Evaluation of Unbleached Pulps from *Miscanthus x giganteus* and *Miscanthus* Cultivars for Tissue Paper Production

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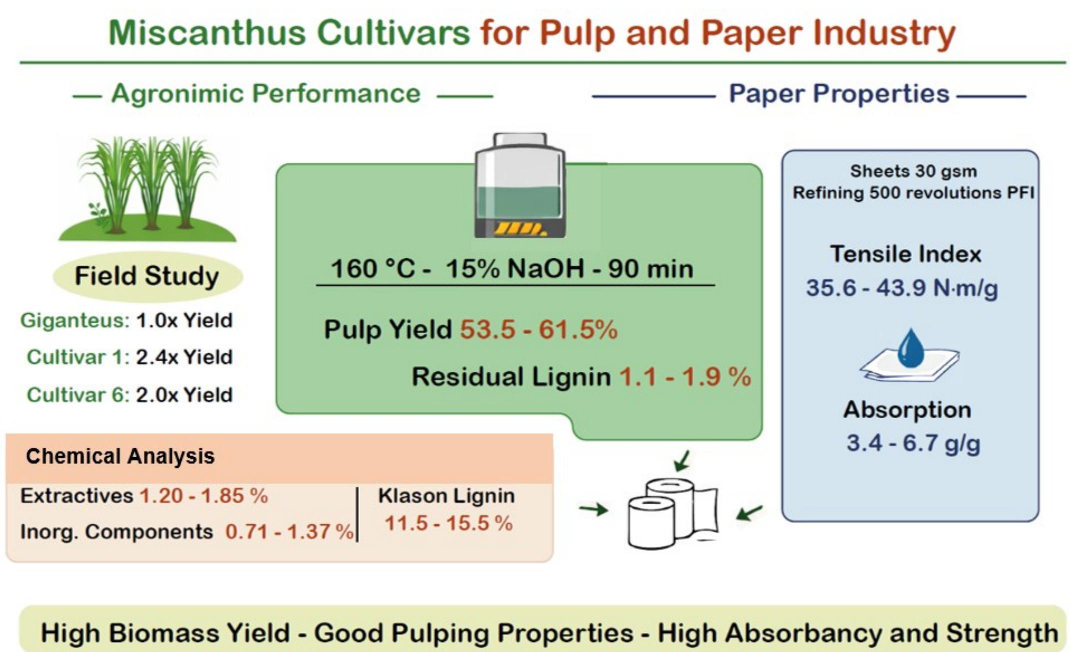
GRAPHICAL ABSTRACT



Evaluation of Unbleached Pulps from *Miscanthus x giganteus* and *Miscanthus* Cultivars for Tissue Paper Production

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This study assessed the suitability of four *Miscanthus* cultivars as alternative raw materials for pulp and paper production. A field evaluation revealed that cultivars 1 and 6 achieved the highest biomass yield ratios, at 2.4 and 2.0, compared to *Miscanthus x giganteus.* Chemical characterization identified cultivar 6 as favorable for pulping, exhibiting low extractives (1.35%), Klason lignin (14.5%) and moderate ash contents (1.37%). Pulp yields of up to 61.5% were achieved by soda pulping at 160 °C for 90 min and the addition of 15% NaOH by weight of the raw material. Cultivar 23 had the lowest residual lignin content at 1.1%. After refining to 500 PFI revolutions, sheets (30 gsm basis weight) produced from cultivar 6 achieved a tensile index of 43.9 N·m/g. The same tensile index as eucalyptus (44.0 N·m/g) was exhibited after 3000 rotations in the PFI mill. Overall, the results demonstrated that the selected *Miscanthus* cultivars, especially cultivar 6, is a promising source of fiber, particularly for products that require high absorbency and strength.

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Keywords: Miscanthus x giganteus; Cultivars; Soda pulping; Fiber properties; Paper; Pulp yield

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INTRODUCTION

Current State

Over the past decades, economic growth and rising living standards have been accompanied by a steadily increasing demand for energy and raw materials, resulting in a strong dependence on fossil resources (Ghatak 2011). In response, renewable biomass has gained increasing attention as a sustainable source for energy and chemicals (Alexopoulou 2018; Świątek *et al.* 2020; Cabrera-Jiménez *et al.* 2022; Lopez *et al.* 2023; Daimary *et al.* 2025), as well as for material applications (Henniges *et al.* 2014; Lavrič *et al.* 2021; Kapun *et al.* 2022; Tofani *et al.* 2024; Ganesh *et al.* 2025). Biomass feedstocks are commonly categorized into first- and second-generation energy crops. First-generation crops, such as maize, sugarcane, soybeans, and rapeseed, have been widely used for bioenergy and bioproducts. However, their cultivation competes with food production and is associated with high energy and resource inputs (Fargione *et al.* 2008; Allwright and Taylor 2016). In contrast, *Miscanthus*, switchgrass, poplar, and willow, which are identified as second-generation crops, offer considerable advantages. These include the ability to grow on low-quality land, low fertilizer and irrigation requirements, and high biomass yields with reduced environmental impact (Heaton *et al.* 2008; Allwright and Taylor 2016).

These advantages have led to the development of new applications. For *Miscanthus*, for instance, these include the construction and building sector as demonstrated in the works of Beck *et al.* 2004; Kursawe 2006; Ferrández-García *et al.* 2012; Dias *et al.* 2021; Schulte *et al.* 2021), or as mulch for fruit trees (Pude *et al.* 2006). Chemical pathways such as the synthesis of 5-hydroxymethylfurfural (HMF) (Światek *et al.* 2022) and bioethanol (Lask *et al.* 2021) have been investigated. What is more, *Miscanthus* is contributing to biodiversity and providing essential habitats for various species (Fritz and Fromowitz 2009)

At the same time, growing environmental consciousness and government regulations aimed at reducing plastic waste have led to a renewed focus on paper-based products. Paper and paperboard are attractive alternatives to petroleum-based packaging materials within a recycling-focused economic model, since they are biodegradable, recyclable, relatively low in density, and mechanically resilient (Oloyede and Lignou 2021). However, the limited availability of wood resources has increased the need to identify alternative fibrous raw materials for pulp and paper production (Danielewicz and Surma-Ślusarska 2019). In this context, annual non-wood plants such as *Miscanthus* have emerged as promising feedstocks, particularly as resource efficiency, environmental performance, and regional availability become increasingly important criteria for sustainable material selection (Fiedler *et al.* 2023).

Among paper products, the tissue and hygiene paper sector represents an attractive application for alternative fiber resources. According to recent market projections, the global tissue and hygiene paper market is expected to reach a value of USD 325.22 billion in 2026. A growth of 3.34 % is predicted for the market by 2030. Toilet paper remains the largest market segment, with an anticipated value of USD 104.61 billion in 2026. Per capita, global consumption is projected to reach approximately 16.9 kg per person per year, equivalent to an average revenue of USD 41.30 per person (Statista 2025). The steadily increasing demand for tissue products makes this sector suitable for the integration of novel fiber sources such as *Miscanthus*.

Miscanthus as a Renewable Biomass Resource

Miscanthus, a perennial grass, belongs to the Poaceae family and is classified as a C4 plant. Native to East Asia, the genus comprises approximately 17 to 20 species (Fritz and Fromowitz 2009). *Miscanthus* was introduced to Europe in the early 20th century, and the genotype later known as *Miscanthus* × *giganteus* originated from a clone collected in Japan and cultivated in Denmark (Clifton-Brown *et al.* 2015). Based on morphological characteristics, the genotype was later recognized as a natural cultivar between *Miscanthus sacchariflorus* and *Miscanthus sinensis* (Greef and Deuter 1993). *Miscanthus* has gained considerable attention as a biomass crop due to its high productivity and efficient use of water and nutrients. Its C4 photosynthetic pathway enables high biomass yields with relatively low inputs, while a single annual harvest and long lifetime allow low-maintenance cultivation (Lewandowski *et al.* 2003).

Despite these advantages, the widespread use of *Miscanthus x giganteus* has been limited by its narrow genetic base, as it originates from a single sterile clone. This genetic uniformity restricts adaptability to different environments and may increase vulnerability to pests and diseases (Sang and Zhu 2011; Hodkinson *et al.* 2015). The narrow genetic base underscored the need for the development of new, site-adapted cultivars to ensure long-term productivity and ecological resilience (Lewandowski *et al.* 2003; Sang and Zhu 2011;

Hodkinson *et al.* 2015). Genetic diversity within the genus enables growth across a wide range of climatic and soil conditions (Heaton *et al.* 2008; Kalinina *et al.* 2017).

Beyond its established role as an energy crop, *Miscanthus* has attracted increasing interest as a renewable raw material for industrial applications. Its fast growth, relatively low lignin content, and adaptability to various climatic conditions could enable energy-efficient pulping processes. In addition, decentralized cultivation of *Miscanthus* can lower transportation-related emissions while providing new income opportunities for farmers, thereby supporting regional bioeconomy concepts and rural development (Lewandowski *et al.* 2003; Gupta *et al.* 2022; Neelisetty *et al.* 2024).

In the last years, a lot of investigations have been carried out, testing the potential of *Miscanthus* for different pulp and paper applications. A comparison of the current literature reveals that many publications on pulp and paper production use *Miscanthus x giganteus* as the primary raw material (Danielewicz *et al.* 2018; Bocianowski 2019; Danielewicz and Surma-Ślusarska 2019; Barbash *et al.* 2020; Tsalagkas *et al.* 2021; Singh *et al.* 2022; Neelisetty *et al.* 2024). The article addresses the current research gap concerning the use of different *Miscanthus* cultivars to expand the genetic diversity for industrial applications and to identify the most suitable *Miscanthus* plants for pulp and paper production. Thus, the quality of the final product could be improved by selecting a different *Miscanthus* cultivar as the raw material. It integrates biomass characteristics, pulping performance, fiber properties, and paper-related quality parameters. In addition, the paper properties are to be compared with those of commercially available eucalyptus pulp in order to classify the properties. In doing so, this research advances the understanding of *Miscanthus* as a versatile lignocellulosic feedstock and the strategic selection of cultivars for specific applications.

EXPERIMENTAL

Miscanthus Cultivars

The raw material was provided by H. Gallin-Ast from "Landwirtschaftliches Technikum F&E – Energiepflanzen". The study compared several *Miscanthus* cultivars with *Miscanthus x giganteus* as reference material. The plant material was obtained from a small *Miscanthus* trial field located near Dachau (Germany). The cultivation of the plants was initiated in a greenhouse in 2011.

Fig. 1. Comparison of the heights of various *Miscanthus* plants. The red lines indicate the location of the individual plants. From left to right: *Miscanthus x giganteus*, Cultivar 1, Cultivar 2, Cultivar 3, and Cultivar 4.

The plants are cultivars of the species *Miscanthus sacchariflorus*, *Miscanthus sinensis*, and *Miscanthus lutarioriparius*. The seeds used for cultivation were collected in various regions of China. Subsequent to the initial planting in the greenhouse, the seedlings were transferred to the trial field. Consequently, the cultivars have been in the field for 13 years. It can be assumed that they have reached their maximum yield potential. As they develop in close proximity to one another, they are subject to uniform climatic and soil conditions, and site-related variability is minimized.

A representative view of the cultivar trial field is shown in Fig. 1, illustrating the pronounced differences in plant height and morphology. *Miscanthus x giganteus* (G) is positioned on the left, followed by cultivar 1 (1) and the remaining cultivars in ascending numerical order, highlighting the substantial phenotypic diversity present within the *Miscanthus* population. Each plant is rendered by red lines.

Preparation of *Miscanthus* for Research

The sample collection took place on 10 September 2024. The material used for the experiments consisted of dried culms from the 2023 growing season that had not been harvested during the typical spring harvest period. The plants were left standing in the field to enable a direct comparison between the 2023 biomass and the 2024 actively growing plants. This provides insight into morphological differences. Based on the morphological survey, four *Miscanthus* cultivars were selected for detailed analysis, along with *Miscanthus x giganteus* as the reference species. The selected cultivars were designated as cultivar 1, cultivar 6, cultivar 23, and cultivar 50. The samples were harvested as they were found on the field. Leaves were not observed on the culms of any of the *Miscanthus* cultivars, which is a good basis for even sample collection. Therefore, only the dried culms of the plants were used for the experiments. They were harvested manually using pruning shears. The collected biomass served as raw feedstock for all subsequent experiments and was stored in paper bags at room temperature in a dry room.

Fig. 2. Comparison of the dried culms and chopped stalks of different *Miscanthus* plants used in this investigation. From left to right: *Miscanthus x giganteus*, Cultivar 1, Cultivar 6, Cultivar 23, and Cultivar 50.

In order to determine the chemical composition of the plant material, the size of the dried culms needed to be reduced. The initial fragmentation was performed using an SM 300 cutting mill (Retsch GmbH, Germany), which was operated at a speed of 1000 rpm and equipped with a 6 mm sieve. In order to carry out the extraction process, the sample was pulverized. The precut material was therefore milled to a particle size of approximately 80 µm using a ZM 300 ultra centrifugal mill (Retsch GmbH, Germany). Figure 2 shows the dried culms and chopped stalks of different *Miscanthus* plants used in this investigation.

An overview of the applied methods is provided in Table 1. The determinations were carried out in duplicate.

Table 1. Overview of the Analytical Methods for the Plant Characterization

Analysis	Method	Standard
Inorganic components	Phoenix Microwave Furnace Asher (CEM Corporation)	TAPPI T211 (2007)
Extractives	Acetone extraction (Acetone 99.9%, CHEMSOLUTE)	TAPPI T204 (2007)
Klason lignin	Acid hydrolysis (Sulphuric acid, CHEMSOLUTE)	TAPPI T222 (2006)

Pulp Production and Characterization

The samples were evaluated for their suitability for chemical pulping. A soda pulping process was applied with an autoclave (Büchi Switzerland) and a volume of 5 L in combination with a Lauda oil heating device. For each cooking process, 350 g of oven-dried biomass was processed at 160 °C for 90 minutes. This corresponds to an H-factor of 740. A NaOH content of 15%, based on the raw material, and a dry-to-liquid ratio of 1:5 were applied. After cooking, the autoclave was opened at approximately 80 °C, and the pulp and black liquor were removed. First, the black liquor was separated from the pulp by washing with water in a screen frame fitted with a nickel-plated sheet-forming screen from a Rapid-Köthen sheet former. Then, the pulp was washed with water using a Rapid-Köthen sheet former to remove residual chemicals and neutralize the pH to 7. Subsequently, the pulps were characterized. Table 2 provides an overview of the applied methods and relevant standards. One pulp cooking was carried out for each *Miscanthus* sample, and the resulting material was used for further testing. All tests were carried out in duplicate. The residual lignin values were calculated from the Kappa number determination by multiplying the Kappa number with the factor 0.12.

Table 2. Overview of Analytical Methods for Pulp Characterization

Analysis	Method	Standard
Yield	Determination of oven-dry mass	DIN EN ISO 638-2 (2022)
Kappa number	Degree of delignification (Sulphuric acid, CHEMSOLUTE) (Potassium permanganate, CHEMSOLUTE) (Potassium iodide, CHEMSOLUTE) (Sodium thiosulphate, CHEMSOLUTE) (Starch, Merck kGaA)	DIN 54357 (1978)
Fiber properties	Optical image analysis	Valmet FS5
Drainage resistance	Schopper-Riegler (Frank PTI)	ISO 5267-1 (1999)

Fiber Processing and Paper Characterization

The pulps were processed to evaluate their suitability for paper making. Before refining, all pulp samples were prepared according to ISO 5263-1 (2004) to ensure consistent samples. The refining was performed using a PFI mill (Frank PTI GmbH, Germany) described in ISO 5264-2 (2011). Afterwards, sheets were produced using a Rapid-Köthen sheet former (ISO 5269-2 2005). The basis weight was reduced to 30 gsm in order to simulate tissue-relevant conditions. After formation, the sheets were air-dried for 24 h in a controlled climate room (DIN EN ISO 187 2022), with one side exposed to the environment, as described by Prinz (2022). This prevents distortion of the softness of the sheets during the drying process. Additionally, the properties of the sheets of unbleached *Miscanthus* pulps were compared with those of a commercially available bleached eucalyptus pulp. In Table 3 the testing methods are shown. For the paper testing, 10 measurements were taken per sample for tensile strength, softness, and capillary rise. The water absorption capacity was tested in duplicate.

Table 3. Overview of the Paper Testing Methods

Analysis	Method	Standard
Tensile strength	RetroLine (ZwickRoell)	ISO 12625-4 (2022)
Softness	TSA (Emtec Electronic)	
Water absorption capacity	Absorption Tester 18010 (Frank-PTI)	ISO 12625-8 (2011)
Capillary rise	Klemm method	DIN ISO 8787 (1994)

RESULTS AND DISCUSSION

Plant Characteristics

The initial differentiation of the *Miscanthus* cultivars was based on observable morphological traits. From the larger cultivar population, four cultivars and the reference species *Miscanthus x giganteus* were selected for a detailed laboratory analysis. The main morphological parameters are summarized in Table 4. Among the plants investigated, cultivar 50 stood out for reaching the greatest culm height (4.3 m) and for its thick-walled, brown culms with a wood-like structure. In addition to visual classification, biomass productivity was evaluated. A 0.5 m² area was used for the measurements, and the number of stalks was counted. Then, the number of stalks per square meter was calculated. The biomass could be determined by combining the weight per stalk with the number of stalks. For comparison, the yield of *Miscanthus x giganteus* was defined as a reference value of 1.0, and the yields of the cultivars were expressed as relative ratios.

Table 4. Plant Characteristics of cultivars from the Testing Field

Name	Stalk height (m)	Stalk diameter (cm)	Weight per Stalk (g)	Stalks per square meter (n)	Biomass Ratio
Giganteus	3.2	0.9	59.74	62	1.0
Cultivar 1	4.1	1.7	158.99	56	2.4
Cultivar 6	3.9	1.8	127.41	56	2.0
Cultivar 23	3.2	1.8	103.97	62	1.8
Cultivar 50	4.3	1.4	118.24	50	1.5

Cultivars 1 and 6 exhibited the highest relative biomass yields of 2.4 and 2.0. This indicates that, under identical site conditions, up to twice the amount of biomass could be harvested compared to *Miscanthus x giganteus*. These elevated yields highlight the potential of these cultivars for large-scale cultivation and industrial utilization.

The chemical composition was analyzed to evaluate the suitability for pulping applications (Table 5). The inorganic content of *Miscanthus x giganteus* was 0.94%. Similar values were observed for cultivars 1, 23, and 50, ranging between 0.71% and 1.0%. Cultivar 6 showed the highest inorganic content among the *Miscanthus* plants investigated, with 1.37%. In literature inorganic content for *Miscanthus* typically ranges from 0.9 to 2.95% (Neelisetty *et al.* 2024) or even 1.6 to 4.0% (Bergs *et al.* 2020), confirming that the cultivars examined in this study exhibit comparatively low inorganic content. Nevertheless, these values remain low compared to other annual lignocellulosic feedstocks, such as 12.4% for banana (Melesse *et al.* 2022), 8.9% for wheat straw (Sheoran 2020), or up to 20% for rice straw (Sinha and Sanjay 2021).

Table 5. Comparison of Plant Components

Name	Inorg. Components (%)	Extractive (%)	Klason lignin (/)
Giganteus	0.94	1.45	15.5
Cultivar 1	0.84	1.85	15.0
Cultivar 6	1.37	1.35	14.5
Cultivar 23	0.71	1.70	11.5
Cultivar 50	0.95	1.20	14.5

The Klason lignin represents a key parameter for the suitability of plants for pulping, as the primary objective of chemical pulping is the separation of cellulose fibers from the lignin matrix (Bajpai 2018). A lower initial lignin content is therefore advantageous. *Miscanthus x giganteus* showed a Klason lignin content of 15.5%, while all investigated cultivars exhibited lower values. Cultivar 23 showed the lowest lignin content with 11.5%. Kim and Um (2020) reported a Klason lignin content of 20.9% for *Miscanthus*. The lower lignin contents observed in the present study could not be fully explained within its scope, but they indicate favorable conditions for efficient delignification.

Pulp Production

The suitability of the selected *Miscanthus* cultivars for chemical pulping was evaluated using a soda pulping process. A key parameter for assessing the pulping performance is the pulp yield (Fig. 3). *Miscanthus x giganteus* exhibited a yield of 53.5%. In contrast, cultivar 6 and cultivar 23 achieved the highest pulp yields, each reaching 61.5%, corresponding to an increase of approximately eight percentage points relative to *Miscanthus x. giganteus*. These yields are within the expected range for annual plants. Pulp yields between 45% and 55% are reported for *Miscanthus x giganteus* (Danielewicz *et al.* 2018).

Together with the biomass productivity of the plants, these results reveal clear differences in overall feedstock suitability. *Miscanthus x giganteus*, defined as a reference with a relative biomass yield of 1.0, showed both low field biomass productivity and a low pulp yield. In contrast, cultivar 6 combined a high relative biomass yield (2.0) with a high pulping yield (61.5%), indicating a higher potential pulp output per unit area.

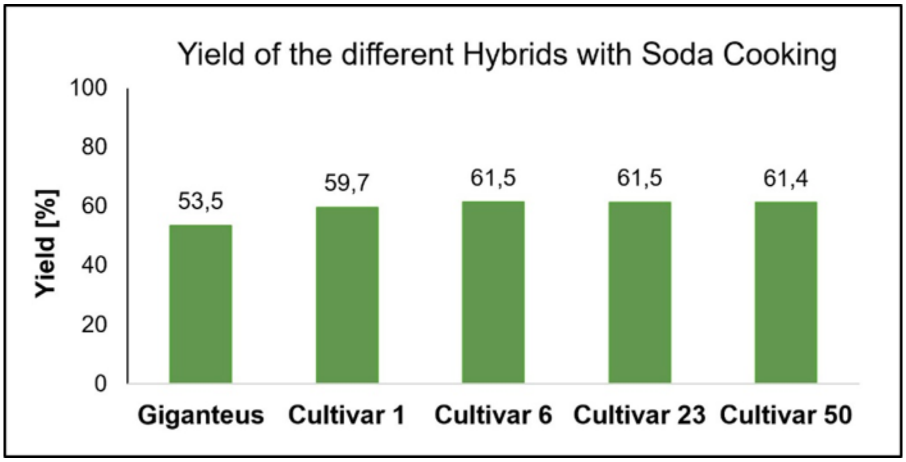

Fig. 3. Pulp yield comparison of *Miscanthus x giganteus* and different *Miscanthus* cultivars

Fiber morphology was further assessed to evaluate the pulp quality. The length-weighted average fiber length, Lc(l) ISO, ranged from 0.89 mm to 0.93 mm for all investigated samples (Table 6). The fiber length differences between the samples were minor, indicating comparable fiber dimensions across the investigated plants. Neelisetty reports a fiber length of 0.656 mm for *Miscanthus sinensis* that was treated with a steam explosion process (Neelisetty *et al.* 2024). Danielewicz and Surma-Ślusarska (2019), on the other hand, show numbers between about 1.0 and 1.13 mm. The cited authors reported that fiber length also depends on the adjustments to the pulping method used.

In addition, the fines A content was analyzed. Fines A represents small, rounded particles below 200 µm, which can increase drainage resistance and negatively affect strength properties when present in high proportions (Niskanen 1998). Cultivar 6 exhibited the lowest fines A content (25.5%), whereas cultivar 23 showed the highest value (30.1%), which is a difference of 4.6 percentage points. Although both cultivars achieved similarly high pulp yields, the substantially higher fines content of cultivar 23 suggests inferior pulp quality compared to cultivar 6.

Table 6. Fiber Characteristics

Name	Fiber length (mm)	Fiber width (µm)	Fines A (%)	Kappa Number (/)	Residual Lignin Content (%)
Giganteus	0.93	20.61	28.0	15.7	1.9
Cultivar 1	0.89	20.16	27.1	12.4	1.5
Cultivar 6	0.89	19.96	25.5	10.0	1.2
Cultivar 23	0.93	20.71	30.1	9.1	1.1
Cultivar 50	0.92	23.74	27.9	10.5	1.3

The effectiveness of the delignification during the soda pulping was assessed by comparing the initial Klason lignin content of the raw material with the residual lignin content after cooking (Fig. 4). The residual lignin values were calculated from the Kappa number determination by multiplying the Kappa number with the factor 0.12. The residual lignin indicates the amount of lignin that remains in the pulp after the chemical treatment. A greater reduction suggests a more efficient pulping process.

For *Miscanthus x giganteus*, the Klason lignin content decreased from 15.5% to 1.9%, corresponding to a reduction of 13.6 percentage points. Cultivar 6 showed a comparable reduction, with a lignin decrease from 14.5% to 1.2%. Cultivar 23 achieved the lowest residual lignin content with 1.1%. For all the plants investigated, the lignin content could be greatly reduced, demonstrating effective lignin removal. The results indicate that soda pulping is an effective method for *Miscanthus*.

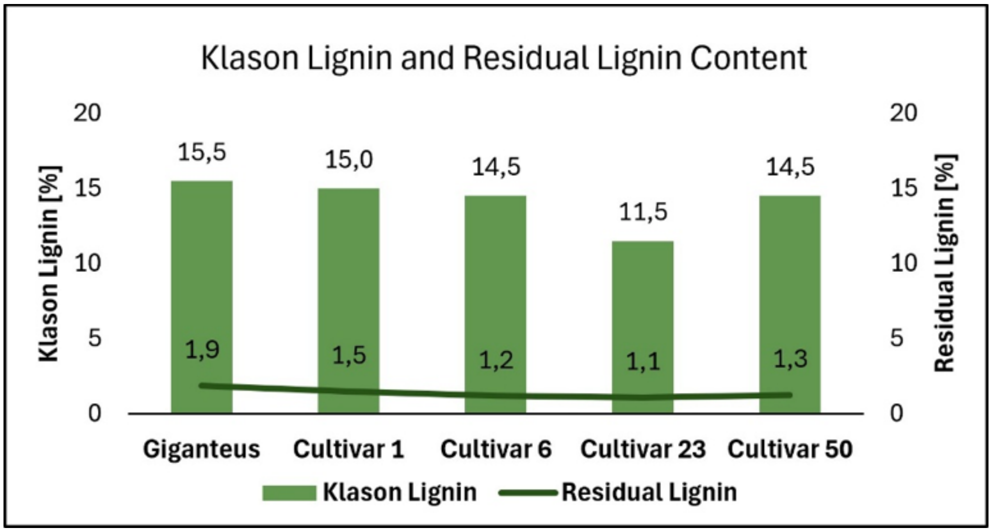

Fig. 4. Comparison of Klason lignin and residual lignin contents after the pulp cooking of *Miscanthus x giganteus* and different *Miscanthus* cultivars

Paper Properties

The paper properties were evaluated and compared with sheets made from industrial reference pulps to assess their suitability for tissue applications. As a reference point, bleached eucalyptus kraft (BEK) was used and refined with 1000, 2000 and 3000 rotations in the PFI mill. The eucalyptus pulp results were obtained from Prinz (2022). The reference material provided a relevant framework for comparison. The *Miscanthus* results presented in this section refer to sheets produced from pulps refined at 500 revolutions in the PFI mill.

Figure 5 illustrates the correlation between the tensile index and the Schopper–Riegler (SR) results. The eucalyptus-based samples start in the lower-left region of the diagram, indicating comparatively low drainage resistance and moderate tensile strength. After refining in the PFI mill at 2000 rotations, the eucalyptus showed a tensile index of 37.1 N·m/g, which was a little high in comparison to *Miscanthus x giganteus* (35.6 N·m/g) and cultivar 23 (35.9 N·m/g). The *Miscanthus* cultivars in total were shifted towards higher SR values, reflecting a reduced drainage but generally enhanced strength development. Within the *Miscanthus* group, differences in tensile performance were observed. Cultivar 6 achieved the highest tensile index of 43.9 N·m/g, indicating superior bonding potential and fiber interaction. Cultivar 6 exhibited the same tensile index at 500 rotations in the PFI mill as eucalyptus (44.0 N·m/g) did after 3000 rotations. This demonstrates its great potential for paper production. Moreover, the influence of refining on tensile strength is particularly pronounced for cultivar 6. Without refining, the tensile index of cultivar 6 was 13.8 N·m/g, whereas refining to 500 revolutions increased the value to 43.9 N·m/g. Considering that these measurements were performed on sheets with a basis weight of 30 gsm, this result highlights the strength potential of cultivar 6, making it a promising candidate for tissue paper products.

Fig. 5. Tensile index to Schopper-Riegler at 500 revolutions in the PFI mill for *Miscanthus x giganteus* and different *Miscanthus* cultivars, compared to bleached eucalyptus kraft refined at 0, 1000, 2000 and 3000 revolutions in the PFI mill.

In addition, the tensile index was evaluated in combination with softness, as both parameters are critical for assessing the suitability of pulps for tissue paper applications (Fig. 6). From an application-oriented perspective, an optimal tissue pulp combines high tensile strength with high softness, which corresponds to the lower right region of the diagram. In general, an increasing tensile index is accompanied by a reduction in softness, expressed by higher TS7 values. *Miscanthus x giganteus* is located near the center of the plot, achieving a tensile index of 35.6 N·m/g. However, this higher strength is associated with reduced softness, limiting its direct applicability for tissue production. A similar trend was observed for the other *Miscanthus* cultivars. Cultivar 6 reached the highest tensile index among all tested samples but simultaneously exhibited a comparatively rough surface. These results highlight that, although *Miscanthus* cultivars have promising strength properties, they cannot be used for tissue production without blending with softer raw materials, such as eucalyptus, to achieve a balanced property profile.

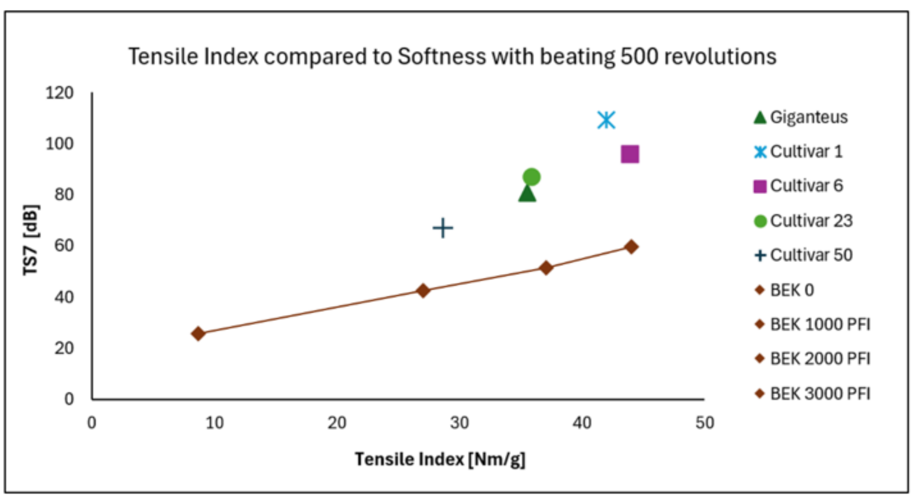

Fig. 6. Tensile Index to Softness at 500 revolutions in the PFI mill for *Miscanthus x giganteus* and different *Miscanthus* cultivars, compared to bleached eucalyptus kraft refined at 0, 1000, 2000 and 3000 revolutions in the PFI mill.

Comparable trends have been reported by Prinz (2022), who investigated the correlation between tensile index and softness for pulps from various non-wood raw materials. Unrefined bagasse exhibited a tensile index of approximately 14 N·m/g with a TS7 of 43 dB, while wheat straw showed a tensile index of 16 N·m/g and a TS7 of 55 dB (Prinz 2022). The unrefined cultivar 6 showed a tensile index similar to that of bagasse. At the same time, a TS7 of 31.0 dB was reached. *Miscanthus x giganteus* even underscored this value with a TS7 of 27.5 dB. Compared to other annual fiber sources, *Miscanthus x giganteus* and cultivar 6 were in the lower TS7 range, which indicates that they have comparatively softer surfaces. Overall, the results confirm that no single alternative fiber can fully substitute eucalyptus for tissue paper production without property trade-offs.

The water absorption behavior was evaluated using the capillary rise and water absorption capacity as complementary indicators of the liquid uptake. The capillary rise represents the capillary-driven vertical water uptake in a paper stripe, while the absorption capacity reflects the total amount of water retained after full immersion. The results are presented in Fig. 7.

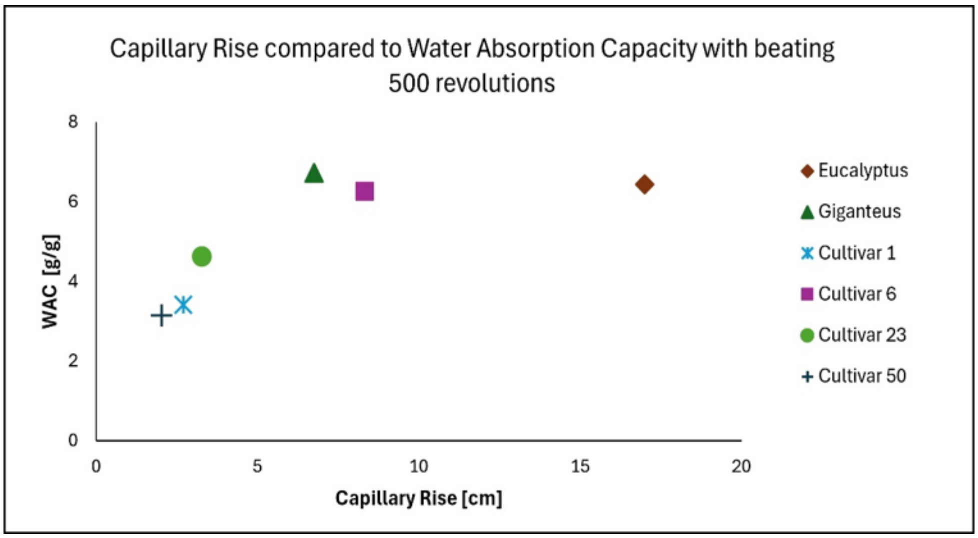

Fig. 7. Capillary rise to water absorption capacity at 500 revolutions in the PFI mill for *Miscanthus x giganteus* and different *Miscanthus* cultivars, compared to bleached eucalyptus kraft (all own data).

The commercial eucalyptus pulp is located in the upper right region of the diagram and exhibited the highest capillary rise (18.0 cm) combined with high absorption capacities of about 6.4 g/g. *Miscanthus x giganteus* and cultivar 6 are located in the central region. They demonstrated a moderate capillary rise, yet their absorption capacities were comparable to those of the reference materials. *Miscanthus x giganteus* reached an absorption capacity of 6.7 g/g, while cultivar 6 achieved 6.3 g/g. This property combination suggests potential suitability for absorbent tissue applications such as kitchen towels.

In addition to the quantitative results, distinct differences in wettability were observed during testing. Unrefined sheets initially floated on the water and required manual force for immersion, indicating limited wettability. This effect was particularly pronounced for unrefined *Miscanthus x giganteus* and cultivar 6, which showed low absorption capacities of 1.9 g/g and 2.2 g/g. Refining markedly altered this behavior. After 500 PFI revolutions, both materials exhibited an increase in absorption capacity, exceeding the values of the commercial references. This improvement is likely due to the increased accessible surface area of the fibers resulting from refining. The newly exposed surfaces may contain fewer hydrophobic substances, thereby enhancing fiber wettability and water absorption capacity.

CONCLUSIONS

1. Initial field analysis provided insights into the agronomic behavior of various *Miscanthus* cultivars cultivated in a single harvest location. Distinct growth patterns and structural differences among the cultivars were identified. In terms of harvest yield, cultivars 1 and 6 were the most efficient, with promising yield ratios of 2.4 and 2.0, which indicates their superior biomass potential.
2. Further, the material characterization was used to classify each plant. Cultivar 6 exhibited favorable chemical characteristics for pulping, such as low extractives (1.35%), low Klason lignin (14.5%), and moderate ash content (1.37%). In comparison, *Miscanthus x giganteus* had a higher extractive (1.45%) and lignin content (15.5%).
3. Among all *Miscanthus* plants, cultivar 6 was judged to be the most promising source of fiber under the given pulping conditions. Despite its slightly shorter fibers, reflected in a Lc(l) ISO of 0.89 mm, it offered the highest yield of the investigation. In particular, its lower fines A content (25.5%) and residual lignin of 1.2% after pulping indicate a high processing efficiency. Although cultivar 23 achieved a comparable yield and the lowest residual lignin content (1.1%), it exhibited a higher fines A content (30.1%), which may impact its mechanical properties and processability.
4. Comprehensive paper testing revealed that *Miscanthus* pulps performed well in key papermaking parameters. After 500 revolutions of refining, cultivar 6 reached a tensile index of 43.9 N·m/g, demonstrating a high strength potential. It exhibited the same tensile index as eucalyptus (44.0 N·m/g) after 3,000 rotations in the PFI mill. Its water absorption capacity of 6.3 g/g indicates its suitability for tissue and hygiene applications. However, due to its lower softness values, it must be blended with other pulps to meet the comfort expectations of tissue products.
5. Overall, the findings of this study highlighted the potential of *Miscanthus* cultivars, especially cultivar 6, as a potential sustainable alternative to wood-based fibers. Nevertheless, this study is the beginning of further research. To evaluate the *Miscanthus* cultivar further, harvests from different years must be compared to assess their stability. Additionally, the soda pulping process must be optimized for *Miscanthus* to achieve the best possible yield and fiber quality. It is also important to consider black liquor and its potential uses. The blending of *Miscanthus* pulp with other types of pulp also needs further investigation. To validate the laboratory results on a larger scale, further validation at the pilot or industrial scale is required. Based on this work, the questions are to be clarified within a doctoral dissertation.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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