.5 (0.4)
Pine	29	239.3 (1.4)	1323 (11)	2007 (6)	30.8 (0.2)	0.142 (0.006)	22.2 (0.6)	16.6 (0.3)

Table 5. Mechanical and Optical Properties of Paper Sheets Produced from Refined Pulps (freeness 30°SR +/-1°SR)

Material	Bulk [cm^3/g]	Tensile index [N·m/g]	Stretch [%]	TEA [J/m^2]	Burst index [kPa·m^2/g]	Tear index [mN·m^2/g]	Brightness [%]	Opacity [%]
Poplar cultivar 'Hybrid 275'	1.267	109.0 (2.6)	3.51 (0.12)	197.6 (6.4)	8.3 (0.2)	3.8 (0.5)	27.14 (0.51)	99.68
European larch	1.634	90.0 (1.8)	3.03 (0.18)	136.9 (2.9)	7.8 (0.3)	8.0 (0.3)	14.09 (0.30)	97.31
Tall wheatgrass	1.517	81.6 (2.0)	2.24 (0.06)	114.0 (3.8)	6.4 (0.4)	3.2 (0.3)	33.55 (0.31)	99.59
Smooth bromegrass	1.565	89.0 (1.4)	3.05 (0.09)	137.1 (2.0)	7.1 (0.1)	4.4 (0.4)	29.45 (0.33)	99.02
Tall fescue	1.520	85.7 (1.6)	3.03 (0.09)	130.9 (2.3)	6.2 (0.1)	4.4 (0.3)	31.64 (0.58)	99.64
Switchgrass	1.608	68.9 (1.2)	2.32 (0.04)	78.9 (1.6)	4.3 (0.3)	3.7 (0.6)	30.13 (0.42)	99.74
Miscanthus giganteus	1.342	73.4 (2.4)	2.30 (0.12)	96.7 (3.2)	4.4 (0.2)	3.7 (0.5)	31.03 (0.35)	99.02
Birch	1.185	105.8 (0.8)	2.92 (0.06)	156.8 (1.1)	7.2 (0.3)	3.8 (0.4)	21.24 (0.33)	98.06
Pine	1.316	103.9 (1.0)	2.69 (0.05)	131.3 (1.4)	6.9 (0.2)	6.1 (0.2)	21.87 (0.33)	98.06

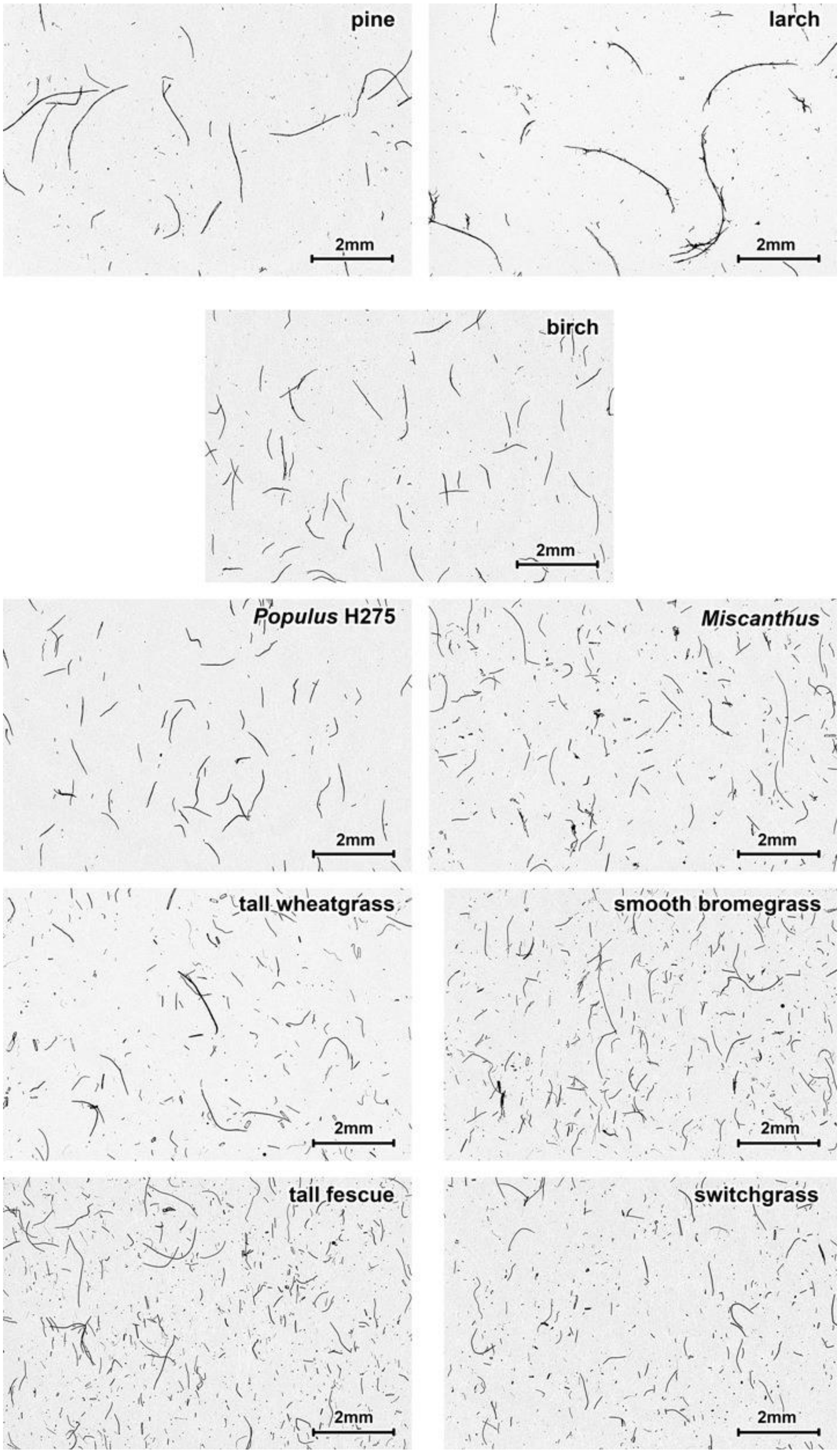

Fig. 1. Microscopic images of the tested fibrous materials recorded using a Morfi Compact Black Edition apparatus

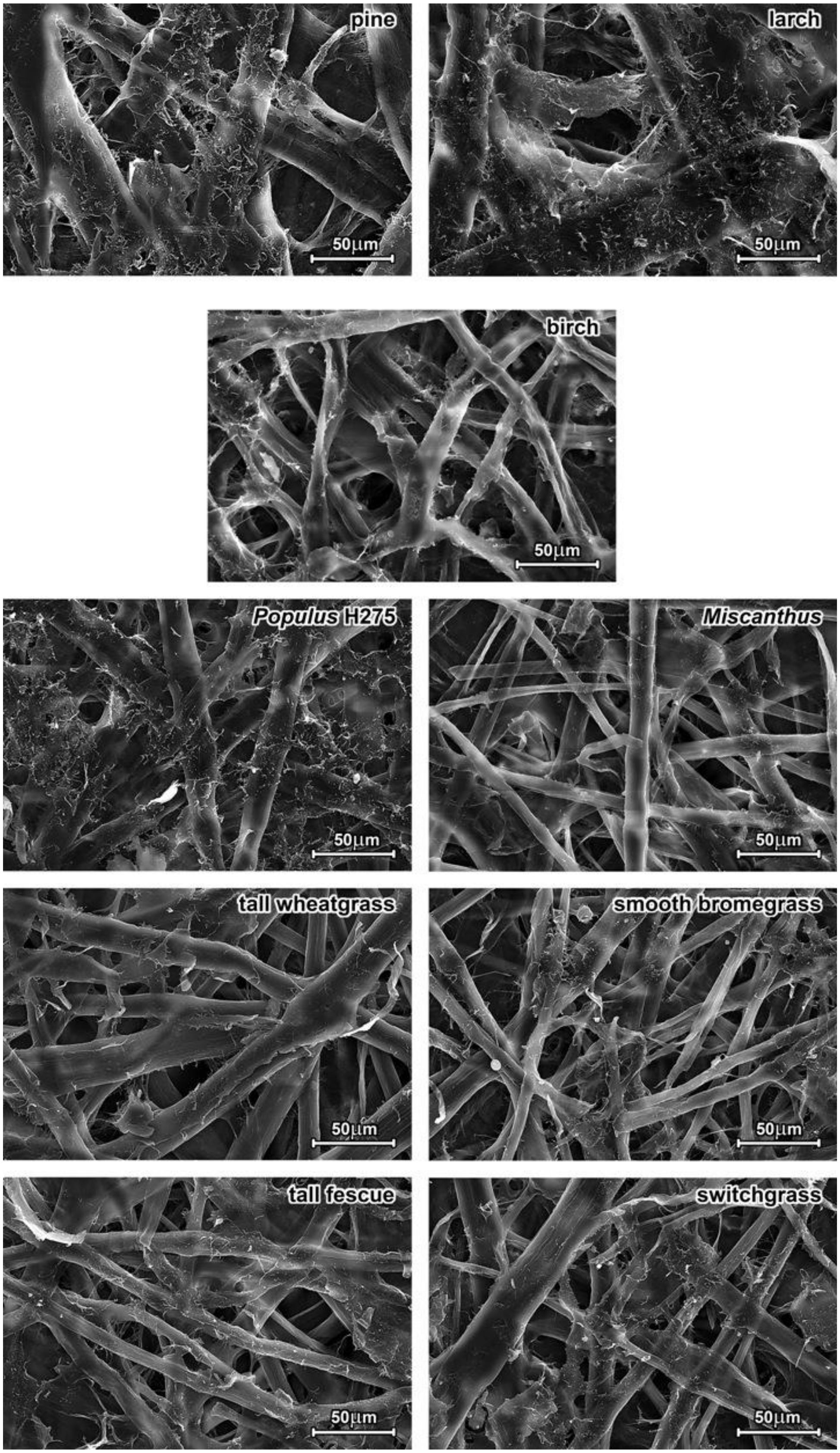

Fig. 2. Microscopic images of the paper sheets derived from the refined pulps derived from the tested fibrous materials recorded using a SEM/EDS Hitachi S-4700 microscope

Novel, fast growing fibrous resources that may be used in papermaking instead of wood have been sought after for many years (Oggiano *et al.* 1997). A particularly promising crop is *Miscanthus giganteus* because its annual biomass harvests from one hectare may reach 30 tons (Marín *et al.* 2009). This biomass may be used for production of kraft cellulosic pulps as well as TMP and CTMP pulps (Cappelletto *et al.* 2000). These pulps may be added to the pulps obtained from recycled paper and used as replacements of hardwood pulps (Madakadze *et al.* 1999). The papermaking utility of *Miscanthus giganteus* is well documented in numerous scientific publications (Pažitný *et al.* 2013; Danielewicz *et al.* 2015). Our research indicate that higher yield of miscanthus pulp can be achieved (47.12%). Also, other grasses, byproducts of food processing such as orange and lemon peels (Żubrzak 2014; Finell 2003), and algal biomass were tested as alternative fiber resources for paper production (Ververis *et al.* 2007). However, commercial application of these materials at the present time is problematic because it requires modification of pulping technology and investments in a new equipment (Dietz *et al.* 2014). Moreover, in all of the mentioned raw materials, both pulp and paper properties were significantly lower compared to the investigated fast growing grasses and trees. From the technological point of view, this is much easier to produce paper from fast growing grasses (Law *et al.* 2001; Shatalov and Pereira 2006; Madakadze *et al.* 2010) and trees from managed plantations, *e.g.* fast growing poplar species (Semen *et al.* 2001; Francis *et al.* 2006; Ai and Tschirner 2010, Zamora *et al.* 2013). This information was confirmed also by our research. Kappa number, for all investigated grasses and poplar 'Hybrid 275' ranged from 12.25 (tall wheatgrass) to 14.31 (*Miscanthus giganteus*). Although the papermaking potential of certain grasses, such as tall wheatgrass (Smith 1996), has already been estimated, the majority of studies focused on problems related to their cultivation and biomass yields. This is the first work presenting properties of pulps obtained from the selected fast growing plants and paper produced from these pulps. No comprehensive information regarding properties of pulp and paper for smooth bromegrass are presented in the scientific literature. The available information is mainly limited to biomass yield (Coffey *et al.* 1997). The results suggest that the most attractive materials are tall wheatgrass and poplar cultivar 'Hybrid 275' that may be used in papermaking as birch wood replacements. Cellulosic pulp from tall wheatgrass was characterized by lower fiber length (819 μm) and higher fines content (27.7%). Tensile properties of hand sheets of paper are approximately 10% lower than for paper produced from poplar 'Hybrid 275' but still at acceptable level. Because of the limited resources of birch wood (Koski and Rousi 2005; Soleimani *et al.* 2012), the biomass of fast growing plants may be regarded a profitable and technologically attractive alternative. The alternative fiber resources may be used to produce kraft and semi-chemical pulps (Cappelletto *et al.* 2000). Properties of the pulps derived from grasses and birch wood are similar (Kürschner and Hoffer 1929; Thykesson *et al.* 1998; Albert *et al.* 2011). However, they are worse compared to the pine wood pulps that are characterized by the higher fiber length (2256 μm) and coarseness (0.148). According to the literature, the chemical composition of pulps from biomass of grasses and length of fibers depend not only on botanical origin but also time of harvesting and site of plantation (Pahkala and Pihala 2000; Jahan *et al.* 2007). The chemical composition of the pulps produced in this study from the presented grass species was different than that reported by other authors, and the differences in the contents of cellulose and lignin were around 15% (Ververis *et al.* 2004). The differences in chemical composition cause differences in the properties of pulp and paper. To minimize the effect of pulping and refining conditions on paper characteristics, the nine materials used in this study were subjected to kraft pulping under the same conditions and refined to the same freeness.

CONCLUSIONS

1. Properties of cellulosic pulps from fast growing trees and grasses were investigated in this study and believed to be potentially attractive for papermaking. The pulp from wood of European larch is much less attractive despite the high length and coarseness of fibers.
2. Among the woods tested, the highest and lowest pulp yields were obtained from the poplar cultivar 'Hybrid 275' (51.6% w/w on a wood dry weight) and European larch (36.6% w/w), respectively. The latter pulp was rich in shives that had to be discarded by screening. Among the tested grasses, the highest pulp yield was obtained from *Miscanthus giganteus* (7 to 13% more than from the biomass of the other grasses).
3. The fibers contained in the pulps from poplar wood and biomass of grasses were only slightly shorter than the birch pulp fibers. Among the pulps from grasses, the fibers from tall wheatgrass were characterized by the greatest weighted length and coarseness.
4. The lowest fines content in the pulps from the fast growing plants was observed in the pulp from the European larch (similar to the contents of fines in the pine and birch pulps). The other pulps contained around 2 to 6 times more fines. However, because of the lower fiber coarseness the high fines content had no impact on the density of paper produced from other pulps. The large part of fines in these pulps originated from the biomass subjected to pulping.
5. Paper sheets produced from the poplar cultivar 'Hybrid 275' showed the highest tensile strength among paper sheets produced from the fast growing trees. The static strength of paper sheets from the poplar cultivar 'Hybrid 275' and birch were nearly the same. Paper produced from the European larch pulp exhibited the high dynamic tensile properties (by 25% higher than the paper from pine pulp), which were ascribed to the high length and coarseness of fibers.
6. Paper sheets produced from the grasses tall wheatgrass, smooth brome, and tall fescue were characterized by nearly the same mechanical properties as sheets of birch paper, while properties of paper sheets from *Miscanthus giganteus* were only slightly worse.
7. The pulps produced from fast growing trees and grasses are interesting substitutes of hardwood pulps. These fiber resources are attractive from the technological and economic points of view because of the short period of growth and productive crops.

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REFERENCES CITED

Aase, J. K., and Siddoway, F. H. (1974). "Tall wheatgrass barriers and winter wheat response," *Agricultural Meteorology* 13(3), 321-338. DOI: 10.1016/0002-1571(74)90073-9

Ai, J., and Tschirner, U. (2010). "Fiber length and pulping charakteristics of switchgrass, alfalfa stems, hybrid poplar and willow biomasses," *Bioresource Technology* 101(1), 215-221. DOI: 10.1016/j.biortech.2009.07.090

Albert, S., Padhiar, A., and Gandhi, D. (2011). "Fiber properties of *Sorghum halepense* and its suitability for paper production," *Journal of Natural Fibers* 8(4), 263-271. DOI: 10.1080/15440478.2011.626236

Almeida, A. C., Soares, J. V., Landsberg, J. J., and Rezende, G. D. (2007). "Growth and water balance of *Eucalyptus grandis* hybrid plantations in Brazil during a rotation for pulp production," *Forest Ecology and Management* 251(1-2), 10-21. DOI: 10.1016/j.foreco.2007.06.009

Arias, D., Calvo-Alvarado, J., Richter, D. D., and Dohrenbusch, A. (2011). "Productivity, aboveground biomass, nutrient uptake and carbon content in fast-growing tree plantations of native and introduced species in the Southern Region of Costa Rica," *Biomass and Bioenergy* 35(5), 1779-1788. DOI: 10.1016/j.biombioe.2011.01.009

Bajpai, P. (2016). *Pulp and Paper Industry: Energy Conservation*, Elsevier, Amsterdam, NL.

Boruszewski, P., Jankowska, A., and Kurowska, A. (2017). "Comparison of the structure of juvenile and mature wood of *Larix decidua* Mill. from fast-growing plantations in Poland," *BioResources* 12(1), 1813-1825. DOI: 10.15376/biores.12.1.1813-1825

Cappelletto, P., Mongardini, F., Barberi, B., Sannibale, M., Brizzi, M., and Pignatelli, V. (2000). "Papermaking pulps from the fibrous fraction of *Miscanthus x Giganteus*," *Industrial Crops and Products* 11(2-3), 205-210. DOI: 10.1016/S0926-6690(99)00051-5

Carle, J. B., and Holmgren, L. P. B. (2009). "Wood from planted forests: Global outlook to 2030," *Planted Forests: Uses, Impacts and Sustainability*, J. Evans (ed.), CAB International and Food and Agriculture Organization of the United Nations, Rome, Italy. DOI: 10.1079/9781845935641.0047

Christersson, L. (2008). "Poplar plantations for paper and energy in the south of Sweden," *Biomass and Bioenergy* 32(11), 997-1000. DOI: 10.1016/j.biombioe.2007.12.018

Coffey, K. P., Brazle, F. K., Higgins, J. J., Moyer, J. L., Hatfield, E. E., and Lemenager R. (1997). "Effects of gathering time on weight and shrink of steers grazing smooth bromegrass pastures," *The Professional Animal Scientist* 13(4), 170-175 DOI: 10.15232/S1080-7446(15)31879-9

Danielewicz, D., Surma-Ślusarska, B., Żurek, G., and Martyniak, D. (2015). "Selected Grass plants as biomass fuels and raw materials for papermaking. Part I. Calorific value and chemical composition," *BioResources* 10(4), 8539-8551. DOI: 10.15376/biores.10.4.8539-8551

Del Lungo, A., Ball, J., and Carle, J. (2006). "Global planted forests thematic study: results and analysis," (Planted Forests and Trees Working Paper FP/38E), Food and Agricultural Organization, Rome, Italy, (www.fao.org/forestry/12139-03441d093f070ea7d7c4e3ec3f306507.pdf).

Dietz, W., Schütt, F., and Dornack, Ch. (2014). "Ersatz klassischer Faserstoffe durch biogene ReststoffeTeil 1," *Wochenblatt für Papierfabrikation* 142(4), 200-205.

Finell, M. (2003). "The use of Red Canary - Grass (*Phalaris arundinacea*) as a short fibre raw material for the pulp and paper industry," Doctoral Thesis, Swedish University of Agricultural Sciences, Umeå, Sweden, (http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.632.2661&rep=rep1&type=pdf).

Fornalski, Z. (2015). "Paper and board production and consumption 2014 in Poland," *Przegląd Papierniczy* 71(9), 482-492.

Francis, R. C., Hanna, R. B., Shin, S. J., Brown, A. F., and Riemenschneider D. E. (2006). "Papermaking characteristics of three *Populus* clones grown in the north-central United States," *Biomass and Bioenergy* 30(8-9), 803-808. DOI: 10.1016/j.biombioe.2005.08.003

ISO 187. (1990). "Paper, board and pulps - Standard atmosphere for conditioning and testing and procedure for monitoring the atmosphere and conditioning of samples," International Organization for Standardization, Geneva, Switzerland.

ISO 534. (2011). "Paper and board - Determination of thickness, density and specific volume," International Organization for Standardization, Geneva, Switzerland.

ISO 1924-2. (2008). "Paper and board -- Determination of tensile properties -- Part 2: Constant rate of elongation method (20 mm/min)," International Organization for Standardization, Geneva, Switzerland.

ISO 1974. (2012). "Paper - Determination of tearing resistance - Elmendorf method," International Organization for Standardization, Geneva, Switzerland.

ISO 2758. (2014). "Paper - Determination of bursting strength," International Organization for Standardization, Geneva, Switzerland.

ISO 5263-1. (2004). "Pulps - Laboratory wet disintegration - Part 1: Disintegration of chemical pulps," International Organization for Standardization, Geneva, Switzerland.

ISO 5264-2. (2011). "Pulps - Laboratory beating - Part 2: PFI mill method," International Organization for Standardization, Geneva, Switzerland.

ISO 5267-1. (2000). "Pulps - Determination of drainability - Part 1: Schopper-Riegler method," International Organization for Standardization, Geneva, Switzerland.

ISO 5269-2. (2004). "Pulps - Preparation of laboratory sheets for physical testing - Part 2: Rapid-Köthen method," International Organization for Standardization, Geneva, Switzerland.

ISO 5351. (2010). "Pulps - Determination of limiting viscosity number in cupri-ethylenediamine (CED) solution," International Organization for Standardization, Geneva, Switzerland.

ISO 16065-2. (2016). "Pulps - Determination of fibre length by automated optical analysis - Part 2: Unpolarized light method," International Organization for Standardization, Geneva, Switzerland.

ISO 23714. (2014). “Pulps - Determination of water retention value (WRV),” International Organization for Standardization, Geneva, Switzerland.

Jahan, M. S., Islam, M. K., Chowdhury, D. A. N., Moeiz, S. M. I., and Arman, U. (2007). “Pulping and papermaking properties of pati (*Typha*),” *Industrial Crops and Products* 26(3), 259-264. DOI: 10.1016/j.indcrop.2007.03.014

Koski, V., and Rousi, M. (2005). “A review of the promises and constraints of breeding silver birch (*Betula pendula* Roth) in Finland,” *Forestry* 78(2), 187-198. DOI: 10.1093/forestry/cpi017

Kürschner, K., and Hoffer, A. (1929). “Ein neues Verfahren zur Bestimmung der Zellulose in Hölzern und Zellstoffen,” *Technol. Chem. Papier und Zellstoff Fabr.* 26, 125-129.

Law, K. N., Kokta, B. V., and Mao, C. B. (2001). “Fibre morphology and soda-sulphite pulping of switchgrass,” *Bioresource Technology* 77(1), 1-7. DOI: 10.1016/S0960-8524(00)00140-1

Leblois, A., Damette, O., and Wolfersberger, J. (2017). “What has driven deforestation in developing countries since the 2000s? Evidence from new remote-sensing data,” *World Development* 92, 82-102. DOI: 10.1016/j.worlddev.2016.11.012

Madakadze, I. C., Masamvu TM, Radiotis T., Li, J., and Smith, D. L. (2010). “Evaluation of pulp and paper making characteristic of elephant grass (*Pennisetum purpureum* Schum) and switchgrass (*Panicum virgatum* L.),” *African Journal of Environmental Science and Technology* 4(7), 465-470. DOI: 10.5897/AJEST10.097

Madakadze, I. C., Radiotis, T., Li, J., Goel, K., and Smith, D. L. (1999). “Kraft pulping characteristics and pulp properties of warm season grasses,” *Bioresource Technology* 69(1), 75-85. DOI: 10.1016/S0960-8524(98)00131-X

Marín, F., Sànchez, J. L., Arauzo, J., Fuertes, R., and Gonzalo, A. (2009). “Semichemical pulping of *Miscanthus giganteus*. Effect of pulping conditions on some pulp and paper properties,” *Bioresource Technology* 100(17), 3933-3940. DOI: 10.1016/j.biortech.2009.03.011

Martyniak, D., and Żurek, G. (2014). “The effect of sowing quantity and row spacing on seed production of few minor grass species,” *Plant Breeding and Seed Science* 66(1), 39-50. DOI: 10.2478/v10129-011-0056-4

Milovanovic, J., Drazic, G., Ikanovic, J., Jurekova, Z., and Rajkovic, S. (2012). “Sustainable production of biomass through *Miscanthus giganteus* plantation development,” *Annals of the Faculty of Engineering Hunedoara* 10(1), 79-82.

Mirski, R., Boruszewski, P., Trociński, A., and Dziurka, D. (2017). “The possibility to use long fibres from fast growing hemp (*Cannabis sativa* L.) for the production of boards for the building and furniture industry,” *BioResources* 12(2), 3521-3529. DOI: 10.15376/biores.12.2.3521-3529

Modrzejewski, K., Olszewski, J., and Rutkowski, J. (1969). *Analysis in Papermaking Industry*. Lodz University of Technology Publisher, Łódź, Poland.

Muylle, H., Van Hulle, S., De Vliegher, A., Baert, J., Van Bockstaele, E., and Roland-Ruiz, I. (2015). “Yield and energy balance of annual and perennial lignocellulosic crops for bio-refinery use: a 4-year field experiment in Belgium,” *European Journal of Agronomy* 63, 62-70. DOI: 10.1016/j.eja.2014.11.001

Oggiano, N., Angelini, L. G., and Cappelletto, P. (1997). “Pulping and paper properties of some fibre crops,” *Industrial Crops and Products* 7(1), 59-67. DOI: 10.1016/S0926-6690(97)00071-X

Pahkala, K., and Pihala, M. (2000). "Different plant parts as raw material for fuel and pulp production," *Industrial Crops and Products* 11(2-3), 119-128. DOI: 10.1016/S0926-6690(99)00050-3

Pažitný, A., Russ, A., Boháček, Š., Bottová, V., and Černá, K. (2013). "Utilization of energetic grass fibre for modification of recovered fibre properties," *Wood Research* 58, 181-190.

Saikia, C. N., Goswami, T., and Ali, F. (1997). "Evaluation of pulp and paper making characteristics of certain fast growing plants," *Wood Science and Technology* 31(6), 467-475. DOI:10.1007/BF00702569

Semen, E., Kuo, M., Su, Y., Hall, R. B., and Stokke, D. D. (2001). "Physical properties of kraft pulp from four-year-old aspen hybrids and crosses," *Wood and Fiber Science* 33(1), 140-147.

Shatalov, A. A., and Pereira, H. (2006). "Papermaking fibers from giant reed (*Arundo donax* L.) by advanced ecologically friendly pulping and bleaching technologies," *BioResources* 1(1), 45-61.

Smith, K. F. (1996). "Tall wheatgrass (*Thinopyrum ponticum* (Podp.) Z.W. Liu + R.R.C. Wang): A neglected resource in Australian pasture," *New Zealand Journal of Agricultural Research* 39(4), 623-627. DOI: 10.1080/00288233.1996.9513222

Soleimani, A., Resalati, H., and Akbarpour, I. (2012). "The effect of using white birch on mechanical properties and fiber length distribution of mixed hardwood CMP pulp," *Lignocellulose* 1(2), 83-91.

Spiegelberg, H. L. (1966). "The effect of hemicelluloses on the mechanical properties of individual pulp fibers," *Tappi* 49(9), 388-396.

TAPPI T203 cm-09 (2009). "Alpha-, beta- and gamma-cellulose in pulp," TAPPI Press, Atlanta, GA.

TAPPI T204 cm-07 (2007). "Solvent extractives of wood and pulp," TAPPI Press, Atlanta, GA.

TAPPI T211 om-12 (2012). "Ash in wood, pulp, paper and paperboard: Combustion at 525 degrees C," TAPPI Press, Atlanta, GA.

TAPPI T222 om-11 (2011). "Acid insoluble lignin in wood and pulp," TAPPI Press, Atlanta, GA.

TAPPI T249 cm-09 (2009). "Carbohydrate composition of extractive-free wood and wood pulp by gas-liquid chromatography," TAPPI Press, Atlanta, GA.

TAPPI T452 om-08 (2008). "Brightness of pulp, paper, and paperboard (directional reflectance at 457 nm)," TAPPI Press, Atlanta, GA.

TAPPI T519 om-11 (2011). "Diffuse opacity of paper (D/0 paper backing)," TAPPI Press, Atlanta, GA.

Thykesson, M., Sjöberg, L. A., and Ahlgren, P. (1998). "Paper properties of grass and straw pulps," *Industrial Crops and Products* 7(2-3), 351-362. DOI: 10.1016/S0926-6690(97)10001-2

Tilman, D., Hill, J., and Lehman C. (2006). "Carbon-negative biofuels from low-input high diversity grassland biomass," *Science* 314(5805), 598-600. DOI: 10.1126/science.1133306

Ververis, C., Georghiou, K., Christodoulakis, N., Santas, P., and Santas, R. (2004). "Fiber dimensions, lignin and cellulose content of various plant materials and their suitability for paper production," *Industrial Crops and Products* 19(3), 245-254. DOI: 0.1016/j.indcrop.2003.10.006

Ververis, C., Georghiou, K., Danielidis, D., Hatzinikolaou, D. G., Santas, P., Santas, R., and Corleti, V. (2007). “Cellulose, hemicelluloses, lignin and ash content of some organic materials and their suitability for use as paper pulp supplements,” *Bioresource Technology* 98(2), 296-301. DOI: 10.1016/j.biortech.2006.01.007

West, P. W. (2006). *Growing Plantation Forests*, Springer Verlag, Berlin, Germany.

Wood Pulp by Gas-Liquid Chromatography,” TAPPI Press, Atlanta, GA.

Zalesny, Jr., R. S., Cunningham, M.W., Hall, R. B., Mirck, J., Rockwood, D. L., Stanturf, J., and Volk, T. A. (2011). “Woody biomass from short rotation energy crops,” *Sustainable Production of Fuels, Chemicals, and Fibers from Forest Biomass,* J. Zhu et al. (ed.), American Chemical Society, Washington, DC, pp. 27-63. DOI: 10.1021/bk-2011-1067.ch002

Zamora, D., Wyatt, G., Apostol, K., and Tschirner, U. (2013). “Biomass yield, energy values, and chemical composition of hybrid poplar in short rotation woody crops production and native perennial grasses in Minnesota, USA,” *Biomass and Bioenergy* 49, 222-230. DOI: 10.1016/j.biombioe.2012.12.031

Żubrzak, M. (2014). “Alternative fibrous materials,” *Przegląd Papierniczy* 70(7), 377-378.

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