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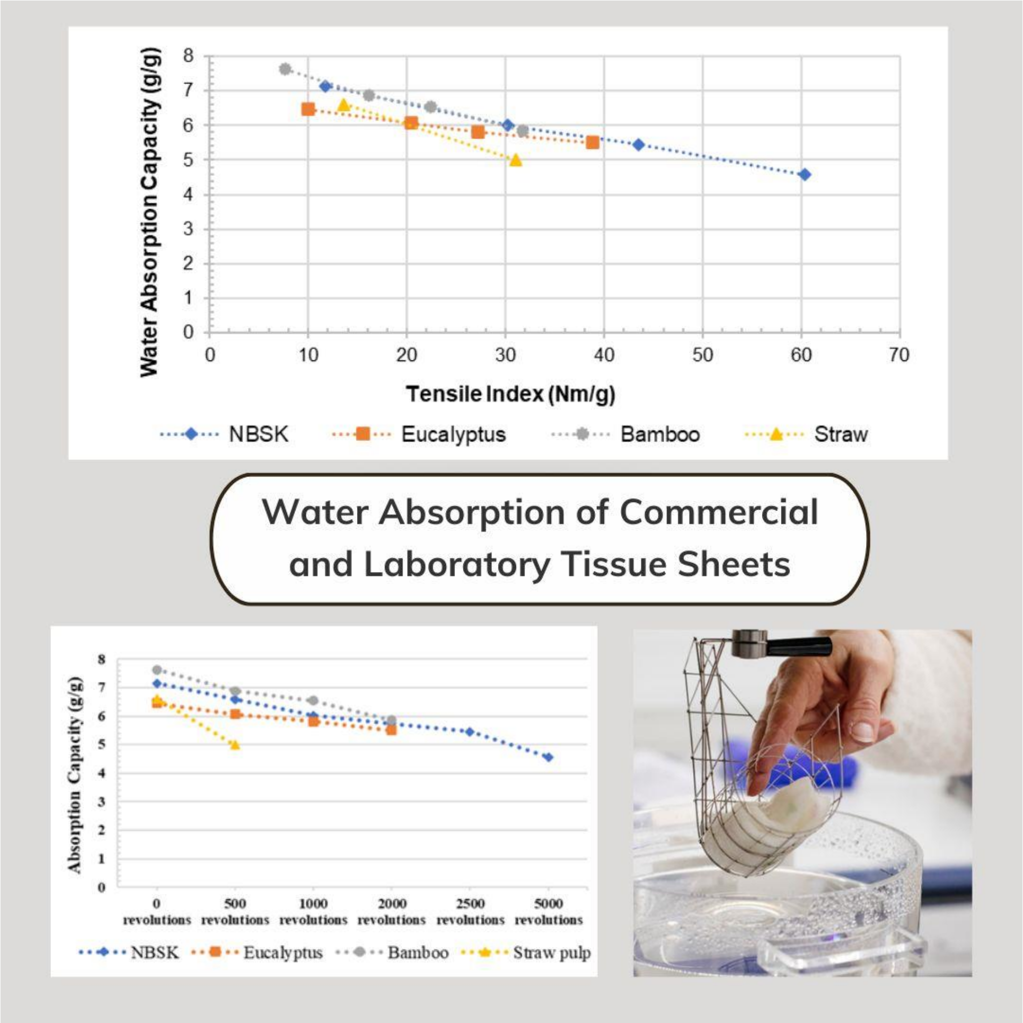
GRAPHICAL ABSTRACT



Water Absorption of Commercial and Laboratory Tissue Sheets

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Commercial kitchen towels (basis weight 39 to 56 g/m²) made of virgin and recycled fiber, produced by Through-Air-Drying (TAD), and conventional Yankee cylinder drying (with creping) were analyzed. The properties of these commercial tissue products were compared to those of handsheets made from them. Laboratory tissue handsheets were also prepared from northern bleached softwood kraft (NBSK), eucalyptus, bamboo, and straw pulp. Fibers were refined with up to 5000 revolutions of a PFI mill. Commercial kitchen towels (kitchen tissue) absorbed 9 to 14 g water per 1 g of fiber, with higher absorption by virgin fibers, and when using TAD. The tensile index (dry) was 3 to 14 Nm/g. Laboratory tissue handsheets made of commercial samples absorbed less water, but the tensile index (dry) was higher in most cases. Higher beating levels (tested at NBSK, eucalyptus, bamboo, straw pulp) increased tensile index. Curl, bulk, softness, absorption capacity, and suction lift were reduced with refining. Best values for absorption capacity (almost 8 g/g), bulk (almost 5 cm³/g), and softness were observed in laboratory bamboo tissue sheets made of non-refined fibers. After refining (2000 revolutions), the tensile index of such tissue sheets made of bamboo increased from 10 to 30 Nm/g.

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Keywords: Water absorption; Refining; Tissue; Trough-Air-Drying; TAD non-wood fibers; Kitchen towels

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INTRODUCTION

The term tissue or tissue paper is increasingly used as a synonym for kitchen towel products. Tissue paper is a collective term for wet, and dry-creped papers with a low grammage. This paper, or the products made with this paper, must have a high degree of softness and water absorbency. Tissue paper is largely made from natural materials. These include virgin fibers from wood, and – to a much lesser extent – annual plants or non-wood pulps, or recovered paper. To achieve certain tissue properties or to optimize the production process, additives (chemicals such as retention agents, wet strength agents, dyes, plasticizers, *etc.*) are also required.

The tissue hygiene paper market consists of the segments baby diapers, face masks, feminine hygiene, household paper, incontinence, paper tissue, and toilet paper. In 2024, the worldwide market revenue is reported to be 352 billion USD, and predicted to grow to 431 billion USD in 2028 (data by STATISTA 2024). The worldwide market size of paper tissue is 19 billion USD, of household paper 90 billion USD, and of toilet paper (including wet toilet paper) 114 billion USD in 2024 (STATISTA 2024). For Germany, the German Environment Agency (UBA) reported for 2017 a hygiene paper consumption of 1,592 kt/a, with less than 10% recycled fibers, of which 80% are short fibers, and 20% are long fibers (Wellenreuther *et al.* 2022). The Association of German Paper Mills (VDP) reported 1,526 kt/a hygiene paper production (sanitary and household) in 2020 in Germany, which is approximately 7% of the production volume of all paper, and board (Moldenhauer *et al.* 2021). Even though such statistics are associated with some uncertainty, the market relevance of tissue is demonstrated by these figures.

Tissue products are designed to absorb and bind liquids in kitchens, and for personal hygiene. Their technical parameters rely on fiber selection (plant, virgin *versus* recycled fibers), fiber refinement (pulping process, beating), fiber characteristics (liquid absorption capacity, mechanical properties), production technology of the tissue machine (conventional, Through-Air-Drying (TAD), wet molding), additives (wet strength agent, filler), embossing (Spina and Cavalcante 2018), and basis weight (typically 10 to 50 g/m²) (Holik 2006; Kocurek and Smook 2016; de Assis *et al.* 2018; Pawlak *et al.* 2022; Sjöstrand *et al.* 2023). Embossing improves perceived tissue softness (Pawlak *et al.* 2022). Kitchen tissue should quickly absorb liquid, have a high liquid absorption capacity, have a high bulk, and a high tensile strength (both dry and wet). Toilet paper, in addition, should be soft.

Kitchen towels (kitchen tissue) is most often made with a basis weight of 38 to 56 g/m^2 according to the Austrian consumer test magazine “Konsument” (2019), with products typically comprising 2 to 3 plies (mostly 3 plies). These tissue towels were made of both virgin and recycled fibers, with end consumer prices ranging from 0.11 to 0.35 €/m². Toilet paper in 2017 was reported to have a basis weight of 47 to 55 g/m^2 in this magazine. This toilet paper also used virgin and recycled fibers, with end consumer prices for 100 sheets ranging from 0.11 to 0.27 €/m² (Konsument 2018; Konsument 2019). Wang analyzed “bath tissue” and reported instances of 1 to 3 plies (mostly 2 plies); a basis weight of approximately 18 to 55 g/m² for tissue made *via* light drying-crepe (LDC), and 30 to 48 to 55 g/m² for tissue made *via* TAD (Wang 2019b). It has been reported that multiple plies increase tissue softness (Pawlak *et al.* 2022). Tissue paper made of cellulose fibers absorb typically 2 to 10 g (Gigac *et al.* 2020), or 8 to 10 g (Morais *et al.* 2019) of water per 1 g of fiber. Removing lignin from the pulp improves water absorbency.

Tissue paper is made of pulp derived from wood, agricultural residues, or recycled paper. Wood fibers are classified into two categories: softwoods, or conifers (*e.g.*, pine, and spruce); and hardwoods (*e.g.*, birch, eucalyptus, and beech) (Kocurek and Smook 2016). Producers of kitchen tissue favor softwoods due to their long fibers (1.4 to 6.0 mm), which contributes to greater strength. In contrast, hardwoods with shorter fibers (0.4 to 1.6 mm) contribute to the tissue’s softness, an important property for handkerchiefs and toilet paper (Holik 2006; Gullichsen and Paulapuro 2000). Tissue is also made from recycled paper. Impurities, such as metal, plastic, glass, and synthetic materials, are removed from it during processing. During stock preparation not only flotation deinking is required but also a washing to remove the fillers is necessary. A trend in the pulp industry is the use of non-wood plants (Pawlak *et al.* 2022; Lexa *et al.* 2023). Therefore, in addition to wood and recycled fibers, virgin non-wood fibers from bamboo, hemp, kenaf, sugarcane bagasse, and agricultural straw are used for tissue. These non-wood fibers offer an alternative to address the increasing fiber demand, especially when the availability of wood fibers is limited (Ashori 2006). As mentioned before, the quality of tissue products depends on the choice of raw materials, chemicals, machine settings, and converting processes. Key additives, including wet strength agents, dyes, retention aids, and coating chemicals, play a significant role and impact the final properties of tissue paper used.

Cellulose fibers are hydrophilic and form hydrogen bonds with water, which is crucial for liquid absorption. Capillary forces also contribute to the liquid penetration and absorption, leading to wicking by the porous medium. Factors influencing water absorption include the raw materials, additives, fibrous network structure, pressing, creping, number of plies, grammage, porosity, and pore size. Additionally, high fiber coarseness enhances bulk and absorbency, while low fiber bonding strength aids in creating inter-fiber pore volume, resulting in bulkier, and more liquid absorbent products made from curly fibers (de Assis *et al.* 2018).

Fibers are often curly. Curled fibers may form fewer inter-fiber bonds. However, the curl of fibers increases bulk, and wet web stretch, which are desired effects. Softness is a complex property of hygiene papers influenced by fiber selection, including hardwood and softwood fibers, fiber stiffness, compressibility, and surface roughness (Trepanier 2017). Curly fibers contribute to higher softness, while low coarseness allows for more flexible fibers, resulting in better softness. For a tissue from recycled fiber, lower softness was observed (Jordan 2020).

Creping is an important process for tissue paper (Qin *et al.* 2023). With creping, the tissue becomes softer, and water absorption increases. The creping process breaks some of the fiber bonds; free fiber bonds as well as crepe folds develop, adding bulk, and softness (Preeyanuch *et al.* 2015; de Assis *et al.* 2020; Jordan 2020; Pawlak *et al.* 2022; Qin *et al.* 2023). Tissue strength is often an antagonist to softness (Morais *et al.* 2019; Kumar *et al.* 2022), and liquid absorbency (Zambrano *et al.* 2021; Kumar *et al.* 2022), *i.e.*, it is reduced by creping (Preeyanuch *et al.* 2015; de Assis *et al.* 2020).

An option to increase strength in paper products is the refining of fibers. As a side effect, the drainage rate of the fiber suspensions is reduced (Ahmed *et al.* 2024). This can be measured by the degrees Schopper-Riegler (SR) value. A higher content of fines (which partially can contribute to improving the fiber bonding) reduces at the same time the open pore volume (*i.e.* less cavity for water absorption) and also the softness in the end-product. A low SR value is indicative of efficient drainage within the fiber web. This characteristic is highly desirable in tissue paper production because effective water removal during the tissue papermaking process significantly and positively influences both product quality and manufacturing efficiency. In the context of absorption, a lower SR value is preferable, as it allows the tissue paper to retain liquid more effectively (higher bulk of paper), contributing to improved absorption performance. Conversely, a high SR value signifies inadequate drainage within the tissue paper pulp, causing water to drain more slowly. However, higher strength properties are obtained. Therefore, the significance of the SR value varies depending on the specific requirements of paper products, whether it is for drainage efficiency or absorption capacity.

Tissue paper is produced by three methods and types of machines: conventional tissue machines, through-air-drying (TAD) tissue machines, and wet molding tissue machines. 1) Conventional tissue machines operate at speeds of up to 2200 m/min, with a typical width of 2.8 to 5.70 m and a length of about 45 m. The maximum performance of a tissue machine is up to 70,000 tpa of tissue papers. The web, produced within a gap former (specifically, a crescent former equipped with both a wire and felt), is transported to the dryer section using a felt. In this section, the dewatering process first occurs through a vacuum mechanism, followed by the application of pressure *via* a suction press roll or a shoe press, which acts against the Yankee cylinder. Subsequently, the web undergoes a drying process, attaining approximately 95 to 96% dryness through direct contact with the Yankee cylinder. In addition to contact drying with the Yankee cylinder, the paper web is also dried using impingement drying with hot air from the hood. Lastly, it undergoes a creping process facilitated by a creping doctor (Holik 2006). 2) TAD technology, known as the "Through-Air-Dry" technique (Sjöstrand, 2023), produces a structured tissue product with greater bulk and absorption capacity compared to tissue products produced on a conventional tissue machine at the same basis weight. This is achieved by passing air through the sheet on the TAD cylinder. Then the paper web is partially pressed against the Yankee cylinder to achieve the final dry content (Kowalska *et al.* 2019). TAD is described as an important development for producing soft tissue (Pawlak *et al.* 2022). The TAD tissue machine produces premium products but consumes more thermal and electrical energy than the conventional tissue machine. It operates at speeds up to 2000 m/min, with a typical width of 2.8 to 5.6 m, and a length of about 60 to 80 m. (Holik 2006; de Assis *et al.* 2018). 3) The wet molding tissue machine produces high-premium tissue with lower energy consumption. It operates at speeds of about 1600 m/min, with a typical width of 2.8 to 5.6 m, and a length of about 50 to 60 m. The maximum performance of wet molding machines is 70,000 tpa. The web formation occurs similarly to a conventional Crescent former, but uses a structured molding fabric instead of a felt. After the structured web is formed, the web is dewatered with the help of a vacuum roll. A hood supplies hot air and steam to increase temperature and decrease water viscosity for more effective dewatering. A press, consisting of a plain shell roll and a suction roll, gently dewaters the web. Due to the structured fabric, only 20 to 25% of the web is pressed at the peaks of the fabric, protecting the fibers in the fabric pockets. After the dewatering stages, the structured web is transferred to the Yankee cylinder for final drying. The web is then creped using a creping blade (Holik 2006).

Publications regarding fiber sources are limited. In particular, a comparative analysis is lacking. The intention of this study was to compare various types of kitchen tissues, and investigate four different pulps (NBSK, eucalyptus, bamboo, and straw), and the study aimed to examine different drying methods (air-drying, oven-drying, and dryer of the tissue handsheet maker) on two of these fibers.

EXPERIMENTAL

Commercial Kitchen Towels (kitchen tissue) for Measuring the Water Absorption

First part

In the first part, six different, commercial kitchen towels (kitchen tissues) (Table 1) were analyzed to gain benchmark values.

Table 1. Tested Kitchen Towels (Kitchen Tissue)

No.	Sample	Fiber	Tissue Production Method
1	2 plies, 42 g/m²	virgin	TAD
2	2 plies, 39 g/m²	virgin, (30% less virgin fiber)	TAD
3	3 plies, 54 g/m²	virgin	conventional
4	3 plies, 56 g/m²	recycled	conventional
5	2 plies, 37 g/m²	virgin	TAD
6	3 plies, 52 g/m²	virgin	conventional

The number of plies (layers) was obvious by visual analysis. Fiber origin (virgin versus recycled) was printed on the packaging and visually detectable from inspecting the samples. The production method is known by the background expertise of the authors.

Water absorption was measured according to DIN EN ISO 12625-8 (2010) with an absorption tester (Frank-PTI, Birkenau, Germany) ten times per sample using tap (Munich, 2022), and deionized water (made with ion-exchanger) to identify any differences. The tap water is classified as "hard", with a total hardness measuring 2.8 mmol/L (15.6 °dH) (SWM 2023). The sample was under water for 30 s, and then the water was drained for another 60 s. The measurements were taken under controlled climatic conditions (23 °C, 50% relative humidity).

Development of a Laboratory Method to Measure Water Absorption Capacity

Second part

The next step focused on the development of a reproducible tissue handsheet making and drying procedure regarding water absorption capacity and rate using two different types of fibers: NBSK (Södra, long fiber from pine and spruce), and eucalyptus (Santa Fe, short fiber). The aim was to develop a laboratory method to evaluate the influence of fiber type on the water absorption capacity, and rate. The method developed for the absorption tests is based on the method of testing the hand-feel potential (Prinz *et al.* 2020).

Tissue handsheets with a grammage of 30 g/m² were analyzed. Following DIN EN ISO 5263-1 (2004) guidelines, the pulps were disintegrated, and handsheets were produced using the Rapid-Köthen handsheet former. These sheets were dried, and the water absorption was measured. In order to study the influence of the drying method onto the absorption properties, three different drying methods of the tissue handsheets were used: air drying in a climate room (23 °C, 50% relative humidity); drying in a Rapid-Köthen handsheet former; and drying in an oven at 105 °C for 60 min.

Third part

Next, water absorption capacity and rate of commercial kitchen towels (kitchen tissue) were compared with laboratory handsheets produced according to a newly developed tissue handsheet making procedure. For this investigation three different kitchen towels (kitchen tissue, No. 4, No. 5, No. 6, see Table 1) were chosen. To produce the tissue handsheets these kitchen towels were soaked for at least 12 h in water, disintegrated to a fiber slurry, and then used to produce tissue handsheets using a sheet former (Rapid-Köthen S95854, Frank-PTI, Birkenau, Germany), and a handsheet maker according to DIN EN ISO 5269-2 (2004). All samples were produced on the Rapid-Köthen handsheet maker.

For both the kitchen towels and the tissue handsheets, various properties were measured. These included basis weight (DIN EN ISO 12625-6 (2016)); caliper density (DIN EN ISO 12625-3 (2014)); softness using the Tissue Softness Analyser (TSA, emtec Electronic GmbH, Leipzig, Germany) (Perng *et al.* 2019; Wang 2019; Prinz *et al.* 2020); suction lift (Klemm Capillary Rise Tester; DIN ISO 8787 (1994)); absorption capacity and absorption rate (Absorption Tester, Frank-PTI, Birkenau, Germany; DIN EN ISO 12625-8 (2010)); tensile strength (ZwickRoell, Ulm, Germany; DIN EN ISO 12625-4 (2022)).

Pulps for Measuring the Influence of Refining on Tissue Properties

Fourth part

The aim was to analyze tissue handsheet properties of four different types of pulp, each subjected to refining processes. The pulps examined were “Södra blue 85Z” (Växjö, Sweden), which is a northern bleached softwood kraft pulp (NBSK); Santa Fe (Santiago Chile), which is a hardwood pulp from eucalyptus; bamboo pulp; and straw pulp (J. Rettenmaier & Söhne GmbH+CO KG, Rosenberg, Germany). The pulp was soaked for 4 h and then disintegrated (DIN EN ISO 5263-1, 2004). The different pulp samples were refined using a PFI mill, and 30 g/m² tissue handsheets were produced. The tissue sheets were air dried for more than 12 h at 23 °C and 50% relative humidity in a climate-controlled room before their properties were measured. The basic weight, bulk, tissue softness (TSA, emtec, Leipzig, Germany), absorption capacity and absorption rate (adsorption tester, Frank-PTI, Birkenau, Germany), and suction lift were measured according to the given standards. Additionally, SR-value (DIN EN ISO 5267-1 (2000)), fines, and curl (Valmet FS5, Espoo, Finland) were measured from the stock after refining, prior to the handsheet production

RESULTS AND DISCUSSION

Commercially Produced Kitchen Towels (Kitchen Tissue)

First part

The water absorption capacity was tested in a pre-trial using tap water (hardness 15.6 °dH), and deionized water. Taking the error bars into account, the differences were negligible (Table 2). Therefore, available tap water could be taken for absorption tests. Commercial kitchen towels (kitchen tissue) made of virgin fiber using TAD absorbed the most water (Table 2). The tissue made of virgin fiber with a conventional production method absorbed 1.4 to 1.7 g less water per 1 g of fiber, and for the recycled fiber even approximately 5 g less water per 1 g of fiber. Conventionally produced kitchen towels typically absorb 7 to 9 g water per 1 g fiber. As confirmed in this study, tissue manufactured using TAD-technology absorbed more water. Reported values (usually crafted as two-ply) are approximately between 11 to 14 g/g, and in some cases even as high as 17 g/g (Blechschmidt 2013).

Table 2. Liquid Water Absorption of Commercial Tissues Sheets (see Table 1)

No.	Fiber	Production Method	Absorption Capacity (g Water/g Fiber)	
			Deionized Water	Tap Water
1	Virgin	2 plies, TAD	14.2 ± 0.1	14.0 ± 0.1
2	Virgin, (30% less)	2 plies, TAD	13.7 ± 0.6	13.9 ± 0.1
3	Virgin	3 plies, conventional	12.5 ± 0.2	12.6 ± 0.2
4	Recycled	3 plies, conventional	8.9 ± 0.3	9.0 ± 0.2

Dry and wet tensile strengths were determined. The relative wet strength (ratio of the strength in the wet, and dry state) had a maximum value of up to 31% (Table 3). However, the wet strength, a critical factor for practical use, was good across all samples. The high wet strength of No. 4 made of recycled fibers indicated a higher dosage of strength agents. The strength of fiber-based materials made from recycled fibers is usually lower in comparison to virgin fiber materials, unless the strength is improved by additives. Tensile strengths were higher in machine direction (MD) than in cross direction (CD) due to fiber orientation, and in most cases better for tissues made from virgin fibers compared to recycled fibers due to assumably longer fibers, which was also expected. Values for tissue produced by TAD were in many cases higher than for the conventional method.

Table 3. Mechanical Properties

	Tensile Index (Nm/g)		Elongation (%)		Relative Wet Strength (%)
	Dry	Wet	Dry	Wet	
No. 1, CD, virgin fiber, TAD	**10.4**	**2.6**	**9.0**	**6.4**	**25.1 ± 0.9**
No. 1, MD, virgin fiber, TAD	14.3	3.6	12.8	8.5	24.9 ± 0.8
No. 2, CD, virgin fiber, TAD	**10.4**	**1.2**	**12.7**	**6.4**	**11.6 ± 0.7**
No. 2, MD, virgin fiber, TAD	10.6	2.3	13.0	7.3	21.4 ± 1.6
No. 3, CD, virgin fiber, con.	**5.3**	**1.3**	**7.4**	**6.4**	**19.2 ± 1.8**
No. 3, MD, virgin fiber, con.	8.8	1.7	10.7	6.6	25.2 ± 1.0
No. 4, CD, recycled fiber, con.	**3.0**	**0.8**	**5.1**	**4.4**	**27.6 ± 1.4**
No. 4, MD, recycled fiber, con.	5.7	1.8	9.1	5.6	30.9 ± 2.9

CD: cross direction, MD: machine direction, relative wet strength with standard deviation, compare with Table 1

Impact of a Tissue Handsheet Drying Method onto Absorption Properties

Laboratory tissue handsheets of different basis weights, and various drying methods were compared and their impact on the absorption capacity of tissue handsheets was tested. For this investigation, different unbeaten fibers were analyzed. The NBSK pulp had a length weighted average fiber length Lcl(ISO) =2.45 mm, and an average width of 19.4 µm. The eucalyptus pulp had an average fiber length of 0.86 mm, and an average fiber width of 11.9 µm. The optical coarseness of the NBSK fibers was higher (0.12 mg/m) compared to the optical coarseness of the eucalyptus fibers (0.05 mg/m). The eucalyptus pulp had a higher Schopper Riegler (23 SR) compared to 12 SR for the NBSK pulp, and a higher fines content. These parameters can cause a denser sheet structure (less bulk), and therefore a reduced absorption capacity.

For the measurement of water absorption capacity, samples with 76 ± 1 mm width were cut out of the tissue handsheets. The total mass of each sample to be tested was 5.0 ± 0.2 g, which was rolled and added to the basket. A lower basis weight of the tissue handsheet means that more plies (layers) of materials are necessary. Figure 1 shows that with increasing basis weight, the water absorption capacity decreased. One explanation is that water was not only absorbed in the porous structure of the tissue but also on the surface of the tissue layer. This effect had a disproportionately higher impact on samples with a lower grammage. The 30 g/m² tissue handsheets represented more the industrial production; therefore, for subsequent analysis, this basis weight was chosen. The Rapid Köthen drying method densified the tissue handsheets; thus, the water absorption capacity was greatly reduced. Tissue handsheets produced using the air-drying method or the oven drying method had quite similar water absorption capacities. The oven drying method resulted in quite wavy tissue handsheets, which were also stiffer, and therefore these samples were more difficult to be rolled into the basket. Therefore, for all future investigations, the air-drying method was chosen.

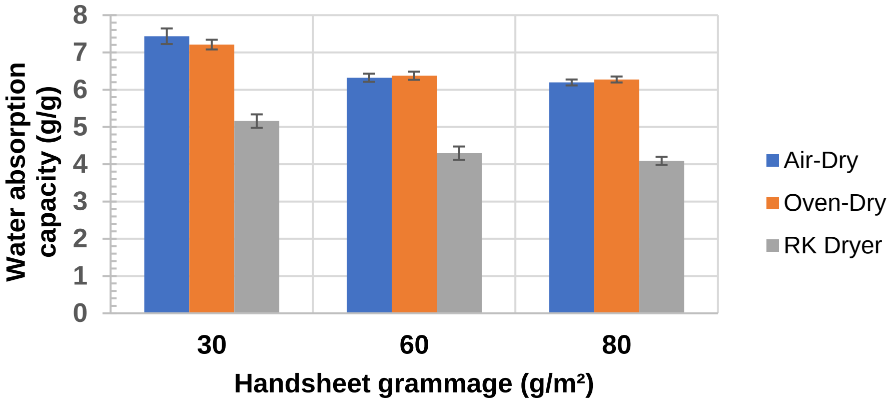

Fig. 1. Water absorption capacity of tissue handsheets with different basis weights, and prepared by different drying methods; NBSK pulp; RK: Rapid-Köthen hand sheet former

Tissue handsheets made of NBSK pulp absorbed more water (Fig. 2). The highest absorption capacity was achieved by applying air-drying by the NBSK pulp with a mean value of 7.4 g absorbed water per 1 g fibers. Furthermore, longer NBSK fibers outperform shorter eucalyptus fibers (mean value 6.4 gg) in terms of absorption capacity. The values were obtained for the 30 g/m² grammage samples because this closely aligns with the grammage commonly found in hygienic tissue papers.

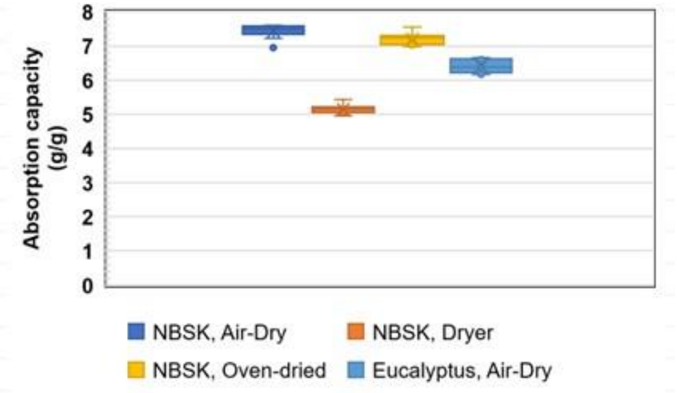

Fig. 2. Water absorption capacity of tissue sheets dried by different methods; handsheets with grammage of 30 g/m²

Comparison of Commercial Tissue with Handsheets

Third part

The original kitchen towels (kitchen tissues) were compared to tissue handsheets made from fibers obtained by re-pulping the kitchen towels to assess their different properties. The results are illustrated in Table 4. In each instance, the original kitchen towels (kitchen tissue) exhibited greater bulk, absorption capacity, and wet strength (the ratio of wet to dry tensile force at break) compared to the laboratory kitchen handsheets made from the same fibers. The optimized industrial production processes for commercial tissue production, and a different fiber structure, and surface in the tissue handsheets are an obvious explanation. The different plies of the commercial sheets increased the surface and enabled water binding between the different plies. The creping process during tissue production (TAD) at sample No. 5 accounted for its high values in paper bulk, and stretch.

The tissues produced by TAD (No. 5) absorbed more water with 13.5 g/g, than tissue produced with the conventional method from virgin fiber (No. 6) with 8.3 g/g, and from recycled fiber (No. 4) with 8.5 g/g due to creping during the TAD process. TAD-produced tissue typically absorb even larger quantities of water (Blechschmidt 2013). The TAD produced tissue (No. 5) absorbed water faster than the conventional-produced ones (No. 6, No. 4), as expected. Additionally, the tissue produced by TAD (No. 5) was bulkier with lower suction lift. Tensile strength of tissue made of virgin fiber was mostly higher compared to tissue made of recycled fibers, as expected. Possibly due to creping, the kitchen towels, especially the ones produced on a conventional machine, had higher tensile strength than the hand sheets. TAD-produced tissue had higher absorption than the conventional-produced tissue. The original tissue had higher absorption than laboratory tissue handsheets due to higher bulk. TAD-produced tissues absorbed water faster, while the tissue made of recycled fibers (No. 4) took longer to absorb water due to fiber hornification (Ballesteros *et al.* 2017). Additionally, TAD-produced tissue had lower values for suction lift, whereas No. 6 had the highest values for suction lift with 15 cm, possibly because of its higher basis weight. Moreover, commercial tissue made on a conventional tissue machine with virgin fiber displayed a higher tensile index compared to TAD and tissue made of recycling fiber, whereas laboratory tissue handsheets made from recycled fibers (No. 4) had the highest tensile index, likely due to the presence of refined fibers and a denser fiber network (lower bulk), as expected. A high SR-value of No. 4 indicated the fibers were refined during recycling.

Table 4. Mean Values of Properties of Original Tissue, and Handsheets

	No. 5, virgin fiber, TAD		**No. 6, virgin fiber, conventional**		**No. 4, recycling fiber, conventional**	
	original	**hand s.**	**original**	**hand s.**	**original**	**hand s.**
Basis Weight (g/m^2)	37.3	31.8	51.9	33.1	55.2	32.2
SR-value	-	11.0	-	12.0	-	14.0
Bulk (m^3/g)	17.9	8.5	12.0	7.2	12.4	5.9
Absorption Capacity (g/g)	13.5	7.5	8.3	6.4	8.5	6.2
Absorption Rate (s)	1.3	1.3	1.6	1.9	2.7	1.6
Suction Lift (cm)	10.2	14.5	15.0	15.8	14.9	15.1
Tensile Index Nm/g (dry)	4.6 (MD)	5.5	5.9 (MD)	5.6	3.6 (MD)	6.2
Tensile Index Nm/g (wet)	1.1 (MD)	0.3	1.4 (MD)	0.6	0.9 (MD)	0.4
Wet Strength (%)	24.5	6.0	24.4	10.2	25.3	6.1

Compare with Table 1; original: original tissue, hand s.: hand sheets made of original tissue

Influence of Fiber Type on Tissue Properties

Fourth part

This next section deals with the influence of various fiber types on the properties of tissue. All samples were first disintegrated and refined using a PFI Mill at different revolutions. After that, handsheets with a basis weight of 30 g/m^2 were produced using a Rapid-Köthen handsheet maker. The samples were then air-dried in the climate room (23 °C, and 50% rel. humidity) for at least 12 h. Even though the used experimental production method was different to industrial methods (as stated earlier) the authors' assumption is that learnings are transferable to industrial production.

SR-values increased with higher refining levels (Fig. 3), as expected (Ahmed *et al.* 2024). Among the various pulp types, NBSK exhibited the lowest SR value when not refined, with bamboo, eucalyptus, and straw pulp following in that order. Refined straw pulp records the highest SR value with a result of 39. Straw pulp also displays the most rapid response to the refining process.

The tensile strength of the 30 g/m² laboratory handsheets was tested using the Zwick Roell tensile tester (Ulm, Germany). With increasing refining, expressed as revolutions using the PFI mill, the fibers were fibrillated, shortened, and more fines were produced. The tensile index increased (Fig. 3). The highest tensile strength was obtained using NBSK pulp. The straw pulp showed a fast response in refining, and, thus, in a high tensile index, about 30 to 35% higher compared to the other pulp samples at 500 revolutions. However, the SR value of straw pulp was 39 at 500 revolutions, whereas the SR values of the other pulp samples were in the range of 12 to 17. The tensile strength property of the bamboo pulp was lower compared to the other pulp samples.

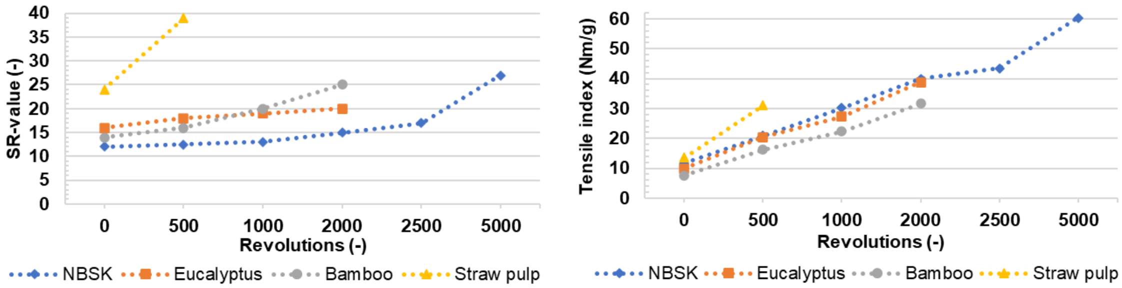

Fig. 3. Refining response measured as SR-values of different fiber types, and as strength development (tensile index) with different refining levels

The fiber curl (ratio of the true length to the projected length of the fiber minus 1) was reduced with an increase in the refining duration (Fig. 4). This can be attributed to the fact that the fibers are straightened due to tension forces in the refiner. Among the unrefined pulps, bamboo fibers had the highest curl values (38%), followed by straw pulp with 18%, NBSK with 19%, and eucalyptus with 15%. Straw pulp was an exception, which could not be explained. The tensile index increased with increasing refining in all cases.

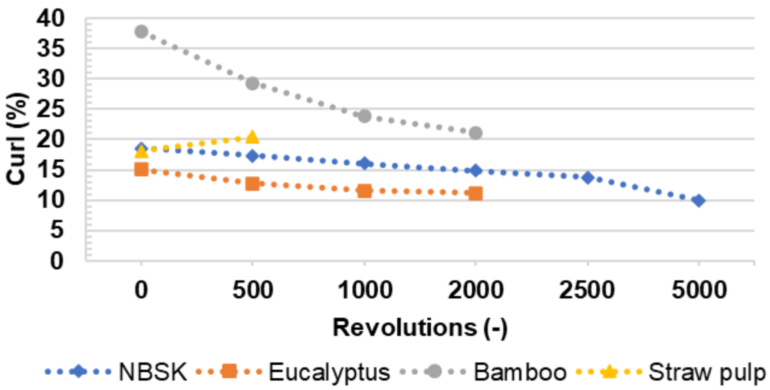

Fig. 4. Fiber curl of different pulp fibers with different refining levels

As the refining level increased, the bulk of the tissue handsheets decreased. As shown before, less bulk correlates with lower liquid water absorption. NBSK and bamboo had a similar response to refining, as depicted in Fig. 5. Refined straw pulp had the lowest bulk values compared to all the other pulps studied. Notably, for tissue handsheets made with straw pulp, the bulk showed the steepest decline with increasing refining, indicating a significant impact of the refining process. The measured bulk values were significantly lower for these tissue handsheets compared to those made from commercial kitchen towels (kitchen tissue), indicating that this difference was due to the different production methods (compare with Table 3 and Table 4).

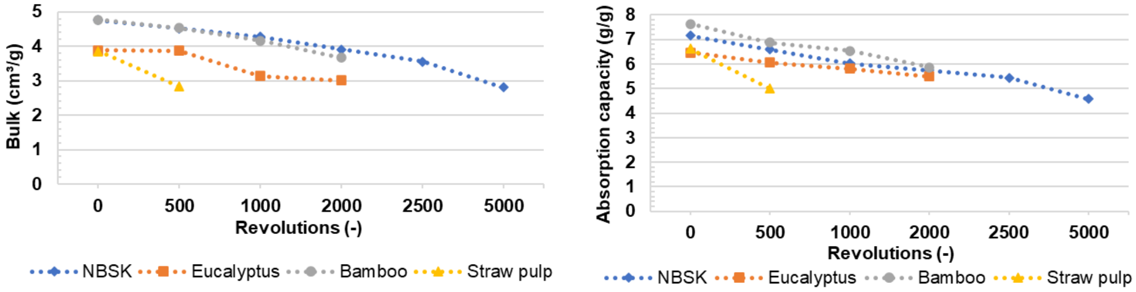

Fig. 5. Bulk and water absorption capacity of laboratory tissue handsheets made of different fibers with different refining levels

Water absorption capacity decreased with increasing refining (Fig. 5). Gigac made a similar observation at sheets of bleached kraft, and sulfite pulps (Gigac and Fišerová 2008). de Assis also measured an inverse correlation between bulk and absorption capacity (de Assis *et al.* 2019), as in this study (compare Fig. 5). Tissue made of unrefined bamboo had the highest absorption capacity. With increasing refining, the suction lift, which measures the height to which water can be drawn in a specified time, decreased (Fig. 6). This behavior indicated a denser, and less bulky paper (compare Fig. 5).

Softness decreased (higher TS7-values) with increasing refining (Fig. 6). Among the unrefined pulps, bamboo was softer, followed by eucalyptus, NBSK, and straw pulp. As refining increased, the softness difference between NBSK, and eucalyptus tended to become smaller. Refined straw pulp displayed the lowest softness.

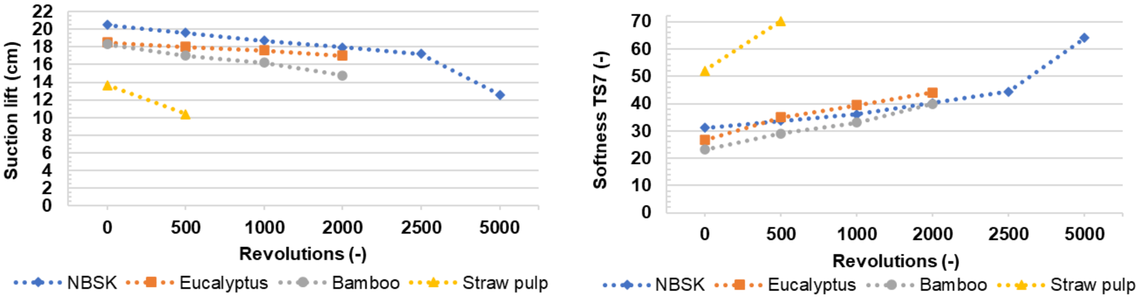

Fig. 6. Suction lift and softness TS7 of laboratory tissue handsheets made of different fibers with different refining levels; high TS7-values correlate with low softness

In summary, it can be said that water absorption capacity, and tensile strength are essential parameters for kitchen towels (kitchen tissue). Therefore, it is important to study the water absorption capacity in relation to the tensile strength to determine the best performance. Looking at the correlation between water absorption capacity and tensile strength, bamboo pulp and NBSK pulp are on the same level (Fig. 7). Therefore, non-wood fibers can be used to substitute NBSK pulps in this application.

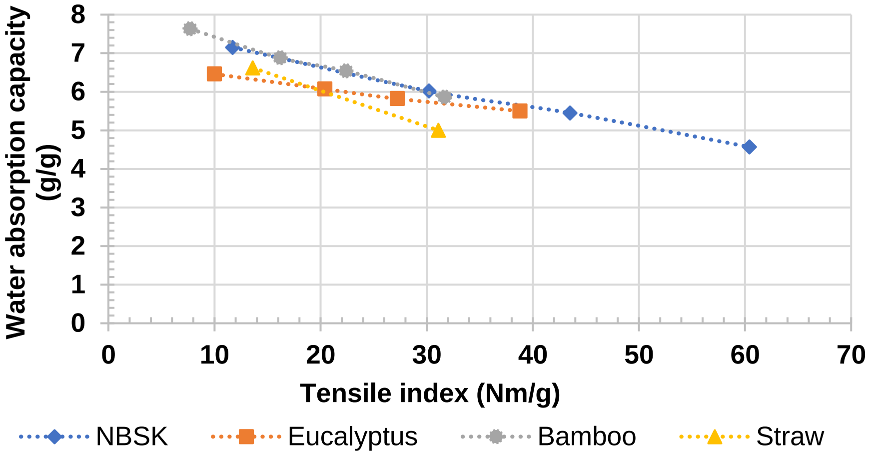

Fig. 7. Water absorption capacity as function of tensile index of different pulps (PFI mill refining)

CONCLUSIONS

The tissue production process and choice of raw materials greatly affect tissue properties. Tissue made from virgin fiber absorbed more water, absorbed it faster, and was bulkier. In contrast, tissue made with recycled fiber had a lower tensile index, reduced absorption capacity, and a slower absorption rate due to refined fibers, more fines, and fiber hornification.

Laboratory tissue handsheets made from two pulps, NBSK and eucalyptus, were analyzed. The air-drying method was found to be the best, followed by oven drying. In contrast, the handsheet dryer method overly densified the handsheets. Consequently, the air-drying method was selected for further investigations. Long fibers demonstrated superior water absorption due to their greater thickness, allowing for higher water uptake. Compression of fibers during the drying process resulted in denser paper, which reduced its water retention capacity. Refining the pulp fibers led to an increase in the degrees SR-value and fines content but a decrease in average fiber length and curl. The laboratory tissue sheets displayed higher tensile strength but lower values in bulk, softness, absorption capacity, and suction lift.

The choice of pulp is crucial for tissue applications, with kitchen towels (kitchen tissue) requiring high absorption capacity, bulk, and tensile strength, while toilet paper necessitates softness, bulk, and absorption capacity. As shown in Table 5, bamboo pulp offers promising attributes, featuring SR-values between NBSK and eucalyptus, high bulk, high suction lift, high curl percentage, high absorption capacity, and softness. Conversely, straw pulp exhibits the highest tensile index and SR-values but negatively impacts critical tissue properties. Eucalyptus pulp is beneficial for tissue softness, while NBSK excels in strength properties and water absorption capacities but has lower tissue softness. Despite its limitations for tissue applications, straw pulp is used commercially in some tissues for sustainability reasons.

Table 5. Mean Values of Properties for NBSK, Eucalyptus, Bamboo, and Straw Pulp (Unbeaten Pulps)

	NBSK	**Eucalyptus**	**Bamboo**	**Straw Pulp**
SR-Value	12.0	16.0	14.0	24.0
Bulk (cm³/g)	4.8	3.9	4.8	3.9
Softness TS7	31.2	26.6	23.2	52.0
Absorption Capacity in (g)	7.2	6.5	7.6	6.6
Absorption Time (s)	0.2	0.3	0.4	0.4
Tensile Index (Nm/g)	11.7	10.0	7.7	13.6
Suction lift (cm)	20.5	18.5	18.3*	13.7
Curl (%)	18.6	15.0	37.8	18.2

* The suction lift measurement for the sheets produced from bamboo is performed for 5 min instead of 10 min, as the water was sucked up to its maximum height in approximately 7 mins.
In Green: Best Values; In Red: Worst Values

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