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ORIGINAL PAPER

Processing of *Miscanthus × giganteus* stalks into various soda and kraft pulps. Part I: Chemical composition, types of cells and pulping effects

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Abstract The weight share of the pith, nodes and internodes in the stalks of *Miscanthus*, as well as the types of cells in these anatomical parts, were examined. Studies have shown that the pith contains mainly parenchyma cells, nodes—short fibres and palisade parenchyma cells, while internodes contains mainly fibres, which are accompanied by a certain amount of vessels and parenchyma cells. Then the whole stalks of *Miscanthus* were subjected to pulping using the kraft and soda pulping methods. These studies have shown that hard, regular, soft and very soft kraft pulps can be obtained using a lower amount of active alkali, with comparable or higher screened yield of pulp than is the case of pulping of birch. Furthermore, it was found that the content of knots and shives was lower in the digester hard and regular kraft pulps from *Miscanthus* compared to birch kraft pulp. Of the two pulping methods studied, kraft pulping gives better results than soda pulping concerning the considerably higher yield of pulp.

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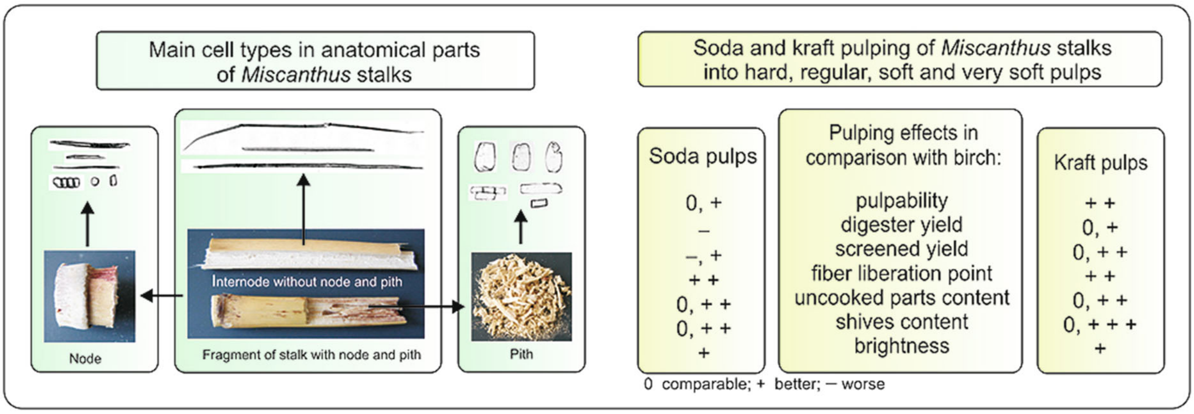
Graphical abstract



Keywords *Miscanthus* × *giganteus* · Pith · Nodes · Internodes · Kraft pulping · Soda pulping · Yield · Screen reject · Brightness

Introduction

Rags containing non-wood fibres were the main raw material for the production of paper until the introduction of groundwood and the first cellulose pulps from wood and straw into industrial practice in the second half of the 19th century (McGovern 1986; McGovern and Carpenter 1987). However, with the development of wood-pulping techniques, the importance of rags and cereal straw began to decrease. The reasons for this were the limited availability of the former material and the lower density and significantly higher mineral content of cereal straw in comparison with wood. However, as concerns these features, individual non-wood raw materials differ significantly, because cereal straws have a considerably lower density and higher content of mineral substances than stalks of industrial hemp or *Miscanthus* × *giganteus* (Turman 1974; Schott et al. 2001; Cappelletto et al. 2000; Kaack et al. 2003; Tutuş and Eroğlu 2004; Marin et al. 2009; Danielewicz and Surma-Ślusarska 2010a; Barbash et al. 2011; Potůček and Milichovsky 2011; Brosse et al. 2012; Potůček et al. 2014; Fišerova et al. 2013; Danielewicz et al. 2015a; Barbash et al. 2016).

Interest in the cultivation of different non-wood plants is increasing today. This is mainly due to the possibility of using the biomass of these plants as an energy source. The example of such plants is the *Miscanthus* genus (Scarlat et al. 2015; Banse et al. 2011). The increasing area of its cultivation makes it possible to use it as raw material for the production not only of energy and energy carriers but also papers and cardboards (Brosse et al. 2012; Kim et al. 2012; Ye and Farriol 2005; Cappelletto et al. 2000). Such use of *Miscanthus* could contribute to a reduction of the demand for wood in the pulp and paper industry, alleviating the shortage of this material now and in the future, and improving the image of the pulp and paper industry as using not only wood from forests but also non-forest biomass.

Miscanthus is a group of perennial plants originating from south-east Asia. The best known varieties are giant *Miscanthus* (*Miscanthus* × *giganteus*), sugar *Miscanthus* (*M. sacchariflorus*), so-called elephant grass (*M.* sinesis), as well as *Miscanthus M. floridulus* and *M. lutarioriparius* (Iglesias et al. 1996; Arnoult et al. 2015; Qin et al. 2012; Brosse et al. 2012). The agritechnical conditions for the cultivation of *Miscanthus* × *giganteus* and biomass harvest logistics have been investigated by many authors. These studies show that giant *Miscanthus* is characterized by a high biomass yield potential (even 20 t biomass/ha/year), a relatively long period of using the plantation (15–20 years), the possibility of using typical agricultural equipment for its harvest, significant resistance to diseases and pests, and a relatively low fertilizing requirement (Iglesias et al. 1996; Lewandowski et al. 2000; Kaack and Schwarz 2001; Kaack et al. 2003; Christian et al. 2008; Borkowska and Molas 2013; Jeżowski 2008; Smith et al. 2015; Burner et al. 2015;

Godin et al. 2013a, b; Stolarski et al. 2017; Lisowski et al. 2017). The advantages of *Miscanthus* × *giganteus* also include the anatomical structure of their stalks, which does not contain a layer of a bast containing long fibres, as in some bast plants, which requires fibre cutting before papermaking (e.g. flax and hemp).

Undoubtedly, a significant disadvantage of *Miscanthus* × *giganteus* is the necessity of breeding through the division of rhizomes, resulting from the inability to multiply the generative *Miscanthus*. On the one hand, this prevents against excessive spread of the plant, but at the same time it forces one to buy expensive seedlings and protect the plantation against frost in the climatic conditions of countries such as Poland (Matyka and Kuś 2011; Boersma and Heaton 2014).

From the literature on the subject it appears that *Miscanthus* × *giganteus* and/or *Miscanthus sinensis* have been converted to fibrous pulp by the kraft method (Thykesson et al. 1998; Danielewicz et al. 2015b), the soda peroxide method (Oggiano et al. 1997), organosolve methods (Thykesson et al. 1998; Rousu et al. 2002; Caridad et al. 2004; Villaverde et al. 2010), as well as by the alkaline sulfite method (Huiben and Shi-lan 1990). Attempts have also been made to evaluate the effects of processing different varieties of *Miscanthus* on semi-chemical, thermomechanical and chemithermomechanical pulps (Iglesias et al. 1996; Cappelletto et al. 2000; Marin et al. 2009). These works, however, usually contain the results of individual pulping tests, because the *Miscanthus* was usually one of the few raw materials investigated in the studies whose suitability for papermaking purposes was determined. Therefore, the suitability of this raw material for the production of various types of cellulose pulp, including very soft (kappa number ∼ 10), soft (kappa number ∼ 20), regular (kappa number ∼ 30) and hard (kappa number ∼ 45), to the best of our knowledge has not been studied.

Taking this into consideration, research was undertaken in which we studied the kinds of cells in the individual anatomical parts of *Miscanthus* × *giganteus* stalks, the effects of pulping the whole stalks using the soda and kraft methods in conditions which allow to obtain the above mentioned pulps, the chemical composition of these pulps and their properties in the form of handsheets. The description of the research results obtained in the work on the former two issues is presented in this publication (part I), while the results concerning the latter two issues will be presented in part II of work, now being in preparation for publication.

Experimental

Fibrous raw materials

The research involved the stalks of *Miscanthus* × *giganteus* obtained from the plantation located in the village of Majdan Sieniawski (Podkarpackie province, Poland) and industrial birch and pine wood chips obtained from the International Paper mill in Kwidzyn (Poland).

Determination of the share of the pith, nodes and internodes in the *Miscanthus* stalks

An assessment of the weight share of anatomical elements in *Miscanthus* stalks was performed for randomly selected stalks without leaves. After weighing the whole stalks, the nodes were cut out from them manually using a small wood saw. The nodes and internodes were weighed. The internodes were then split in half and the pith was carefully scraped out of their centre and weighed. All these anatomical parts were then analyzed for the content of dry matter, after which their weight percentage in the *Miscanthus* stalks was calculated.

Analysis of types of cells of pith, nodes and internodes and their morphological properties

In order to characterize the kinds of cells in the pith, nodes and internodes of the *Miscanthus* stalks, the samples of these anatomical parts were macerated in accordance with the methodology proposed by Brisson, Gardner and Peterson (Gardner 1975). The first step of this procedure is appropriate preparation of raw material. The samples of pith, nodes and internodes were cut using the sharp knife into an approximately 2× 2 particles (pith) and 2× 2× 5 mm matchsticks (nodes and internodes), respectively. Then these particles were placed in vials and they were flooded with maceration solution. The solution was the mixture of one part hydrogen peroxide (30% reagent solution), 4 parts of deionized water, and 5 parts of pure (100%) glacial acetic acid. All chemicals were from commercial sources. The ratio of volume of maceration solution to wood was 100:1 (v/g). The vial were then capped and placed in an oven at temperature of 60 °C for 7 days. After that time the samples appeared as a white-translucent material. The vial were then removed from the oven and allowed to cool to room temperature, and then removed from vials and placed in a clean vial. The samples were then mixed with distilled water for several minutes to separate any fiber bundles into individual fibers. The types of cells in the pith, nodes and internodes were then determined using these obtained samples of separated cells on the basis of microscopic observations. In order to visualize the fibres in the microscopic images, they were stained with Herzberg's reagent (ISO 9184-3: 1990). A Biolar T microscope equipped with a CCD camera (PZO, Poland) was used for microscopic examination of the pulps. The fibres length distribution and the average length of fibres (as average length weighted in length) in these anatomical parts were determined in a MorFi apparatus (TechPap, France) according to the instructions provided by the manufacturer.

Chemical composition of pith, nodes and internodes

Samples of the pith, nodes and internodes of *Miscanthus* stalks were ground with a Körner grinder to sawdust, and then sieved through a set of five sieves with decreasing mesh sizes to separate out coarse splinters and wood dust, which were rejected. The rest of the sawdust was then used to determine the content of cellulose, lignin insoluble in acids, extractives, ash and substances soluble in 1% water solution of NaOH. The contents of the first four chemical components in the particular anatomical parts of *Miscanthus* stalks were determined according to the PN-74/P-50092 standard (Seifert cellulose, acid insoluble lignin, acetone extractives, inorganic substances as ash), while their solubility in 1% NaOH was according to the TAPPI T 212 standard.

Preparation of fibrous materials for pulping

Before being pulped, the *Miscanthus* stalks were cut into 2–3 cm pieces using a small wood saw, and the wood chips were screened in a Santasalo-Sohlberg quake sorter. The fractions that stopped on sieves with a diameter of $\geq$ 23 mm and those passing through a sieve $\leq$ 9 mm were rejected, while the fraction retained on screens with 12, 16, 19, and 21 mm holes were used for research.

Pulping of fibrous raw materials

The pulping of fibrous raw materials was carried out in a Santasalo-Sohlberg rotary sectional digester in autoclaves with a capacity of 300 cm^3. The samples used were sodium hydroxide solutions (soda method), sodium hydroxide and sodium sulphide (kraft method). Alkali were dosed as NaOH and calculated on oven-dried (o.d.) raw material. The sulphidity, liquor-to-wood ratio, heating-up time, and maximum temperature of pulping for all samples were the same: 25%, 4, 120 min, 120 min and 165 °C, respectively. The pulped fibrous raw materials were washed with distilled water in a Büchner funnel, and washed again by diffusion for 16 h in a bucket, filtered, defibrated in a laboratory disintegrator, and then screened in a Weverk laboratory screen sorter equipped with 0.2 mm slots. The screening enabled the purification of the pulps from the uncooked parts of the fibrous raw materials, the determination of the content of these parts in the digester pulps, as well as calculation of the screened yield of pulps.

Pulp properties

The kappa number of the pulps was determined according to the TAPPI T 236 om-13 standard, while the R457 brightness was according to the ISO 2470 (1999) standard in the Whitecolor 01 apparatus (Spectrocolor, Poland). The shives content in the soda and kraft pulps was determined with the MorFi apparatus (TechPap, France).

Elaboration of results

The weight shares of pith, nodes and internodes in *Miscanthus* stalks were investigated using ten *Miscanthus* stalks. The presented results are therefore arithmetic averages from the determinations of the contents of these anatomical parts in 10 stalks. Determinations of the chemical composition of the pith, nodes and internodes were done at least twice. According to the PN-74/P-50092 standard for the outcome of the final determination of the content of cellulose, lignin, extractives and ash, one should assume the arithmetic average of two parallel determinations, the results of which do not differ by more than 0.2%.

The fibre distribution and average length weighted in length in the "maceration" pulps, and the shives contents in the kraft and soda pulps were determined in triplicate. Kraft and soda pulping experiments on the fibrous raw materials were conducted twice. Therefore, the yields of pulps from these materials are the arithmetic averages of two procedures. The mean deviation of yield from the average value for soda and kraft pulping was 0.3% and 0.2%, respectively.

Characterization of kraft pulps involved determinations of the kappa number and brightness. These features were also determined twice and presented as arithmetic averages of two results. The deviation of the kappa number and brightness determined from the average value of these characteristics for soda and kraft pulps was 0.2–0.4 and 0.3–0.6%, respectively.

Results and discussion

The yield and properties of papermaking pulps from wood depend on their chemical composition, physical characteristics, as well as the type and conditions of pulping (Annergren et al. 1963; Agarwal and Gustafson 1995). In the case of non-wood plants, the other factors that can significantly influence the yield and properties of unbleached pulp from these raw materials are the type and the properties of the cells of their various anatomical parts, the latter being greater in the case of many of these raw materials than in wood. In these raw materials one can often distinguish such anatomical parts as internodes, nodes, and sometimes also the pith and bast. The properties of some of these parts can sometimes be so unfavorable that they are separated from the rest of stalks. An example is the separation of nodes from wheat straw and the pith from bagasse stalks (Knapp et al. 1957; Niwiński 1966; Ruckstuhl 1971; Maddern and French 1989; Potter 1996).

Considering the significance of this issue, the anatomical structure of *Miscanthus* stalks was analyzed. This revealed that the stalks of the plant have such anatomical parts as internodes, nodes and pith (Fig. 1).

Taking into consideration the importance of the issue of the relative weight share of these anatomical parts in *Miscanthus* stalks, we determined it. The results of the examination are presented in Table 1.

The data presented in Table 1 show that the weight share of de-pithed internodes, nodes and pith in the studied *Miscanthus* stalks was 83.9, 10.5 and 5.6% respectively. The values of the pith content in *Miscanthus* stalks concur with the literature reports (Cappelletto et al. 2000). The content of pith in the internodes can be considered as low. The main part of the giant *Miscanthus* stems is therefore the internodes, which is a beneficial fact. The pith content in *Miscanthus* stalks is much smaller than in e.g. bagasse, whose stalks contain about 25–35% of pith (Knapp et al. 1957; Ruckstuhl 1971).

The chemical composition of the individual anatomical parts of the *Miscanthus* stalks was also determined and the results are shown in Table 2.

Table 2 shows that the pith is characterized by 3.5% lower cellulose content, and by 0.5% higher lignin content than the internodes. The nodes, on the other hand, contain much less lignin than the internodes (only 10.6%), but also less cellulose (28.4%). The content of extractives and mineral substances in the examined anatomical parts of the *Miscanthus* stalks is in the range of 0.9–1.6%. The data presented in Table 2 indicate also that the internodes contain more extractives than the nodes and pith, while the nodes and pith have more mineral substances than the internodes. What is important is that the level of extractives content can be described as lower than in the wood of many species of trees, while the content of mineral substances, determined as ash, is higher than in wood, but much lower than in cereal straws (Jiménez and López 1993; Fišerova et al. 2006).

The chemical composition of *Miscanthus* × *giganteus* stalks has been investigated by several authors (Cappelletto et al. 2000; Ververis et al. 2004; Brosse et al. 2012). The cellulose contents provided by these authors are usually higher than those obtained in our work. The reason of relatively low cellulose content in anatomical parts of *Miscanthus* stalks obtained in our works may be the result of procedure used for determinations of the cellulose content in fibrous raw materials, which was the same as in the Seifert's method. This method is the one giving lowest values of cellulose contents in fibrous raw materials in comparison with other methods, because apart from lignin and hemicelluloses lower molecular weight fraction of cellulose are also hydrolyzed in strong acid

De-pithed internodes Nodes Pith

Fig. 1 Photographs of de-pithed internodes, nodes and pith

Table 1 Share of the de-pithed internodes, nodes and pith in *Miscanthus* × *giganteus* stalks

Anatomical part	De-pithed internodes	Nodes	Pith
Share	83.9 ± 1.4%	10.5 ± 0.5%	5.6 ± 0.4%

Table 2 Chemical composition of internodes, nodes and pith of *Miscanthus* × *giganteus* stalks and the solubility of these anatomical parts in 1% NaOH

Anatomical part	Chemical component				
	Celullose (%)	Lignin (%)	Extractives (%)	Ash (%)	1% NaOH solubility (%)
De-pithed internodes	36.1	18.9	1.6	1.1	40.3
Nodes	28.4	10.6	0.9	1.6	45.9
Pith	32.6	19.4	0.9	1.4	41.5

conditions during the performance of determination. This increases the possible content of hemicelluloses in fibrous raw materials, if they were calculated as sum to 100%. The presence of larger amounts of easily extractable substances in the stalks of giant *Miscanthus* than in birch and pine wood, probably also cellulose, confirm the results of the research of solubility of pith, nodes and internodes sawdust in 1% NaOH, which were as much as 41.5, 45.9 and 40.3%, respectively (Table 2).

The types of cells from which the individual anatomical parts of the giant *Miscanthus* stalks are built, as well as the fibre length distribution of the cells contained in them, were further investigated. These tests were performed using pulps obtained by maceration of the pith, nodes and internodes. The results obtained are shown in Figs. 2A–C.

Figure 2A shows that the pith contains predominantly barrel-like parenchyma cells resembling those of wheat straw (Barbash et al. 2011) and brick-like parenchyma cells. This is confirmed also by the analysis of the pith pulp in the MorFi apparatus (Fig. 3), which showed sloping type of pith cell length distribution with a maximum at the lowest values of the cell lengths range (i.e. 0.2 mm). The presence of cells with lengths higher than 0.2 mm in this pulp can result from the presence of longer parenchyma cells in the pith and a certain number of fibres, which were removed together with the pith from the *Miscanthus* stalks. About the possibility of presence of ray parenchymatous and tracheidal cells of 0.2–0.35 mm

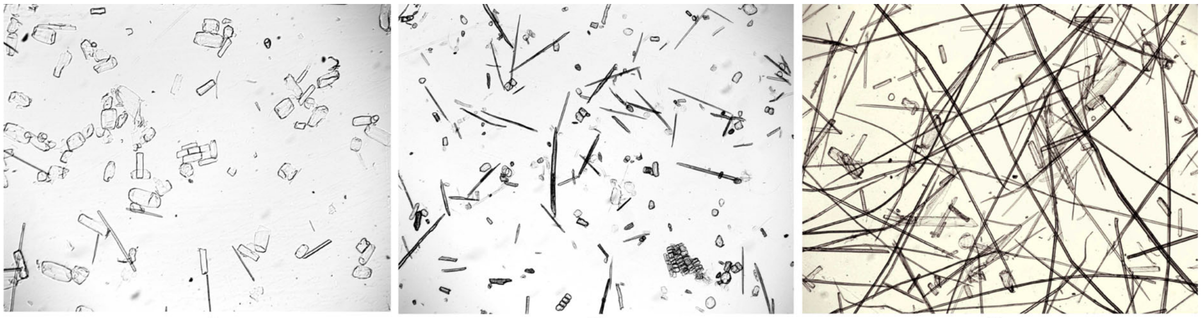


Fig. 2 Photograph of cells of *Miscanthus* pith (**A**), nodes (**B**) and internodes (**C**) (magnification × 40)

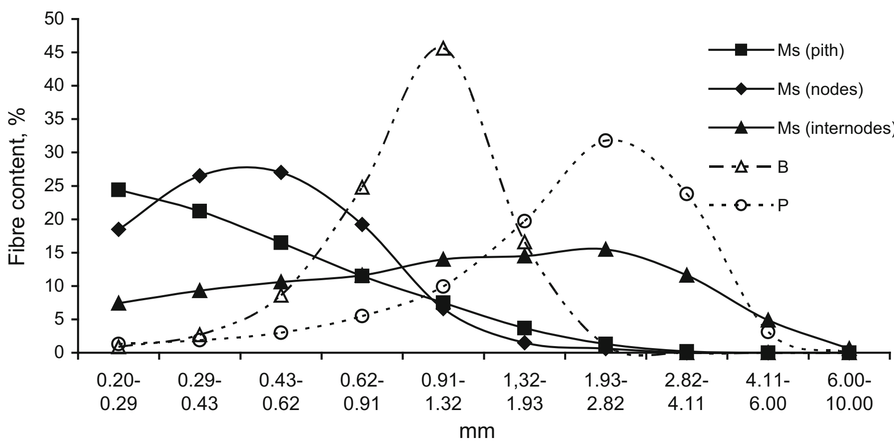


Fig. 3 Distribution of fibre length (average length weighted in length) in the pith, nodes and internodes of *Miscanthus* × *giganteus* stalks, birch and pine

length wrote Nyrén and Back (1959, 1960). The presence of parenchyma cells in pulps used to make paper is considered by most authors to be unfavorable due to their negative influence on the pulp's drainability, poor bonding in the paper structure, and their tendency to stick to the surface of the printing rolls (Hoffman and Timell 1972; Cooley 1973, 1975; Amidon 1981; Klungeness and Sanyer 1981; Heintze and Shalhorn 1995; Shalhorn and Heintze 1997; Wood et al. 2000). The solution to the problem of the presence of a considerable number of these cells in *Miscanthus* pulps could be the separation of the pith from its stalks, as is done with the pith of bagasse stalks (Knapp et al. 1957; Ruckstuhl 1971).

A different cell composition is found for the nodes (Fig. 2B). They contain mainly short spindle-like fibrous cells and small parenchyma palisade cells. As a result, the average fibre length of the nodes is only 0.52 mm, whereas the fibre length distribution has a maximum at this fibre length and a Gaussian shape distribution, as shown in Fig. 3.

As for the kinds of cells in the de-pithed internodes of *Miscanthus* × *giganteus* stalks, the situation is quite different, because they contain a large number of long, straight and narrow fibers, some very narrow needle-type fibres, large and small vessels, different parenchyma cells and epidermal cells (Fig. 2C).

Fibre length, strength and bonding ability are usually the most important fibre parameters influencing the properties of paper and paper boards (Swanson and Steber 1959; Swanson and Jones 1962). However, some authors claim that the proportion of long fibres in the pulp and the fibre length distribution also have a significant effect on these properties (Grant 1968; Forgacs 1963; Mannström 1967). Assessing the distribution of the length of the fibres from *Miscanthus* internodes it can be stated that it is advantageous (Fig. 3), because these contains significant amount of longer fibres in the length range of 1.32–4.11 mm, what makes that the average length of fibres of this pulp relatively high (1.537 mm). Thus, separation of the pith and internodes from the stems of the

Miscanthus should make it possible to obtain pulps with a fibre length greater than that of fibres from whole *Miscanthus* stalks (Cappelletto et al. 2000), and greater than that of most pulps from hardwoods (Koran 1989; Tiikkaja 1999; Paavilainen 2000; Danielewicz and Surma-Ślusarska 2010b).

As seen in Fig. 2C, the pulp obtained by maceration of the internodes also contains a certain number of parenchyma and vessels cells. These types of cells can have a significant impact on the properties of the pulp, because their content per gram for some pulp may be significant. For example, it is given that 1 g of eucalyptus pulp contains 150,000 vessels (Foelkel and Zvinakevicius 1980). However, the vessels cannot be separated by fractionation. Marton and Agarwal (1965) proposed flotation for removing the vessels from hardwood pulps. The problem of the negative influence of an excessive amount of vessels on the pulp properties can also be solved by the appropriate beating of pulps, as suggested in the literature on the subject (Heintze and Shalhorn 1995).

In this work, the issue of the presence of nodes and especially pith in *Miscanthus* stalks was addressed only to indicate the existence of this problem. Despite the possible certain negative influence of these anatomical parts on the effects of pulping and properties of pulps, pulping studies were performed using cut *Miscanthus* stalks containing these parts (Fig. 4), while the issue of the effect of their separating from the *Miscanthus* stalks on pulping effects is left for further research.

The interrelation between the amount of active alkali used in the pulping processes and the kappa number of pulps is shown in Fig. 5.

The analysis of the data in Fig. 5 indicates that the susceptibility to pulping of the stalks of *Miscanthus* by the kraft method is clearly greater in the whole range of the pulps' kappa numbers than for birch and pine. At a given amount of active alkali used in the pulping process, *Miscanthus* kraft pulps are more deeply delignified than birch or pine pulps. The susceptibility of *Miscanthus* stalks to delignification in soda pulping is slightly higher in comparison to birch in kraft pulping in the kappa number range of 25–60, and comparable in the kappa number range of 15–25. The deeper delignification of *Miscanthus* stalks using the kraft pulping method than using the soda method probably results from the much faster rate of degradation of lignin of *Miscanthus* stalks in kraft pulping than in the soda process, as suggested by Kleinert (1966), who compared the rate of delignification of wood in the kraft and soda processes.

The characteristic feature of the pulping of most virgin fibrous raw materials into cellulose pulps is the large loss of their mass (about 50%) due to the dissolution of lignin and hemicelluloses, which negatively affects the economical side of the process

Fig. 4 Cut *Miscanthus* × *giganteus* stalks used in pulping experiments

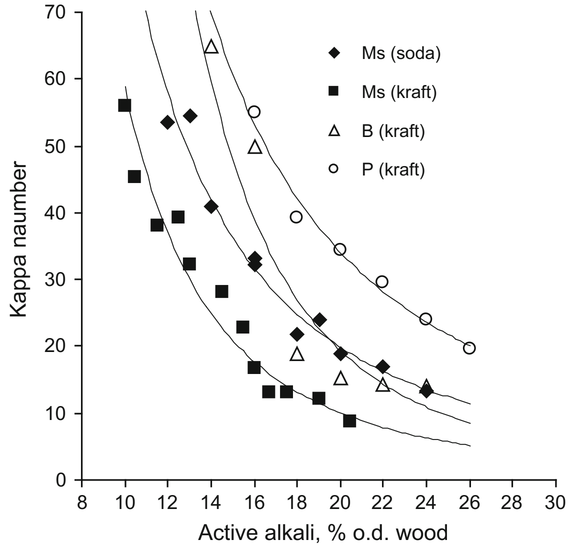


Fig. 5 Kappa number of screened pulps versus the active alkali used in kraft and soda pulping processes

(Annergren et al. 1963). Because the amount of pulp produced daily in large pulp mills is significant (min. approx. 1000 tons), an increase in pulp yield of about 0.1% from wood is of great importance. Taking this into account, both the crude pulp yield from the digester and the screened yield of the kraft and soda pulps from *Miscanthus* stalks were determined. The shaping of crude (digester) yield as a function of the number of kappa of pulps is shown in Fig. 6, against the background of the yields of kraft pulps from birch and pine.

Figure 6 shows that by subjecting *Miscanthus* stalks to kraft pulping a pulp can be obtained with a higher digester yield than in the case of soda pulping. For example, at the level of kappa number 20, the difference in the yield of these pulps is around 4.5%. The crude yield of soft, regular and hard kraft pulps, as well as birch and pine kraft pulps is also interesting. As concerns the yield of regular and hard *Miscanthus* kraft pulps, as shown in Fig. 6, it is comparable with the yield of these types of pulp from birch, and therefore also higher than that of pine. The digester yield of soda pulps from *Miscanthus* is less favorable, being lower than that of kraft pulp from this raw material, as well as that of kraft pulps from birch, but higher than the yield of kraft pulps from pine. The difference in the digester yields of the kraft and soda pulps from *Miscanthus* is similar to the difference in yield of this type of pulp from Douglas fir, as reported by Eckert et al. (1985). Lower yield of pulps from *Miscanthus* chips results from higher amount of alkali needed to delignify to a specific kappa number and certainly can be assigned to the decrease in the yield of xylan contained in the stalks of *Miscanthus*.

In our study, we have also tried to investigate what kinds of pulp can be produced from giant *Miscanthus* by subjecting it to the soda and kraft processes. Efforts were made to determine whether it is possible to obtain such kinds of cellulose pulp as: very soft, soft, regular and hard. As the factor differentiating the degree of pulping, the amount of active alkali was used. In determining the kind of pulp that can be obtained from *Miscanthus* × *giganteus*, the relationship of the screened yield, as well as the content of uncooked parts of wood versus the kappa number of the pulps was used. As the upper limit of the ability to produce cellulose pulp from fibrous raw material, the so-called fibre liberation point was assumed, i.e. the kappa number of the screened pulp at which there is a clear reduction in the screened yield of pulp from a given fibrous raw material.

The relationship of the kappa number of pulps and their screened yield, as well as the content of uncooked parts of the fibrous raw materials in digester (crude) pulps are presented in Figs. 7 and 8. In this work, as the criterion for the possibility of producing cellulose pulps, the content of shives in the pulps was also used. The content of shives in the screened pulp was

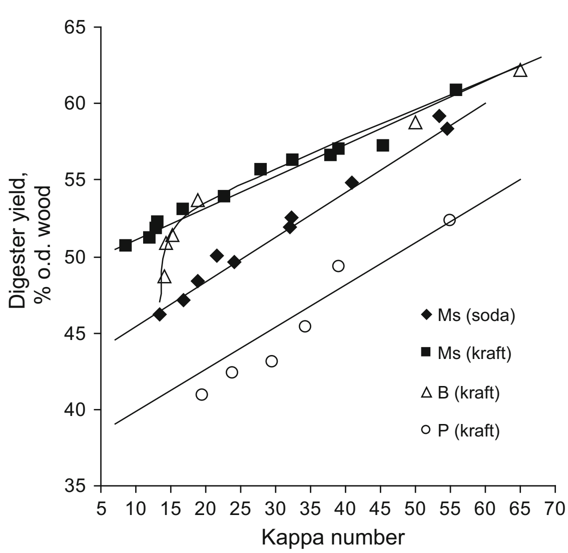


Fig. 6 Digester yield versus kappa number of pulps

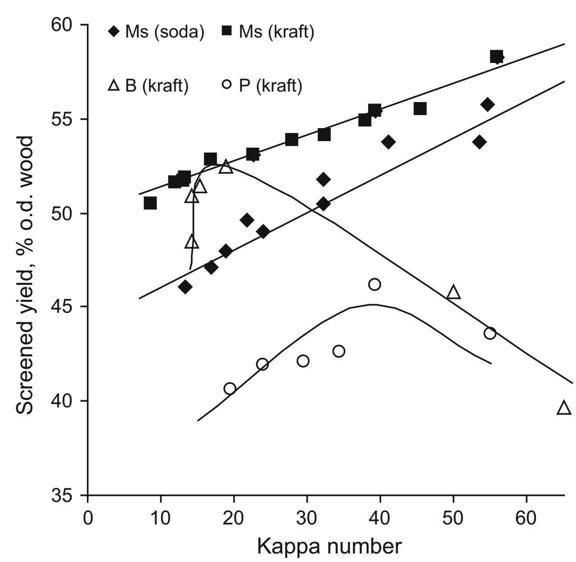


Fig. 7 Screened yield of pulps versus kappa number of screened pulps

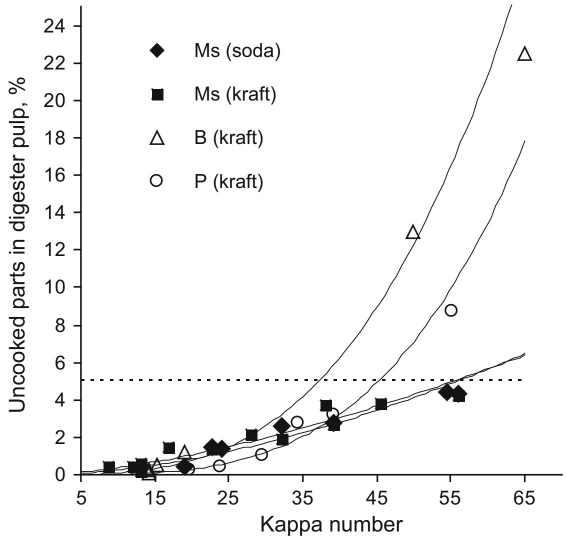


Fig. 8 Content of uncooked parts of fibrous raw materials in pulps versus their kappa number

determined in the MorFi apparatus. The results are shown in Fig. 9.

The method of determining the limit of the possibility of producing a given type of pulp from fibre raw material illustrates well the interrelation between the kappa number of the pulps and the pulps' screened yield or/and the content of the uncooked wood parts in the birch and pine pulps (Figs. 7, 8). As

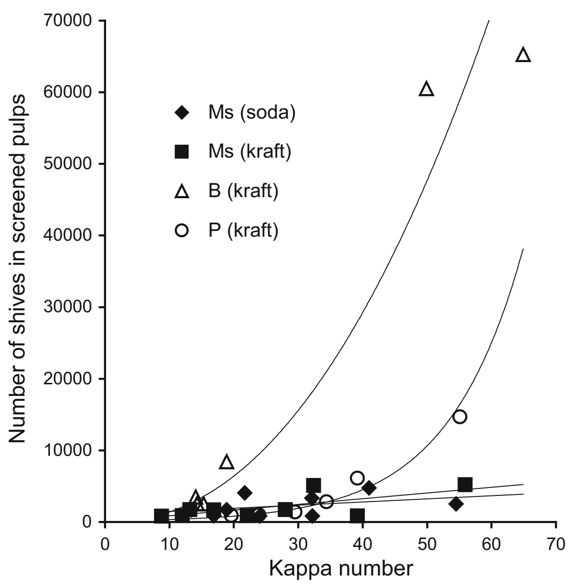


Fig. 9 Shives content in screened pulps versus their kappa number

seen in Fig. 7, birch is the most suitable for the production of soft pulp, i.e. with a kappa number around 20. This type of wood is less useful for making hard pulps due to the large reduction in the screened pulp yield when the kappa number of the pulps increases (Fig. 7), the sharp increase in the share of uncooked parts of fibrous materials in the digester pulp with the increase of this number (Fig. 8), and a sharp increase in the content of shives in the birch pulp (Fig. 9). On the other hand, it is possible to create pine pulps not only soft, but also regular one and also hard one, because the point with the highest screened pulp yield for pine is located at the kappa number of around 45 (Fig. 7), which is the level of kappa number of hard kraft and sulfite pulps (Wandelt 1996).

The data presented in Figs. 7, 8, 9 enable a similar analysis of the possibility of producing regular and hard pulps from *Miscanthus* × *giganteus*. Figure 8 shows that due to the low content of uncooked parts in the *Miscanthus* digesters' kraft and soda pulps, the upper limit of the possibility of producing regular papermaking pulps from *Miscanthus* lies at a higher kappa number than in the case of birch, which Mróz and Surewicz (1981) established at kappa number 16–19. Moreover, for the hard pulps this limit probably lies at an even higher kappa number than in the case of pine pulp. This is clearly indicated by the data presented in Fig. 7, which show that the screened yield of *Miscanthus* soda and kraft pulps has not yet reached the fibre liberation point at which its value is reduced, as in the case of the processing of birch and pine. These data indicate that, in the case of giant *Miscanthus*, not only soft pulps (kappa number ~ 20) can be easily obtained, but also regular and hard pulps with a degree of pulping similar to that of pine pulp, i.e. kappa numbers 30 and 45, respectively.

The data in Fig. 7 allow to compare the screened yield of very soft, soft, regular and hard soda and kraft pulps from *Miscanthus* with the yield of these kinds of pulp from birch and pine. This shows that the screened yield of very soft kraft pulp from *Miscanthus* should be higher than the yield of birch pulp by a few percent. The yield of soft *Miscanthus* kraft pulp should be comparable with the yield of this type of birch pulp. Regarding the screened yield of regular and hard *Miscanthus* pulps, it can be stated that they should be higher than the yield of these types of pine pulps by about 10–11%.

In terms of the screened yield of pulp much lower values can be obtained in the processing of *Miscanthus* stalks into soda pulps. As seen in Fig. 7, the yield of very soft screened soda pulp was comparable to that of very soft birch pulp, while the yield of regular and hard soda pulps from *Miscanthus* was higher by 6–7% than that of pine pulp. The higher digester and screened yields of *Miscanthus* kraft pulps than soda ones can be explained by the stabilizing effect of the sulphide ions on *Miscanthus* hemicelluloses. Procter and Apelt (1969) showed that hydrogen sulphide pretreatment of hydrocellulose stabilizes the end groups of this carbohydrate equally effectively as sodium borohydride, hydroxylamine and peroxide compounds, and even more effectively than polysulphide, hydrazine, sodium hypochlorite and sodium dithionite.

The beneficial feature of the regular and hard pulps of *Miscanthus*, compared to birch and pine, is also the lower level of the content of shives in the screened pulps (Fig. 9), the content of which in paper pulp is one of the criteria for assessing a pulp's purity (Dewhirst and Hopes 1962).

The brightness of pulps is also an important technological feature, especially in the case of pulps obtained using alkaline pulping methods for which it is low. The higher it is, the easier to bleach are pulps and the brighter are the packaging papers and cardboards made of them. The development of brightness of kraft and soda pulps from *Miscanthus* compared with the brightness of kraft pulps from birch and pine, depending on the kappa number, is presented in Fig. 10.

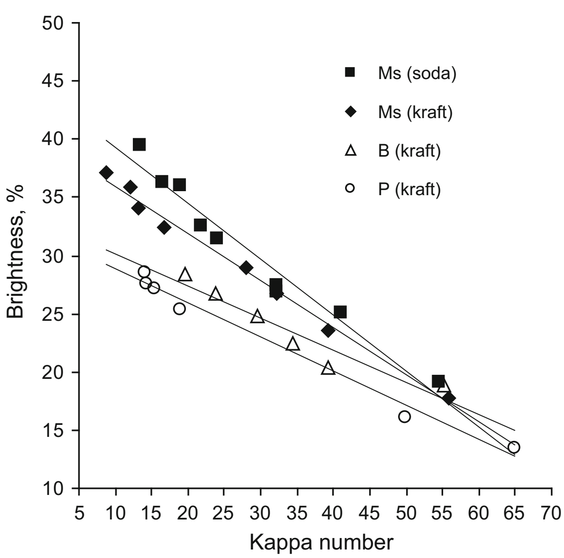


Fig. 10 R457 brightness of pulps versus their kappa number

The comparison of the brightness of the soda and kraft pulps obtained from *Miscanthus* shows that in the soda pulps it is slightly higher than in the kraft pulps. The research results indicate that the use of NaOH and Na_2S for pulping of *Miscanthus* causes the formation of more chromophore groups in lignin than when using only NaOH. Interestingly, Knapp and Wethern (1957) observed a similar tendency in the case of bagasse soda and kraft pulps. In addition, the data presented in Fig. 10 indicate that the brightness of unbleached kraft and soda pulps from *Miscanthus* was higher than the brightness of the equivalent pulps of birch and pine wood, particularly in the case of soft and very soft pulps.

Conclusions

1. The internodes of *Miscanthus* × *giganteus* stalks are characterized by a more preferable cellular composition from the papermaking point of view than the nodes and pith of these stalks.
2. The proportion of pith in the stalks of *Miscanthus* × *giganteus* is small. It contains brick- and barrel-like cells that would contribute little to the sheet strength. Removal of pith from *Miscanthus* stalks before pulping should increase average fibre length of pulp from de-pithed material.
3. Giant *Miscanthus* stalks are more susceptible to kraft pulping than birch and pine, and require less alkali to obtain a pulp with a certain degree of delignification.
4. By subjecting *Miscanthus* × *giganteus* stalks to the alkaline pulping process it is possible to obtain pulps with a wider range of kappa numbers compared with birch.
5. The crude yield of soft, regular and hard kraft pulp from *Miscanthus* × *giganteus* was comparable to that of birch kraft pulp, whereas the yield of very soft pulps was higher than in the case of birch pulp.
6. The screened yield of regular papermaking and hard kraft pulps from *Miscanthus* × *giganteus* is higher than that of birch.

7. The cleanness (shives content, brightness) of *Miscanthus* kraft pulps is better than birch kraft pulps.

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