Review: The Softness of Hygiene Tissue

Joel J. Pawlak,* Ryen Frazier, Ramon E. Vera, Yuhan Wang, and Ronalds Gonzalez

The hygiene tissue industry has an extensive global market that is quickly growing. Market research has indicated that softness is one of consumers' most highly desired properties. For certain hygiene tissue products (specifically bath tissue), this property can influence prices. A better understanding of the science of softness would allow companies to engineer soft tissue more economically and efficiently. Softness is a subjective perception related to physical aspects that make it challenging to express and measure. Human handfeel panel testing, which ranks the specimens through physical tests, has been recognized as the most reliable method to measure tissue softness. Much effort has been expanded in correlating the panel test results with some measurable properties. In this regard, equipment has been recently developed by combining several different mechanical, surface, and acoustic properties to characterize softness. In comparison with panel tests, these instruments (*e.g.*, tissue softness analyzer) have been found to give equivalent softness metrics. A combination of materials selection and manufacturing operations are used to create softer tissue sheets. This paper reviews the sensation of softness as perceived by the human touch, techniques for measuring softness, the influence of fiber on softness, manufacturing techniques, and additives used for softness enhancement.

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INTRODUCTION

Hygienic tissue is one of the most important consumer products in the forest products industry. It serves to clean and protect. In 2019, 40.5 million tons of tissue were consumed globally, including 9.3 million tons in North America (RISI 2019). The global tissue market has steadily grown over the years (RISI 2019). Hygienic tissue includes both toilet tissue and paper towel. A minor component of this market includes napkins and facial tissue. Toweling is an area that continues to grow. For toweling, the critical properties associated with higher consumer prices include the strength of the sheet, absorbency, absorption rate, and marketed sustainability (de Assis *et al.* 2018). For towels, softness is not strongly correlated with consumer pricing. However, at home toilet tissue softness has been shown to correlate with consumer pricing in the North American market (Wang *et al.* 2019b). The importance of softness provides an incentive for papermakers to characterize it in a routine manner.

The overall hygienic tissue market has a global value of $100 billion despite the relatively small tonnage produced (*ca.* 40.5 million tons market per year). The overall industry has been showing steady growth globally at a 3% CAGR over the past five years, and regionally the growth rates can be much higher (RISI 2019). This market appears to be an area of opportunity for the future growth of the forest products industry.

The manufacture of hygienic tissue has three broad areas of variables associated with it. These variables include fiber selection, manufacturing technology, and the additive used or applied to the sheet (Gigac and Fišerová 2008). Converting processes are necessary to optimize tissue product properties such as strength, softness, and absorbency. Moreover, the importance of converting should not be discounted in determining the final product the consumer purchases. Multi-ply sheets, embossing patterns, and winding all impact the final product and can be directly observed by the consumer.

In terms of fibers, three main groups of fibers are commercially important. Virgin wood fibers are produced by chemical pulping followed by bleaching. Recycled fibers are mainly derived from mixed office waste (MOW) papers and undergo a cleaning and deinking process before use (FisherSolve International 2017). While significantly lower in tonnage compared to virgin fiber and recycled fiber, non-wood fiber such as bamboo and wheat straw has gained interest, as consumers are willing to pay a premium for tissue made from such fiber material.

Fibers that have not been previously made into paper are called virgin fibers. Most of these fibers are chemically pulped and then bleached, derived from hardwood (angiosperms) and softwood (gymnosperms) trees. These fibers have distinct differences and could be blended to balance tissue strength and softness (FisherSolve International 2017; de Assis *et al.* 2018). On the other hand, tissue sheets can be layered such that one layer is made of hardwood fibers to give softness, and another layer is made of softwood fibers to provide strength (Boudreau 2013). Softwood fibers typically have twice the aspect ratio (length:width) compared to hardwood fibers. This difference in physical dimensions makes softwood better for enhancing strength (de Assis *et al.* 2018). The finer hardwood fibers allow for more free fiber ends to occur at the surface of the tissue, adding to the velvety feel of the tissue surface (Wang *et al.* 2019b). Recycled fibers are recovered from waste paper and undergo processing before being used in tissue. Recycled fibers typically have more fines and are hornified, reducing their ability to bond and creating lower bulk, softness, and water absorbency when compared to virgin fibers (Welf *et al.* 2005, Banavath *et al.* 2010). Recycled fiber is most often used in away-from-home market segments, but such fibers can also be found in the at-home segment.

The softness of tissue in the at-home market segment has been found to be one of the most important properties (Hollmark and Ampulski 2004; Wang *et al.* 2019b). Several strategies exist to enhance the softness, and the tissue industry uses a number of industry-specific manufacturing technologies. Many of these technologies focus on the pressing and drying aspects of tissue manufacturing to prevent densification that occurs in conventional papermaking. Lightly refined or unrefined fibers are used to form the tissue at basis weights typically ranging from 15 to 50 g/m^{2,} with an average consumer sheet weight being about 40 g/m^2. The sheets are lightly pressed or not pressed and then typically dried in one of four major types of drying technologies: light drying-crepe (LDC), creped through-air dry (CTAD), creped through-air dry belt (CTADB), and uncreped through-air dry (UCTAD) (Kullander *et al.* 2012).

Thru-Air Drying (TAD) is a specialized drying technique that uses wet mold tissue with air passed directly through it to create a bulky and soft tissue. The molding process can be used to create areas of softness and strength in a honeycomb-like structure (Valmet 2014). The sheets are dried with air passing through the sheet at a constant pressure drop and temperature that ranges from 100 to 250 °C. Often the TAD dryer is combined with a traditional Yankee dryer that additionally allows for creping and the development of bulk. Uncreped Thru-Air Drying (UCTAD) developed by Kimberly-Clark does not use a Yankee dryer and only TAD (Wendt *et al.* 1998). The elimination of the creping step can increase the productivity of the machine.

The development of various drying technologies for tissue has been primarily driven by improving the softness of the tissue sheet. Besides drying, other processes strongly influence tissue product performance and properties such as softness. Some of them are creeping and converting processes during papermaking (de Assis *et al.* 2018, 2020). Creping involves scraping the tissue sheet from the Yankee dryer surface using a creping blade (described in a later section) to create crepe folds in the tissue structure. As a result, softness perception has been demonstrated to increase (de Assis *et al.* 2020). Moreover, creeping performance will depend on the type of creping blade and creping blade angle (de Assis *et al.* 2020). On the other hand, converting processes provides finished tissue products with critical functional properties (*e.g.*, brand patterns) that add both value when placed into the commercial market and improve properties such as softness perception (Vieira *et al.* 2020b)

Panel softness has been the traditional benchmark for softness characterization, but it requires a trained panel and has a good deal of subjectivity associated with it. Thus, many researchers have explored more analytical methods for characterizing softness. This exploration includes using algorithm methods and instrumental softness testers. Understanding the nature of softness also gives insight into the development of softness measurement techniques. Softness is a perception that combines a complex set of inputs, including appearance, mechanical properties, friction properties, vibration characteristics, and sound. Giselher Grüner (Grüner 2016) developed a tissue softness analyzer that is a purpose-built instrument for measuring tissue softness. The method has found a degree of acceptance in the industry due to its ability to reasonably predict panel score softness rankings (Wang *et al.* 2019b).

This review explores the many aspects of tissue softness. The authors cover many areas, including fiber selection, manufacturing technologies, and softness measurements. The physical nature of the softness sensation is also reviewed to understand better the connection between softness measurement, materials selection, and manufacturing. The review's goal is to provide a complete discussion of the various aspects of softness.

DEFINING THE PERCEPTION OF SOFTNESS

It is challenging to select the most effective and affordable method to achieve a desired softness level because the property is difficult to quantify (Patterson 2013). Therefore, there is an interest in defining softness in a manner such that it can be evaluated via analytical testing. The property of softness includes several texture perceptions such as velvety, delicate, and bulky (Hollmark and Ampulski 2004; de Assis *et al.* 2018). A person's experience and regional differences can affect the softness perception. The softness perception involves a number of senses, including tactile, visual, auditory, and olfactory (Leporte 1970). These sensory inputs are processed in the mind to make a softness evaluation (Gallay 1976). Though "mainly based on hand-felt sensing," softness can also include auditory and visual aspects (Teng *et al*. 2011). The complex nature of softness makes it difficult to determine analytically. However, studies have shown that the tactile component shows the best relationship with the overall softness (Gallay 1976).

There are three important anatomical components of a human hand used for softness evaluation: lamellar and tactile corpuscles and Merkel cells (Wang 2019a). The lamellar corpuscle on the human finger touches each free fiber protruding from a tissue's surface when the human hand moves across the surface and initiates vibrations that have "an optimal sensitivity at 250 Hz" (Wang 2019a).

As one of the most important properties of hygiene tissue (de Assis *et al.* 2018), softness has been rarely studied in the papermaking field. Softness has been linked to tissue bulk, smoothness, roughness, hardness, stiffness, strength, *etc.* No single property is directly related to softness, as softness is the interaction of many properties.

Objects can have two types of tangible object properties: "macro-spatial properties, including shape and orientation; and material properties, such as roughness, softness, and temperature" (Kitada *et al.* 2019). Neuroimaging studies have found that macro-spatial properties and material properties require different network engagement for processing (Kitada *et al.* 2019). For the property of softness, there have been very few studies of the "neural correlates underlying the perception of object compliance and softness." It has been found that "tactile perception of softness is based on the spatio-temporal variation of pressure on the skin" (Kitada *et al.* 2019).

In the paper industry, tissue paper is often defined by physical and mechanical properties. The desired properties include "high softness, low grammage, high bulk, and high liquid absorption capacity" (Vieira *et al.* 2020a). Softness can be broken down into two major segments, bulk softness, and surface softness. Bulk softness "can be indicated by the elasticity of the sheet" (Ismail *et al.* 2020) and can be estimated by "measuring the stiffness and the thickness of the sheet" (Raunio and Ritala 2013). Although there is no explicit mention of elasticity as a direct indicator of bulk softness by Ko *et al*. (2018), they concur that bulk softness can be determined from bulk stiffness and defines the bulk stiffness measurement as "the slope between the two specified points in a load-elongation curve from tensile testing." Elasticity is inherently involved since, in tensile testing, the initial slope (Young's modulus) in the stress-strain curve is in the elastic region. It should be noted that the stiffness described here is in-plane stiffness, and it is significantly different from bending stiffness. However, simply measuring the bulk softness is not a comprehensive measurement of overall softness. The softness of the surface "is a complex combination of roughness, friction and elasticity of the surface" (Raunio and Ritala 2013). This complex property of surface softness might be determined from a surface tester that includes several measurements (stiffness, roughness, bulk softness, friction, *etc.*) described above (Ko *et al.* 2018).

One review considers softness "a state-of-the-art technology" which "belongs to one of the most protected proprietary areas for tissue and towel manufacturers" (Ko *et al.* 2018). Softness evaluation is labeled as an art rather than a science because it has not been distinctly defined. Described as a "psychological phenomena which involve many different components that may interact with each other," softness itself is quite difficult, if not impossible, to isolate from other factors that may contribute to or be dependent on softness (Ko *et al.* 2018). "Softness is difficult to quantify even with modern equipment that imitates a human hand because it can vary between individuals, markets, and cultures" (Ismail *et al.* 2020). Despite this variation, specific properties can together influence the perception of softness, including but not limited to "crepe count [number of crepes per centimeter], crepe-to-stretch ratio, sheet density, strength, stiffness, and creping geometry" (Ismail *et al.* 2020). These properties on their own can be individually measured. They can help determine relative softness, but it is difficult to quantify a universal softness metric with any single property alone. For example, Hollmark (2004) attempted to decouple bulk and surface softness from overall softness but failed because these two properties depend on each other. Likewise, strength, stiffness, and softness typically depend on sheet density and creping geometry. This dependence makes relying on any linear regression analysis questionable for developing a tissue softness model. Therefore, studying the autocorrelation between physical properties is important when creating a softness model.

Properties Affecting the Feeling of Softness

Changing the furnish or the tissue machine operation can change softness properties. Even after the tissue product is made, specific surface treatments can affect softness (Patterson 2013). A change in the crepe count and the height and structure of the crepes affect the quality of the end product and how a human might perceive the feeling of softness on this product. Crepe folds are a strong microstructure generated on the paper web and increase softness feel while stretching the sheet along the machine direction (Raunio and Ritala 2013). Factors such as these can affect the softness of tissue paper. If a paper machine blade becomes worn down, "the integrity of the tissue is altered," which affects final product softness. One experiment supported the notion that the greatest contributor to softness is this fiber bonding destruction that occurs due to both doctor-blade motion and the addition of creping agents on the Yankee cylinder (Teng *et al*. 2011). It has also been found that increasing the crepe distance can affect softness perception in end products (Ismail *et al.* 2020).

The perceptual softness of tissue paper is said to be distinguishable by "hand feel and surface smoothness" (Ismail *et al.* 2020). The hand feel metrics follow the same pattern as the crepe count, where both are low at the time directly before the exchange of the old doctor blade during the doctoral blade cycle, which corresponds to higher surface smoothness. Near the end of production time, surface smoothness increases slightly "due to the fact that more of the inhomogeneous and broad crepes are considered 'soft'" (Ismail *et al.* 2020). In one study, when the tissue structure was less homogeneous, the smoothness of the surface increased, but the perceptual softness on average did not change. The explanation for this is "the irregular peaks stacking together," such that they form even larger crepes, making for a soft feeling on the surface. A human finger "cannot differentiate roughness below 270 nm in height" (Ismail *et al.* 2020). Other properties also can influence or help predict softness, including out-of-plane elastic modulus and the presence of surface-extending free fiber ends. The out-of-plane elastic modulus "has been measured to correlate with subjective softness evaluation" (Ko *et al.* 2018), and it is known that the density of free fiber ends on tissue paper can impact the softness feel, with higher densities typically feeling "softer" (Raunio and Ritala 2013). The reduction in the contact area between the tissue web and a hand that occurs when free fibers are present increases the feeling of softness (Wang 2019a). However, neither out-of-plane elastic modulus nor free fiber density is heavily relied upon for standard softness measurements. It is important to note that these indicators of relative softness are not necessarily measurements of softness itself.

The Brain and Softness

The brain must process electrical signals from more than "17,000 mechanoreceptive units" on a human hand (Wang 2019a). Each fiber is subjected to both pressing and deflective forces upon touching a tissue surface. The forces, in turn, send an impulse to the brain. If the impulse is higher, that indicates a less soft surface (Wang 2019a).

In one study, functional magnetic resonance imaging was used to determine whether certain parts of the brain, specifically the parietal operculum and insula, were used to perceive tactile softness (Kitada *et al.* 2019). The study took a sample of 56 participants who "estimated perceived softness magnitude using their right middle finger" (Kitada *et al.* 2019). The stimuli given in the study "had the same shape but different compliances" (Kitada *et al.* 2019)

The results of the study showed that "activity in the parietal operculum, insula, and medial prefrontal cortex was positively associated with perceived softness magnitude, regardless of the applied force" (Kitada *et al.* 2019). In the ventral striatum, more softness perception activity occurred in the high-force condition than the low-force condition. From this study, it can be concluded that "a distributed set of brain regions" are required to perceive softness, and the clarity of the softness perception is related to "the magnitude of deformation of an object under an applied force" (Kitada *et al.* 2019).

It is necessary to know more about the brain networks involved to make substantial leaps in determining softness. According to a study on tactile softness perception in the brain, "the brain networks that are involved in extracting information on compliance or softness perception are still unknown" (Kitada *et al.* 2019).

Softness as a Vibrotactile Sensation

The perception of softness is contributed by direct static touching and frictional sliding (Di Luca 2014). These two steps generate vibrations at different frequencies and amplitudes, which contribute differently to softness perception (Rust *et al.* 1994; Okamura *et al.* 2001; Kuchenbecker *et al.* 2006; Kobayashi *et al.* 2008; Kildal 2010, 2012; Okamoto 2010; Takahiro *et al.* 2010; Porquis *et al.* 2011; Visell *et al.* 2011; Giordano *et al.* 2012; Ikeda *et al.* 2013).

These vibrations stimulate receptors both on the skin's surface and deep in the tissues (Di Luca 2014). Meissner and Pacinian corpuscles, which are responsible for fast-adapting (FA) afferents, can respond to either transient or high-frequency mechanical stimuli. Merkel disks and Ruffini corpuscles receive the slow-adapting (SA) afferents that respond to relatively static or low-frequency stimuli (Freeman and Johnson 1982; Vedel and Roll 1982; Ribot-Ciscar *et al.* 1989; Johnson 2001).

Static Direct Touching

The first major contribution to softness perception is direct vertical skin touching. The direct touching causes deformation of both the sheet and finger. Due to the high viscoelastic nature of the system, the normal force is commonly treated as constant. In this relatively static contact, the effects of FA can be treated as insignificant (Di Luca 2014). The pressure generated at the proximity becomes the first cue of softness. It is believed that broad and gradual pressure and indentation are preferred.

As shown in Fig. 1, the finger was to some extent wrapped into the material for soft material, which resulted in a higher contact area. This implied a lower and broader pressure on the finger for a given force. Such deformation is less likely for a hard object, which results in a narrow and intense pressure on the finger. The broader contact area also triggers larger activated areas, which provide large, slow, and gradual signals to the central nervous system.

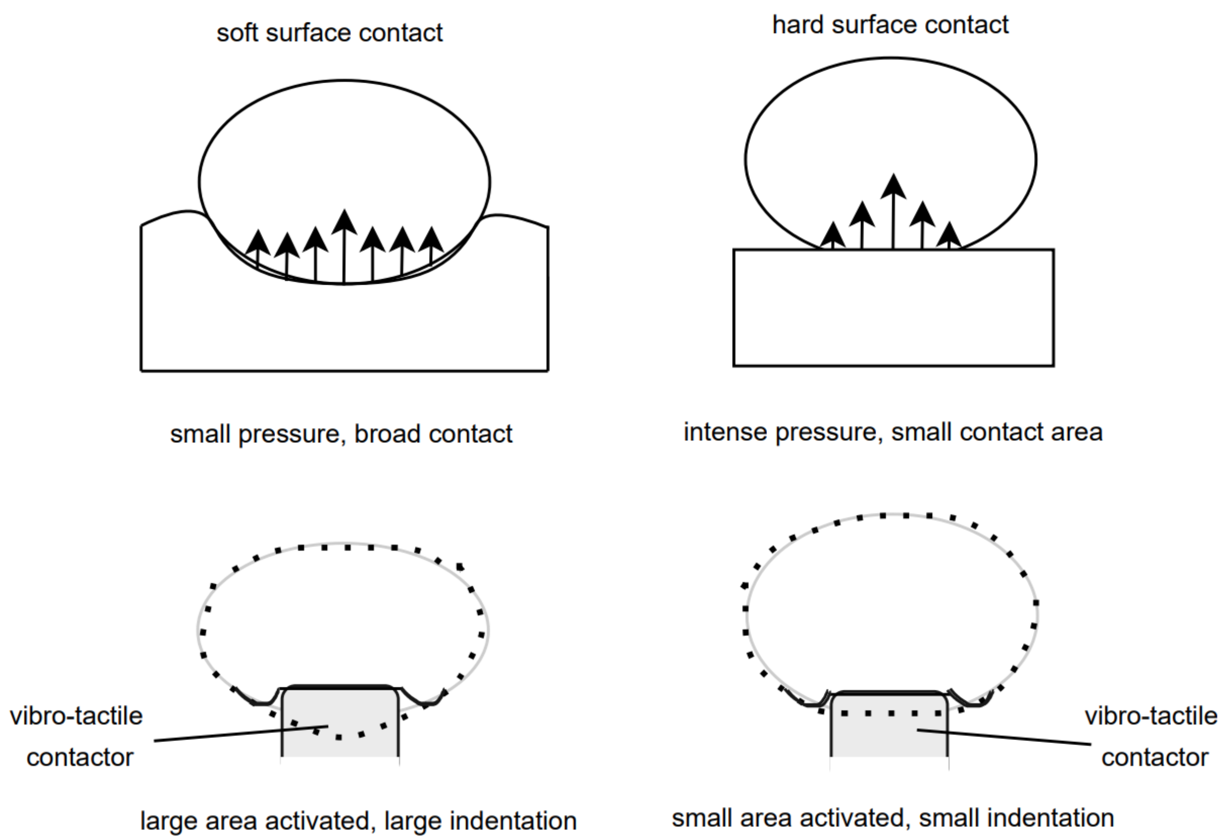


Fig. 1. Image based on information and sketch from Di Luca (2014). Contact pressure distributed on a material, deformation from indentation

Roughness and Low-Frequency Vibration on Softness

The surface of a material, especially tissue, is usually non-uniform. Bonds, voids, and fibers create bumps and valleys on the surface, which result in profile roughness. Roughness can be defined as the deviation of the surface from a flat plane. While under contact, the roughness can vary significantly, depending on the mechanical properties of the tissue. For example, certain processes in tissue-making, such as creping, can dramatically increase the roughness while at the same time lowering the z-direction mechanical properties. This structure leads to a rough but highly compressible tissue surface perceived as "soft." It should be noted that roughness is both a physical property describing the shape of a sheet and a mechanical property that can be measured on the sheet in some lab tests. Roughness is constantly linked with softness due to their similar perceptual process. In general terms, the perception of roughness is part of the softness perception. The surface profile and the mechanical properties combine to create a perception of "roughness" in softness terms. Perceiving "roughness" can be contributed by static touching and low-frequency vibration. Perceiving roughness can be regarded as sensing the spatial difference in the profile and mechanical properties on the surface. When there exists a great deal of mechanical and profile variation on the surface of the samples, the "roughness" can be sensed by direct static touching. Due to the mechanical and profile variation, the contact areas are different locally, which results in different pressures and sensations. In most scenarios, the surface of a tissue or fabric is fine enough that static touching is difficult to differentiate. The "roughness" difference in finer surfaces has to be differentiated by sliding fingers on materials, adding the frictional properties between the finger and tissue.

Hollins *et al.* (2000) proposed a "duplex model of tactile roughness perception," which argued that the perception of fine texture by the induced vibration is different from the perception of coarse textures. Fagiani *et al.* (2012) developed experiments to support the duplex model and further argued that the roughness perception by friction-induced vibration is responsible for the SA mechanoreceptors at 2 to 100 Hz. At these low frequencies, the roughness perception is a function:

- of sample roughness wavelength, when the sample roughness wavelength is much smaller than the fingerprint wavelength.
- of fingerprint wavelength, when the sample roughness wavelength is much larger than the fingerprint wavelength.
- of the ratio of two wavelengths, when the width of the two wavelengths are comparable.

Frictional Sliding and Induced Vibration

As one of the most significant contributors to softness perception, friction-induced vibration provides the signal components related to the relative displacement of the objects at high-frequency, where the frequency bandwidth can overlap that of the vibrotactile sense (Ibrahim 1994; Akay 2002). It is plausible to relate softness perception to friction-induced vibration since the vibration may contribute by both surface and internal characteristics. The physical aspects at the proximity are too complicated when stroking fingers over the surface of samples, which makes it difficult to measure and interpret. Friction-induced vibration results from complex interactions involving contact mechanics, tribology, and non-linear dynamics at the micro-macro levels (Dahl 1976; Akay 2002; Cao *et al.* 2014). For a given sliding pair system, the dissipation of frictional energy involves four different mechanisms. The first two mechanisms include breaking boundary films between components and deforming the contacting asperities elastically and plastically. In the third mechanism, energy dissipation triggers interaction beyond the interface, which results in a vibration response of the whole system (Cao *et al.* 2014). The vibration changes the true contact area and force between the two components and forms a closed-loop feedback relationship in the fourth mechanism (Akay 2002; Sheng 2007; Cao *et al.* 2014). Classic friction-vibration interactions include stick-slip (Van Campen *et al.* 1998), modal couplings (Kippenberg *et al.* 2002), vibro-impact (Cao *et al.* 2014), sprag-slip (Sinou and Jézéquel 2003), and closed-loop interaction (Akay 2002; Cao *et al*. 2014), which could be taking place during the interactions.

Tactile perception occurs when a surface or material is touched or scanned by a human finger. The interfacial friction that occurs during touching "results in vibrations carried by nerves to the brain, which are interpreted as the level of smoothness" (Ding and Bhushan 2016). The skin is deformed, and friction-induced vibration stimulates human sensory receptors. The texture information becomes an electric potential that nerve fibers send to the brain (Ding *et al.* 2018). Determination of the shape or texture of a material involves proprioceptors and mechanoreceptors. People choose certain paper or textile products based on fingertip sliding, "because textures like smoothness, glossiness, and naturalness can be sensed" by mechanoreceptors within human skin (Ding *et al.* 2018). It has been found that a material will be more difficult to identify if a surface has non-periodic roughness. The ability to recognize a vibrational frequency pattern allows for better perception. Further, tactile determination "can be improved by discontinuities of the surface texture within the same sample surface" because a person can perceive the discontinuity when applying the same stimuli (Bartolomeo *et al.* 2017).

These friction-induced vibrations mentioned are created by relative motion between the finger and the material touched. Important contact parameters include both load and scanning speed. An increase in scanning speed shows a decrease in the friction coefficient for the contact between a finger and a fabric, but "hairier" fabrics show larger variations in the friction coefficient related to scanning speed (Fagiani *et al.* 2011). More work needs to be done to determine how the magnitude and frequency of spectrum upon fabric touching is changed during tactile scanning (Fagiani *et al.* 2011).

MEASUREMENT OF SOFTNESS

Due to the complex nature of softness, it is challenging to measure and quantify softness. Measurement of bulk softness is trusted as a proper and accurate measurement, easily measured by the elasticity and thickness of a sheet (Raunio and Ritala 2013). However, softness is not just the bulk, but also the surface softness, which is a complicated measurement that sometimes requires a multi-step evaluation process. The surface softness requires a consideration of the topography of the surface, "particularly the crepe structure and its periodicity" (Ismail *et al.* 2020). Usually, tissue softness is studied through panel tests "in which people evaluate the softness of tissue paper subjectively" (Raunio and Ritala 2013). However, human panel tests tend to show variability. According to one study, the variability in human perception of softness can be decreased or mitigated by training (Teng *et al.* 2011), but an instrument that could give a repeatable softness value would be valuable and less time consuming.

Softness is perceived on a tissue surface "when the crepe folds are inhomogeneous, nonperiodic, and long" because a hand "cannot differentiate in the microscale between proper crepe waves and inhomogeneous peaks if they are less than 760 nm in height" (Ismail *et al.* 2020).

It has proven difficult to create reliable physical test methods for the softness of hygiene tissue papers (Ko *et al.* 2018). Despite this, there has been much effort in the pulp and paper industry to develop methods that can "be used to predict in-use performance of a consumer product that is also reasonably well-correlated with subjective softness evaluation" (Ko *et al.* 2018).

Since softness is a human perception, much of the work in developing measurement devices have been done "with the goal of correlation with the rating by softness panels" (Raunio and Ritala 2013). However, this has proven difficult because these devices have often shown a poor relationship with panel test results. This weak correlation has been attributed to two major factors: 1) "the uncertainty of factors affecting the subjective feeling of softness" and 2) "the current devices measure the forces that are not in the same sensitivity scale as what humans perceive" (Raunio and Ritala 2013). It has even been suggested that "objective softness evaluation should be impossible since softness is subjective in nature" (Ko *et al.* 2018).

Benchmarking / Previous Softness Measurements Models

Several different measurement methods have been designed to attempt to understand tissue paper softness, including internal methods created within companies and external processes, where other instruments are brought to test samples. In-house methods are not well known because companies generally do not publish internal methods. Many methods involve softness modeling, and several different softness models have been developed over the years.

Direct Measures of Softness

Panel testing

The panel test (Fig. 2) has become a widely accepted method for softness evaluation (Institute of Paper Chemistry 1967). This test is also the most common method for the tactile perception of the softness of fabrics, qualitatively measuring the perception of softness feeling (Thieulin *et al.* 2016). Two principal types of panel tests can be identified. The scoring method involves assigning numerical values of softness to softness references. Panelists are then asked to score the softness of the samples relative to the reference sheets. Two- and three-point reference panels are commonly used. The numerical system may be arbitrary, but it provides relative softness intensity as related to the reference. The ranking method asks the panelist to rank the sheets in order of softness. This panel does not provide a relative softness intensity but only a ranking. The ranking method can be tedious if there are many samples, but panel test methods can be developed to improve the efficiency of this method (Hollmark and Ampulski 2004). The scoring method may add more references to improve accuracy. Too many reference samples can impart a bias to the overall panel, and thus it is important to select the number of references carefully. It also requires more highly trained individuals to get reliable results (Hollmark and Ampulski 2004).

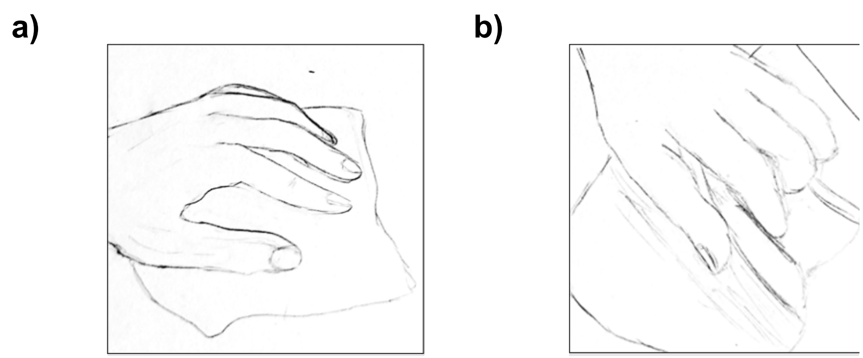


Fig. 2. Drawings of panel testing for a) surface softness and b) bulk softness components

New sensory panel test (N-SPT)

A new type of sensory panel test (N-SPT) similar to a conventional SPT was developed, in which a set of untrained panelists rated, ranked, and compared samples (Ko *et al.* 2018). This N-SPT test "can generate interval-scale softness evaluation from round-robin paired-comparison tests" (Ko *et al*. 2018). This numerical scale is linear and continuous, with equal intervals of physical measurements, including length, weight, and temperature. Undoubtedly, such an interval scale of subjective softness data is critical to developing tissue softness models based on physical and mechanical properties. From the results of this new test, several physical softness models were developed, including the "Handle-O-meter, Clark's Softness Tester, Brown Softness tester, and C.H. Dexter softness tester" (Ko *et al.* 2018).

Artificial finger

Another quantitative method for softness evaluation is using an artificial finger (Fig. 3). This mechanism can measure the friction coefficient between the finger and the material as well as the "acoustic vibratory level generated by sliding the finger on the bathroom tissue" (Thieulin *et al.* 2016). The artificial finger was made in an attempt to "quantify the sensation of the tactile quality of bathroom tissues. The intrinsic characteristics of the bathroom tissues cannot explain the softness and the velvetiness felt by the hand feel panel" (Thieulin *et al.* 2016). This instrument can separate softness and surface texture, both important pieces to the tactile perception. A tribohaptic system was used to measure the friction coefficient and vibratory level (Thieulin *et al.* 2016). The vibrations of a human finger in contact with tissue was used to define the tribohaptic system. An accelerometer attached to the person's finger was aligned parallel to the plane of contact to characterize the vibration. The finger's normal and tangential force measurements were taken underneath the tissue. From this, typical human handling conditions were determined. The measurement conditions include five back and forth movements in the machine direction at a normal force of 0.3 to 0.4 N, a sliding speed of 20 to 30 mm/s, and a 20 mm travel length (Thieulin *et al.* 2016). From this, an average frictional coefficient can be calculated from the ratio of the friction force to the normal force (Thieulin *et al.* 2016). The tribohaptic artificial finger mechanism is shown schematically in Fig. 3.

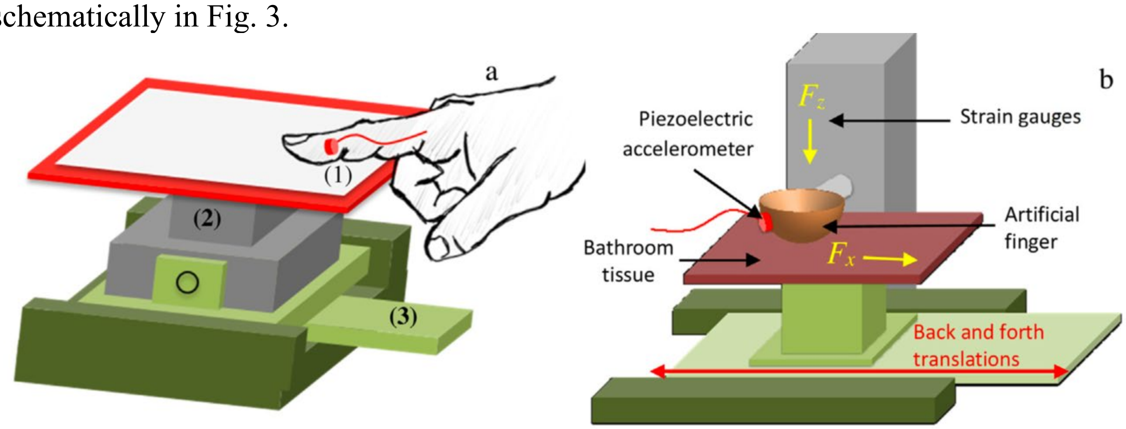


Fig. 3. a) Depiction of artificial finger system with the: 1) accelerometer aligned parallel to the contact plane, 2) force sensors to take measurements underneath the support surface, and 3) a displacement system that can slide back and forth. b) Schematic of the working mechanisms of this artificial finger device. Image courtesy of Thieulin *et al.* (2016)

The artificial finger allows quick, repetitive, and direct measurements of tactile perception. It was found that the artificial finger could measure vibrations that correlated to the softness evaluated by panel tests. The friction coefficient could be related to the tissue surface texture (Thieulin *et al.* 2016). The study found that the internal characteristics of the tissue did not make a big difference on the feeling of softness. Additionally, it was found that there was an increase in softness as thickness increased, which suggested that the softness perception is related to the thickness (Thieulin *et al.* 2016). Additional paper properties were measured and compared to the softness feeling measurements. No significant correlations were determined between other paper properties and softness. This insight can only mean that the feeling of softness does not depend on just one parameter, but several in combination. It was determined that "the acoustic vibratory level was a good marker of perceived softness, and the friction coefficient expressed the velvetiness of the surface" (Thieulin *et al.* 2016); as the acoustic vibration decreases, softness increases. The feeling of the surface (texture) seems related to the friction coefficient, and the feeling of softness seems to be connected to the level of acoustic vibration (Thieulin *et al.* 2016).

Prediction Models for Correlating with Softness

Beyond panel scoring and other more direct measures of softness, instrumented and algorithm-based methods can be used to evaluate softness. Instrumented methods are techniques that use instruments specifically designed to assess softness. The algorithm methods are techniques that use measurements from instruments not specifically designed to measure softness. Typically, this involves making multiple tissue property measurements and then correlating them with panel softness or another accepted softness measurement.

The instruments and algorithmic models used to correlate with softness include:

Handle-O-Meter

The Handle-O-Meter became an accepted TAPPI (Technical Association of the Pulp and Paper Industry) test method in 1985 but was withdrawn in 1996. Increasing weight is used to push the sample through a hole with increasing force (Lashof 1960). While this method is repeatable, it did not correlate well with panel test methods (Lashof 1960).

Kawabata KES system

The Kawabata device combines three major measurements: the friction coefficient, deviation in the friction coefficient, and geometric surface roughness to create a softness parameter (Kawabata 2002). The Kawabata KES systems are used for measuring handfeel of textile and non-woven materials, and the FB4 unit, in particular, measures surface roughness and surface friction. This method can be used to characterize both textiles and hygienic tissue paper. The device was able to determine the softness of paper towels with a degree of accuracy, but it did not work well with toilet tissue (Hollmark and Ampulski 2004).

Hollmark bulk softness model

The Hollmark bulk softness model was based on the foundation that bulk softness was not reliably found using bending stiffness as a parameter. Instead, the thickness should be used for determining bulk softness. A stress-strain curve from Young's modulus is used for the tensile stiffness measurement in Hollmark's model. This model also emphasizes that although bulk and surface softness are different components of softness, they should not be separated because they are dependent on one another (Ko *et al.* 2018)

P&G softness model

Another softness measurement model by Procter & Gamble was designed to determine bulk and surface softness. In this model, bulk softness was measured by bulk flexibility (a slope on the load-elongation curve from tensile testing), and the test was regarded as reliable. The surface softness was found to be related to the surface friction, found by using the FB4 surface tester unit of a mechanical testing system by Kawabata. Surface friction is the "mean deviation from the average friction coefficient" and was used in the P&G model as the main surface softness indicator (Ko *et al.* 2018). Georgia Pacific also created a similar model, which verified the results from the P&G model. This type of model may be sufficient for determining an overall softness measurement because it measures both bulk and surface softness.

Kimberly-Clark softness model

Kimberly-Clark's softness model claimed that bulk softness could be measured from the bulk stiffness measurement in a tensile test. The surface softness can be sufficiently measured using the surface friction component (Ko *et al.* 2018). Hence, any of these models may quantify softness more holistically if softness is defined as a combination of bulk and surface softness. The three major global tissue manufacturers of P&G, G-P, and K-C use similar methods in determining the bulk stiffness and the surface friction.

Ultrasound for out-of-plane properties

A method developed by Pan *et al.* (1989) uses ultrasonic testing, caliper, and basis weight. This study found that the parameters measured correlated well with the panel softness for the limited sample set tested. There were only seven samples characterized, and each was a two-ply sample that was split. Additional work would need to be done to determine whether this method is more widely applicable to hygienic papers, including toweling and tissues made with advice technologies such as through-air drying.

Sled method

The surface friction, creping ratio, and time of service for the creping blade are used in an algorithm developed by Kuo and Cheng (2000) to predict the softness. This method combines both materials properties and operational parameters. It may be most useful in a mill setting, but it does not consider other factors affecting softness, such as converting. The researchers determined that softness increased with the creping ratio and decreased with the time of the creping blade service.

N-SPT algorithms / models

The surface and bulk softness for the N-SPT method was parsed using an algorithm developed by Ko *et al.* (2017). Three parameters were measured and then correlated with the softness. These parameters were tensile stiffness, surface roughness, coefficient of friction. Using the concept of surface and bulk softness, each of these factors were found to be independent in the research.

For commercial bathroom tissues, the best model is the "2-Parameter model of bulk softness and surface friction equation" (Ko *et al.* 2018). This model "predicts that approximately 60% of subjective softness comes from the surface friction component and approximately 40% from the bulk stiffness". The equation for the 2-Parameter model includes bulk softness (BS) and mean deviation from the average friction coefficient (MMD) as follows:

Equation 1:

Equation for 2-parameter model (BS & MMD), $n = 0$

$$X = C + m\log \mathrm{BS} + l \log\mathrm{MMD}$$

$$X = 3.20 - 0.46 \log BS - 0.72 \log MMD$$

where:

C, m, n, l = curve fitting coefficients;

BS = GM_bulk stiffness;
MMD = mean deviation from the average friction coefficient.

Table 1 below summarizes normalized bath tissue softness model data taken from Ko *et al.* (2018) to support the assertions discussed above.

Table 1. 2-Parameter Model for Normalized Bath Tissue Softness Data

2-Parameter Model (BS, MMD)	
R^2	0.95
C (constant)	3.20
m (BS)	0.46
l (MMD_S)	0.73
Component (%)	
BS	39.1
MMD	61.0

Tissue Softness Analyzer (TSA)

The variety of softness evaluation methods leads to a lack of pervasiveness, but one instrument, described below, has gained more widespread acceptance. A dedicated instrument was developed for the measurement of softness along with an accompanying algorithm. Grüner (2012) developed this instrument, the Tissue Softness Analyzer (TSA9, Emtec, Germany), that uses thickness and basis weight as inputs while simultaneously measuring other parameters. The TSA was developed to mimic the interaction of the hand with the tissue sheet by measuring the light brushing of the surface by mechanical lamella. The equipment was designed specifically for managing the quality of sanitary tissue paper.

Fig. 4. Emtec's TSA softness measurement device (Paper Technology International 2021)

As noted by Kim *et al.* (2020), "the TSA converts the vibrations caused by friction of the fabric surface into acoustic spectrums and measures (*the*) acoustic frequency and sound pressure with indexing smoothness and softness." The lamellae spin on the surface of the tissue with a constant applied force. The sample is also stretched to evaluate the mechanical compliance of the sample. The spinning lamellae of the fan generate vibrations in the lamellae and the sheet. The intensity of the sound associated with this excitation can be correlated with softness. The Tissue Softness Analyzer device is depicted in Fig. 4.

The TSA records three primary parameters:

1. TS7, also known as the "real softness," is the amplitude (dB) of the sound spectra peak at a frequency of ~6500 Hz. The TS7 value is associated with the vibrations induced in the lamellae (Grüner).
2. TS750, also described as the "smoothness" or "roughness," is the amplitude (dB) of the sound spectra peak at a frequency between 200 and 2000 Hz (Grüner). The TS750 peak is believed to correspond to the vibration of the tissue membrane and is mainly thought to be caused by roughness and embossing (Furman and Gomez 2007).
3. Mechanical compliance/stiffness, the D parameter, measures the inplane sample deformation, *i.e.* in-plane stiffness, when a load of 100 to 600 mN is applied (Grüner).

These three measurements can then be used to calculate other parameters using proprietary algorithms. These other parameters include Handfeel (HF), fTS750, P, H, and E. The Handfeel value is calculated by "combining several measurements of the sample to obtain a global quantification of softness of the papers" (Vieira *et al.* 2020a). TSA-HF is a compound function. There are numerous algorithms associated with instrument software used to calculate the Handfeel. The sheet caliper and basis weight, as well as the number of plies, is input into the machine, and these parameters are used for the handfeel algorithms. This algorithm gives the instrument the ability to predict the panel softness for various paper types and consumer preferences. Equation 2 below shows the relationship and dependence of measured properties to determine a value for the feeling of softness.

Equation 2:
TSA-HF function

TSA-HF = f (TS-7, TS-750, D, caliper, grammage, and number of plies).

where HF = handfeel

D = stiffness

TS-7 = softness (dB)

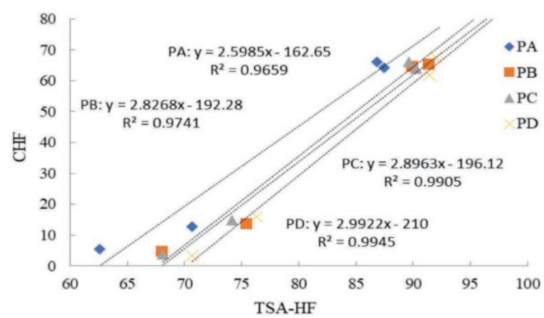
TS-750 = surface smoothness

The TSA can be especially beneficial because it is able to "separately index surface smoothness and fiber softness" (Kim *et al.* 2020), and it mimics a human hand. One study observed non-woven textiles measured and indexed surface smoothness and fiber softness properties in 749 fabrics with this TSA (Kim *et al.* 2020). The TSA results from another study showed that drape and bending properties are the most influential factors indicating surface smoothness (TS750). The surface smoothness was more correlated with drape than bending properties. The samples of this study were compared to simple mechanical characteristics as well, and it was found that the fiber softness (TS7) had a weak correlation with caliper thickness, Young's modulus, as well as weight (Kim *et al.* 2020). The comparison to thickness was made because it has been suggested that the TS7 measurement of bulk softness comes from the sample's thickness (Kim e*t al.* 2020).

The ranking of the softness and smoothness do correspond with rankings by other methods of direct physical measures such as human handfeel tests, but the values measured using the TSA were "not perfectly consistent with the value of subjective handfeel" (Kim *et al.* 2020). In other words, the TSA measures the same value independent of equipment user, whereas human handfeel will inevitably differ slightly. A study by Perng *et al.* (2019) investigated the relationship between hand-felt panel tests and TSA softness measurements (Table 2). It showed high correlations, with R^2 values ranging from 0.9659 to 0.9945, though only four samples were tested (Perng *et al.* 2019). In 2021, this study was furthered. The results from the TSA were correlated with those from Hollmark's softness theory, and it was found that a high correlation (R=0.904) existed between panel-correlated hand-felt softness and the handfeel softness measurement (HF) from the TSA. Still, a relatively lower correlation existed for the respective smoothness measurements (Perng *et al.* 2021). Therefore, it seems that the TSA is more comparable to the panel tests than other theories because it provides a more robust analysis of overall softness.

Table 2. Correlations of Standard (STD) Samples between TSA-HF and Corrected Panel-HF (CHF). Panel-A, B, C, D. Adapted from (Perng *et al.* 2019, 2021)

Panel	Brand	Panel-CHF	TSA-HF
A	B-STD-1	66.1	86.8
B		65.5	91.4
C		66.0	89.6
D		67.6	92.0
A	D-STD-2	64.2	87.4
B		64.7	89.9
C		63.9	90.2
D		61.9	91.4
A	A-STD-3	12.8	71.6
B		13.7	75.4
C		14.9	74.2
D		15.9	75.9
A	C-STD-4	5.5	65.7
B		4.8	68.0
C		3.8	68.1
D		3.2	70.7



Correlations of standard (STD) samples between TSA-HF and corrected HF (CHF). Panel-A, B, C, D.

Recently, a modified version of the TSA device, which includes an additional top microphone for measurement (Fig. 5), has been used to distinguish the influence of hardwood and softwood. A study by Prinz *et al.* (2021) evaluated the influence of four different furnishes on softness properties and assessed the differences in results when using the device with and without a polytetrafluoroethylene (PTFE) film. It was determined that without the film and using the old version of the TSA, some contradictory results were obtained. With the PTFE film and the new two-microphone device, differences that would be expected between hardwood and softwood handsheets were evident (Prinz *et al.* 2021).

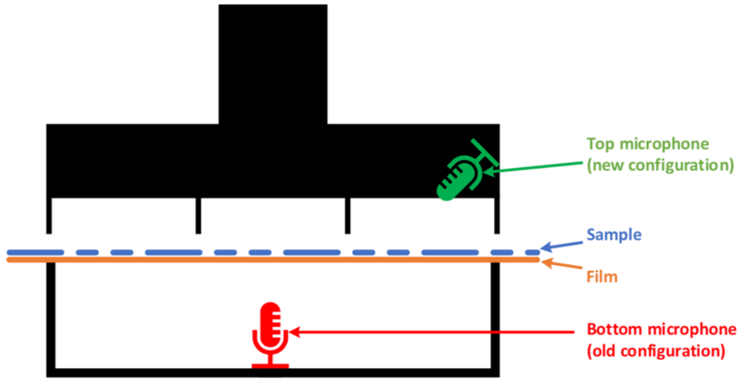


Fig. 5. New modified TSA device, with two microphones and optional film (Prinz *et al.* 2021)

Indication of Surface Topography

There are several types of imaging that can be used to comment on softness properties. Tissue paper's structure has been examined on both micro and macroscopic levels using field emission scanning electron microscopy (FESEM), laser scanning confocal microscopy (LSM), X-ray microtomography technologies (XRT) (Ismail *et al.* 2020), and Shadow-based Imaging (Raunio and Ritala 2013)

Laser scanning confocal microscopy (LSM) imaging

Non-contact measurements of the surface profile using scanning laser microscopes were also found to correlate with panel softness. Furman and Gomez (2007) imaged the surface of six samples and found a strong correlation with panel softness (R^2 = 0.9183). The projected surface area was found to correlate with panel softness. This technique may be promising, but the limited number of samples prompts questions of how this would perform in the broader application of the technique. The algorithm is relatively complicated and may limit the utility in a wider setting. Figure 6 shows how the laser measures the images in LSM imaging.

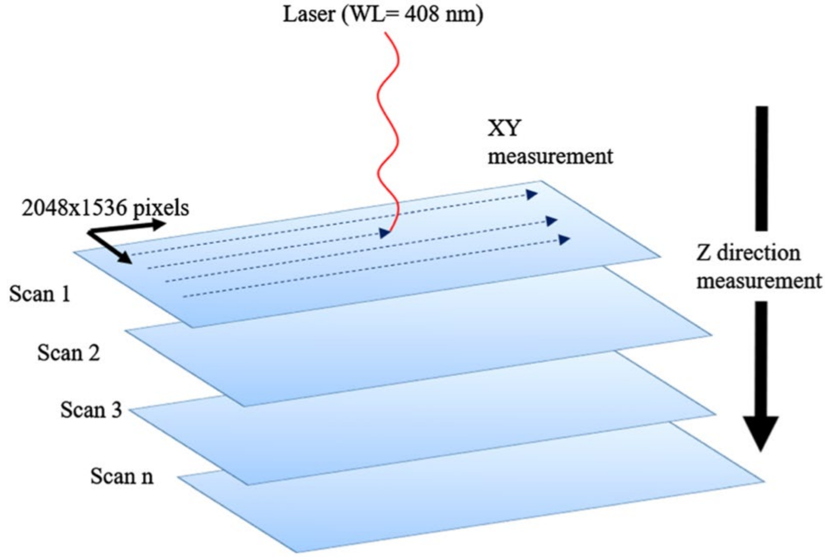


Fig. 6. A schematic of the mechanisms involved in LSM imaging, from models from Ismail *et al.* (2020)

Regarding LSM, surface properties that can be analyzed by this method include "crepe count, waviness, and the average height of the crepes" (Ismail *et al.* 2020). Additionally, relationships between these properties and final product softness have been found. This technology uses "laser confocal optics to measure the depth of field across a specimen," as well as two light sources, one laser, and another white light, that can help determine information about the sample's shape and roughness through image and height data (Ismail *et al.* 2020). The crepe structure and periodicity can be determined by detecting waves on the sample through this technology. LSM is a non-destructive method, meaning "it does not affect the wave structure and height of the sample" (Ismail *et al.* 2020).

Field emission scanning electron microscopy (FESEM) imaging

Field emission scanning electron microscopy (FESEM) has been used to study and characterize the planar morphology of tissue papers (Ismail *et al.* 2020). Detailed surface topography of the tissue samples was possible by imaging when the sample was coated with platinum (to increase conductivity), and 3 to 5 kV of acceleration voltage was applied to them (Ismail *et al.* 2020). The FESEM is advantageous due to its clear resolution.

X-ray microtomography technologies (XRT) imaging

X-ray microtomography (XRT) uses an X-ray tomograph with a supplementary MATLAB code for structural and wave count analysis (Fig. 7). A UK - Hanatek FT3 precision thickness gauge (UK) was used to measure the average thickness of the paper sample (Ismail *et al.* 2020).

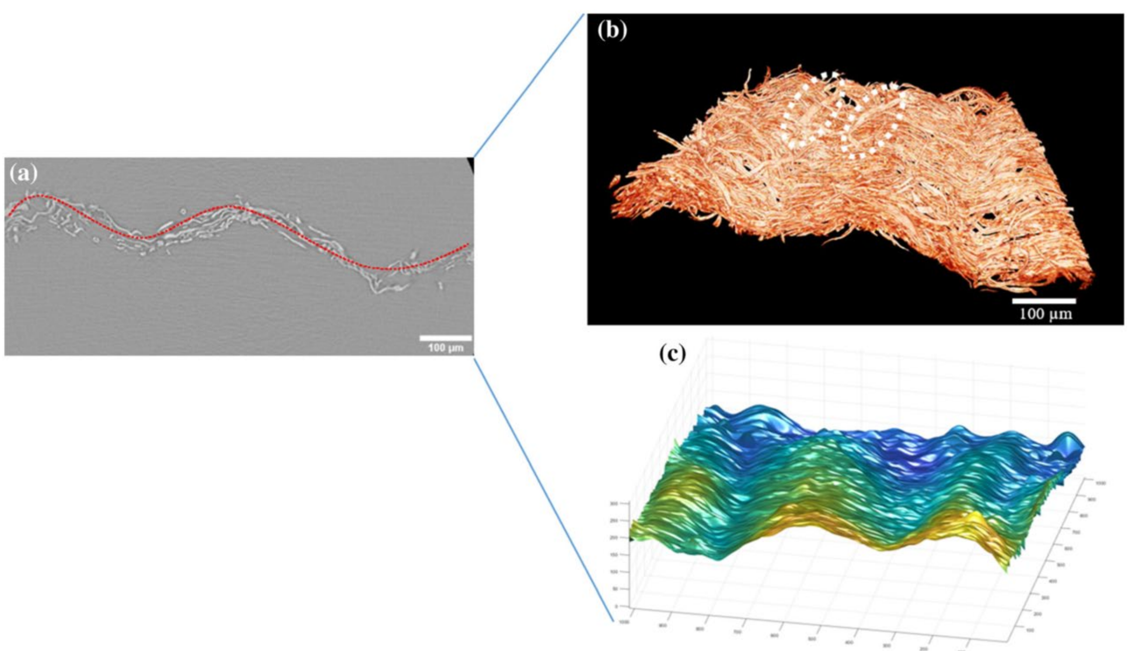


Fig. 7. Depiction of XRT imaging of a single ply sample a) imaged in the µCT, b) viewed in a 3D model to show fiber orientation, and c) viewed in a 3D MATLAB® model. Image courtesy of Ismail *et al.* (2020). This image is published under the creative commons attribution 4 license (CC BY 4.0 license) by Springer (http://creativecommons.org/licenses/by/4.0/).

Shadow-based imaging

Another new surface softness evaluation method of tissue paper is an imaging method "based on detecting shadows caused by the free fiber ends" (Raunio and Ritala 2013). Because of the tissue paper's wavy surface, shadows are difficult to detect on the reflectance image. Therefore, the photometric stereo system was used to estimate the 3D surface information, and "the intensity variations caused by the wavy surface were filtered out" (Raunio and Ritala 2013). Digital images were taken, and the density of surface fibers was measured from these images. This particular method is promising because it showed greater accuracy than some other previous methods, and it could be implemented on a running paper machine (Raunio and Ritala 2013). The mechanism for shadow-based imaging is shown in the drawing below (Fig. 8).

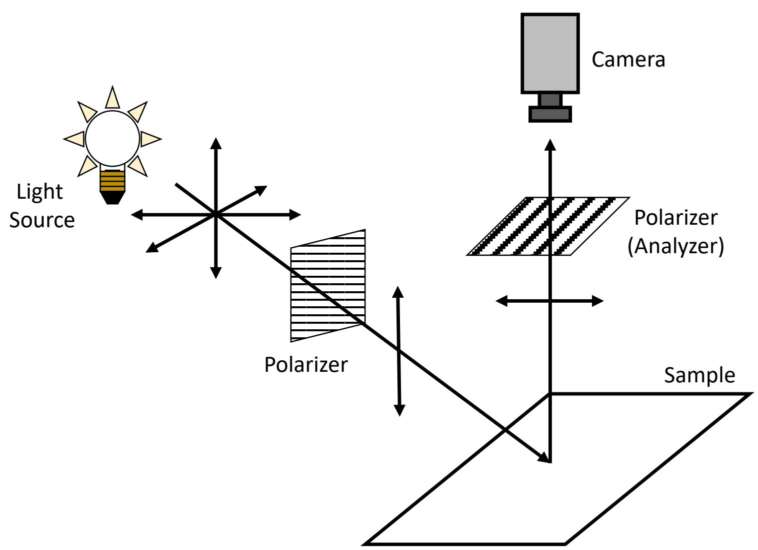


Fig. 8. Drawing based on an image from Raunio and Ritala (2013) depicting the setup of the camera system and polarizers in the shadow-based imaging system

VK analyzer software

VK analyzer software has been used to view and calculate the waviness profile (Ismail *et al.* 2020). This software is used with various imaging techniques to determine the outer profile of a sample. Therefore, this can indicate the surface and may then be correlated to softness.

The previously described softness measurement methods have limitations, as they may be used only in limited circumstances or have good correlations in limited sample types. When samples vary widely in fiber type, fiber orientation, and moisture content, the reliability of these methods to measure softness is greatly reduced (Hollmark and Ampulski 2004). The procedures can also be time consuming, require specialized equipment, and only be applicable to limited sheet types (Ramasubramanian 2002). However, the methods described elucidate several important properties for indicating softness. These properties include tensile strength, friction characteristics, ultra-sonic characteristics (high frequency vibration/elastic modulus), stiffness, surface profile, surface texture, and sheet thickness. Table 3 details and organizes the previously described methods.

Table 3. Summary of Softness Testing Methods and Models

Method Name	Type of Model	Model Equation (if applicable)	Compliance with human softness ratings	Reference
Panel Test	Direct Measure of Softness		Panelists score the softness of the samples relative to the reference sheets, this is the baseline comparison for most tests	Institute of Paper Chemistry 1967, Wang 2019
SPT Sensory Panel Test	Direct Measure of Softness	A preference is converted to a % from a pair- comparison test to an interval scale value	Since environment is controlled, not as realistic, but less variable than typical panel tests	Ko *et al.* 2018
N-SPT	Direct Measure of Softness	A preference is converted to a % from a pair- comparison test to an interval scale value, 2-P & 3-P models detailed below	Variability controlled better, more similar to typical panel test, so more realistic	Ko *et al.* 2018
Artificial Finger	Direct Measure of Softness	Average acoustic vibratory level: $La = 20\log\frac{A_{RMS}}{A_{ref}}$	The measured vibrations have good correlation to the softness from panel tests, and the friction shows a relation to the surface texture of bath tissue	Thieulin *et al.* 2016
TSA: Tissue Softness Analyzer	Prediction model that correlates with softness	Multilinear regression model developed to predict TS7 (real softness): $TS7 = 2.59*V_f + 4.81E\text{-}4 * N_c$	Correlates well (R^2=0.75) with panel testing for the market tissue samples, TPII determined to be the best correlated algorithm, another test found R^2 = 0.9945	Gruner 2012, Wang 2019, Perng 2021
Hollmark bulk softness model	Prediction model that correlates with softness		Correlation not stated	Ko *et al.* 2018
P&G Model	Prediction model that correlates with softness		Correlates well with subjective softness rating for HTR and PSU (panel score unit) because these are human measurements	Ko *et al.* 2018
GP Model	Prediction model that correlates with softness		MMD alone was found sufficient for surface softness, correlation not stated	Ko *et al.* 2018

KC Model	Prediction model that correlates with softness		Single U-tube measurement found higher correlation to handfeel	Ko *et al.* 2018
Kawabata KES System	Prediction model that correlates with softness		Able to determine the softness of paper towels with a degree of accuracy, but it did not work well with toilet tissue, Correlation not stated	Kawabata 2002
Handle-O-Meter	Prediction model that correlates with softness		Found not to correlate well with panel test methods	Lashof 1960
2-P Model (BS, MMD)	Prediction model that correlates with softness	X= C + m*log(BS) + l*log(MMD) X= 3.20 – 0.46*log(BS) - 0.72*log(MMD)	The best correlation model for 2 parameters from N-SPT, $R^2 = 0.95$	Ko *et al.* 2018
2-P Model (BS, SMD)	Prediction model that correlates with softness	X= C + m*log(BS) + n*log(SMD) X= 3.35 – 0.70*log(BS) - 0.55*log(SMD)	Not as good a correlation as 2-P model for N-SPT that includes BS and MMD, R2 = 0.79	Ko *et al.* 2018
3-P Model	Prediction model that correlates with softness	X= C + m*log(BS) + n*log(SMD)+ l*log(MMD) X= 3.15 – 0.44*log(BS) +0.06*log(SMD) +0.78*log(MMD)	A slightly better correlation model for N-SPT than 2-P model with BS and MMD (R2 = 0.96) but more variables	Ko *et al.* 2018
Clark's Softness Tester	Prediction model that correlates with softness		Out-of-plane elastic modulus measurement has been correlated with subjective softness evaluation, specific correlation not specified	Ko *et al.* 2018, Pan et al 1989
Brown Softness tester	Prediction model that correlates with softness		Not successful as softness predictor, Out-of-plane elastic modulus has been measured to correlate with subjective softness evaluation	Ko *et al.* 2018, Pan et al 1989
C.H. Dexter softness tester	Prediction model that correlates with softness		Not successful as softness predictor, Out-of-plane elastic modulus has been measured to correlate with subjective softness evaluation	Ko *et al.* 2018
Ultrasound Method for out-of-plane properties	Prediction model that correlates with softness	Ultrasonic time-of-flight measurements: Velocity of sound, VZD = caliper/time-of- flight (most common) Out-of-plane bulk elastic stiffness,	Parameters measured correlated well with the panel softness for the limited sample set tested, combined regression coefficients squared, r^2 , are 0.884 for bulk softness and 0.785 for surface softness	Pan et al. 1989

		C33 = VZD2 multiplied by density (also used)		
Sled Method	Prediction model that correlates with softness	Not given in text	Results show high correlation with handfeel surface softness perception, considered a good approximation of surface softness, exceptional correlations between handfeel results and sled results: r = 0.972 between the two test methods	Kuo and Cheng 2000
LSM	Indication of surface topography (Imaging)	See VK analyzer equations	Correlates well with panel softness, R^2 = 0.9183, but potentially limited by number of samples	Ismail et al. 2020, Furman and Gomez (2007)
FESEM	Indication of surface topography (Imaging)	See VK analyzer equations	Relationships between surface properties and final product softness have been found, specific correlation not given	Ismail et al. 2020
XRT	Indication of surface topography (Imaging)	See VK analyzer equations	Can determine crepe count but not a direct softness measurement, not correlated to panel testing	Ismail et al. 2020
VK analyzer software	Indication of surface topography (Imaging)	The average waviness of the profile (Wc) and arithmetic mean height (Wa) were determined from the waviness profile. They are defined as: $Wc = \frac{1}{m}\sum_{i=1}^{m} Rti$ and $Wa = \frac{1}{lr}\int_0^{lr} \lvert Z(x)\rvert\, dx$	Not a direct measurement of softness, correlation not given	Ismail *et al.* 2020

La: acoustic vibratory level; A_{RMS}: root mean square value of the acceleration; Aref: 10^{-6} m/s^2; TS7: Softness (dB); *X*: softness model; *C*, *m*, *n*, *l*: curve fitting coefficients; BS: bulk stiffness; SMD: mean deviation of surface roughness; MMD: mean deviation from average coefficient of surface friction; Wc: average waviness of profile; Wa: arithmetic mean height; m: number of periods; Rti: peak-to-peak amplitude of one full period; l_r: sampling length

OVERVIEW OF THE BATH TISSUE MANUFACTURING OPERATIONS AND THEIR EFFECT ON TISSUE SOFTNESS

Compared to the copy paper manufacturing process (intensive pressing during dryness stage), tissue paper manufacturers use heat and air to dry the tissue web (Sanford and Sission 1967). This drying process prevents densifying the web and increases the porosity in the tissue web (Kullander *et al.* 2012). The Yankee dryer is the most common drying unit for drying tissue. The Yankee dryer is a large cylinder of 5 to 6 meters in diameter (de Assis *et al.* 2018). The solid content of the web entering the Yankee dryer is about 45% and increases to 95% when leaving the Yankee dryer. The temperature of the surface of the Yankee dryer is about 100 °C (Kullander *et al.* 2012). Hot steam is injected into the inner wall to heat the entire cylinder. Hot air is blown from the Yankee hood to the surface of the tissue web to accelerate the drying rate. A creping blade is used at the end of the drying process, which gently scrapes on the surface of the tissue web (Kullander *et al.* 2012). The creping process alters the web structure and creates more free fibers to make the sheet bulkier and softer (Padley 2012).

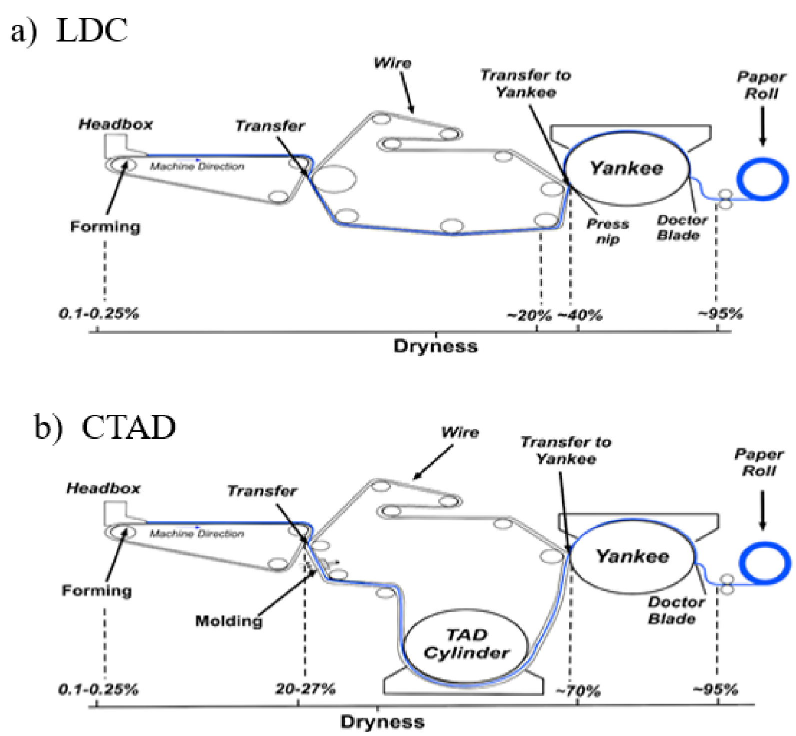


Fig. 9. A. Sketch of a Light Dry Crepe (LDC) drying machine; **B.** Creped-Through-Air Dry (CTAD) drying machine

To satisfy customers' pursuit of softer and bulkier tissues, manufacturers introduced a Thru-Air Drying (TAD) process to the bath tissue industry. Using the hot and force-directed air, TAD is capable of producing a bulkier, softer, and three-dimensional tissue (Wang *et al.* 2019b). The consumption of TAD dried tissue increased from 1.2 million tons (1990) to 3.5 million tons (2012). The energy cost of drying a ton of tissue by TAD is on average 60 dollars (US) higher than Light Dry Crepe (LDC) dryer (de Assis *et al.* 2018). The retail price for TAD dried products is on average 1000 dollars (US) per ton higher. Besides TAD, other advanced tissue machines have been developed, such as the DRC (Double Re-Crepe), ATMOS (Advance Tissue Molding System), and NTT (New Tissue Technology) (de Assis *et al.* 2018). The designs of tissue machines vary with respect to capital investment, configuration, location, and production rate.

The LDC (cf. Fig. 9A) uses a combination of gravity, vacuum, press nip, and a Yankee dryer to dry the wet tissue web (Kullander *et al.* 2012). Tissue manufacturing on an LDC (Fig. 9A) starts with a headbox distributing pulp suspension onto the forming wire. The consistency of the pulp can range from 0.1% to 0.25%. The wet paper web is exposed to gravity and a vacuum box on the transition to the press nip. The tissue web then enters the Yankee cylinder and is dried by heat. The press nip is a roller set against the Yankee cylinder, which applies pressure to the paper web to remove ~20% of water.

There are three common types of Through Air Drying processes: Creped-Through-Air-Dry (CTAD), Creped-Through-Air-Dry-Belted (CTADB), and Uncreped-Through-Air-Dry (UCTAD) (de Assis *et al.* 2018). As shown in Fig. 9B, the most common type of TAD machine is the CTAD, which combines the TAD cylinder with the Yankee Dryer. In CTAD, the TAD cylinder removes ~50% of the water (Kullander *et al.* 2012). The wet web is later transferred to the Yankee dryer for further drying and creping. The tissues produced by CTAD typically have the highest bulk and softness on the market and are categorized as the ultra-grade of tissue.

CTAD (Fig. 9B) eliminates the press nip and adds a molding process. After the wet web is transferred to the TAD cylinder, a constant pressure drop of heated air (100 to 250 °C) is passed through the wet web in a honeycomb pattern (Berndt 1999; Valmet 2014). The temperature and pressure variation depends on the production rate. The heated air temperature is typically limited to 250 °C to prevent odor issues in the finished product and the TAD fabric degradation. The airflow rate at the TAD cylinder is around 1500 to 2200 lb/hr/ft^2 (Berndt 1999; Valmet 2014).

The TAD process does not require wet pressing. Therefore, it is important that the sheet has excellent formation and sufficient wet strength to make it through the process (Valmet 2014). A high mesh forming fabric (Fig. 10) is typically used in the forming section to ensure good fiber support (McCabe 2011).

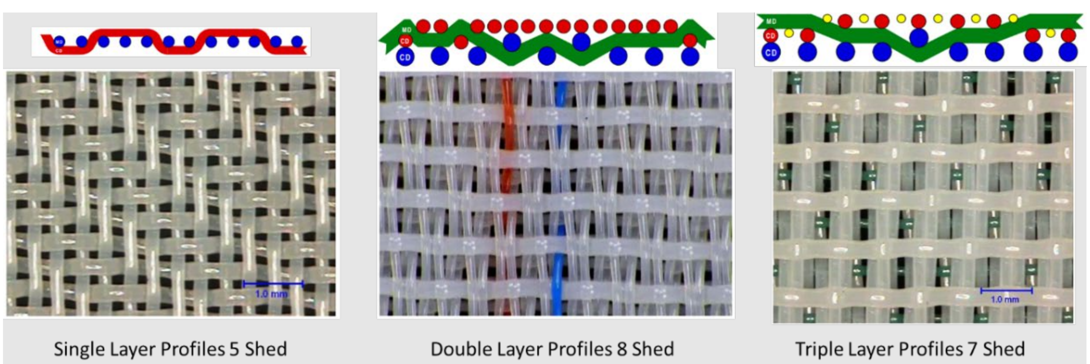


Fig. 10. The forming fabric designs (McCabe 2011)

The materials used for weaving the forming fabric are typically extruded polyethylene or nylon. The strand width ranges from 0.1 mm to 0.45 mm (McCabe 2011). The strands of machine direction (warp) and cross direction (weft) cross each other in different patterns to form the forming fabrics. These fabrics vary by sheds and layers. As shown in Fig. 10, in the double layer profile, two layers of different diameters weft crossed one layer of warp (Tysen 2014). The increased amount of layers and sheds would provide better forming for the wet web. It would also increase the stability and service period of the fabrics (Tysen 2014).

Compared to the forming fabric, the TAD fabric has a relatively low mesh, which results in a higher permeability design and an increase in the paper's efficiency of air drying and bulkiness (McCabe 2011). The vacuum supplied by the TAD roll molds the wet web into the TAD fabric to create a 3-dimensional, bulky sheet (Valmet 2014). As shown in Fig. 11, the TAD fabric used for drying kitchen towels has more out of plane variation compared to the one for bath tissue, which maximizes the amount of sheet being molded into the fabric to create a high bulk sheet.

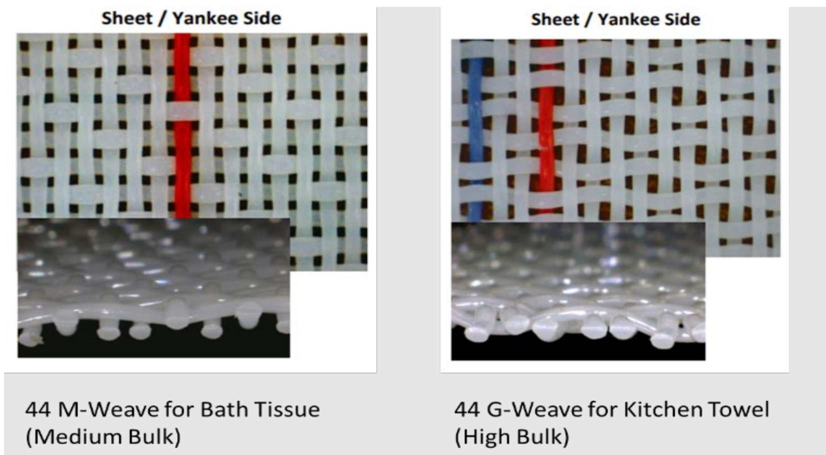


Fig. 11. The TAD fabric designs (McCabe 2011)

Kimberly-Clark (Wendt *et al.* 1998) invented the Uncreped-Through-Air Dry (UCTAD) system by removing the Yankee dryer and using only the TAD cylinder to dry the web. This process results in higher productivity because of the limitation of the rotation speed of the Yankee cylinder. UCTAD also minimizes the reduction of the caliper of the sheet by skipping the pressing nip procedure at the beginning of the Yankee Drying. The negatives of UCTAD are the high energy consumption and the loss of softness since the creping process is removed. Kimberly-Clark mostly manufactures the bath tissues dried by UCTAD and categorizes them as the premium-grade tissue.

Instead of using TAD fabric in drying (CTAD), Creped-Through-Air-Dry-Belted (CTADB) uses a woven fabric belt cast with urethane as the carrier for the tissue web (Smurkoski *et al.* 1992). The molding can provide both uncompressed pillows and compressed lines. CTAD is capable of providing bath tissue with high strength and softness, but the belt itself is expensive and less durable compared to fabric (de Assis *et al.* 2018). The CTADB was invented by Procter & Gamble and has been used in its best quality ultra-soft tissue (de Assis *et al.* 2018).

The consumption of TAD dried tissue increased from 1.2 million tons (1990) to 3.5 million tons (2012) (RISI), which implies that the customers are finding value in softer and bulkier tissue products. Compared to light dry creping drying (LDC), the drying efficiency of TAD is relatively low and requires much more energy to dry the same amount of paper. In Fig. 12, the energy cost USD and pulp cost for ten non-integrated LDC and ten non-integrated TAD tissue mills are summarized. For one ton of bath tissue, TAD mill requires, on average, 80 US Dollars more energy to dry compared to LDC mill (Fishersolve

International 2017). Though using mostly virgin pulp, the pulp cost for the two different mills is similar (Fishersolve International 2017). The retail price for TAD dried tissue is however on average 1000 US dollars higher than LDC, which indicates the significant value generated by TAD.

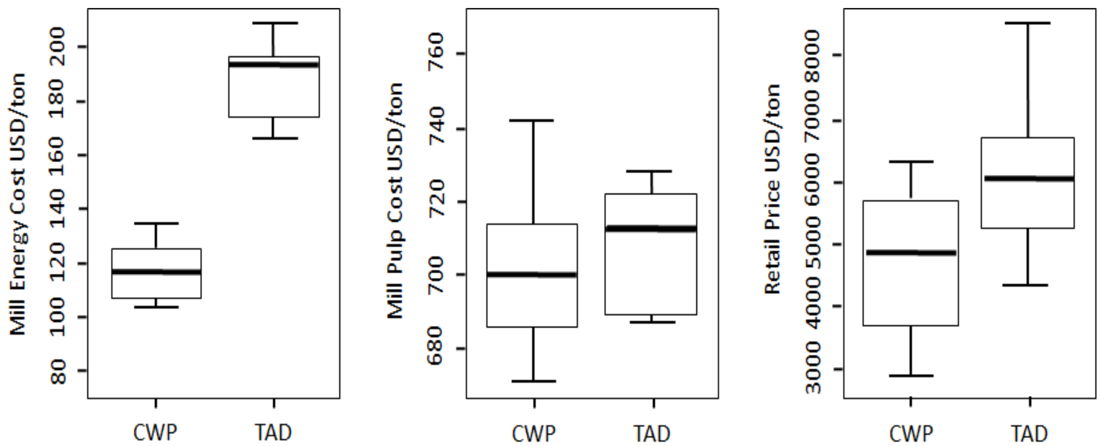


Fig. 12. Cost and retail summary of bath tissue manufacturing (Fishersolve International 2017)

Manufacturing Processes Effect on Tissue Paper Softness

During the papermaking process, pulp and paper are subjected to various mechanisms influencing the tissue paper properties, especially the softness (de Assis *et al.* 2018; Pan *et al.* 2018; Wang *et al.* 2019b; de Assis *et al.* 2020). In this section, these processes are described as follows:

Mechanical refining

Mechanical refining promotes fiber delamination and fibrillation to cause improved fiber-to-fiber bonding, which translates into increased tensile strength and density in paper products (Gharehkhani *et al.* 2015; Zambrano *et al.* 2020, 2021). However, this mechanical treatment may also cut the fiber and peel small parts of the cell wall from the fiber to produce what is known as secondary fines, which are capable of occupying empty spaces in the fiber web (Gharehkhani *et al.* 2015; Liu *et al.* 2016). Hence, the paper sheet gets densified, and the tensile strength also increases from the generated fines. If the refining intensity is too high, the fiber can be cut without additional improvement in bonding, leading to lower tensile strength and improved formation uniformity (de Assis *et al.* 2018). It has been found that paper softness is negatively affected by increased refining level and density (Gigac and Fišerová 2008; de Assis *et al.* 2018; Zambrano *et al.* 2020, 2021). For tissue papers, the objective would be to apply a minimum amount of refining energy to achieve the desired strength without compromising softness and absorbency (de Assis *et al.* 2018). Thus, refining in tissue products is very much an operation of optimization.

Creping

The creping process is an essential step during the production of tissue products to enhance tissue paper properties (de Assis *et al.* 2018). The creping process employs a doctor blade (Fig. 9) to scrape the tissue sheet from the Yankee dryer surface, and in this process, the doctor blade creates crepe folds. The sheet is also delaminated during creping, which contributes to improved bulk, softness, and absorbency properties (de Assis *et al.* 2020). Additionally, the bending stiffness of the sheet of paper decreases due to the breaking of fiber-to-fiber bonds. Moreover, both the material's bulk (inverse of density) and the stress to failure pointedly increase, especially in the machine direction (MD). As a result, softness is increased (Ramasubramanian and Shmagin 2000). As depicted in Fig. 13, the creping process produces buckling, distortion, and surface delamination of fibers as well as the creation of crepe folds. These changes in structure enhance water absorbency and softness but reduce the tensile strength (de Assis *et al.* 2020). A high number of short folds is desired to enhance softness, and the crepe frequency can be altered by sheet and creping conditions. These conditions include making tissue with low basis weight, high web bulk, and high creping angle (de Assis *et al.* 2020). The creped structure of the tissue paper relies on several variables related to the paper web (*e.g.*, fiber type, basis weight, density, caliper, moisture, *etc.*) and tissue making process (*e.g.*, refining, wet-end additives, formation, wet pressing, creping chemistry, temperature, blade angle, speed, crepe ratio, *etc.*) (Pan *et al.* 2018; de Assis *et al.* 2020). Several researchers claim that the final features of the creped tissue structure are the result of a balance between the level of adhesion between the paper web and Yankee surface, the cohesion of the paper web before the creping (doctor) blade, the creping forces experienced by the paper web at the creping blade, and the crepe ratio. Moreover, a more effective creping is more likely to happen when adhesion and creping forces are high and paper web cohesion is low (Pan *et al.* 2018; de Assis *et al.* 2020).

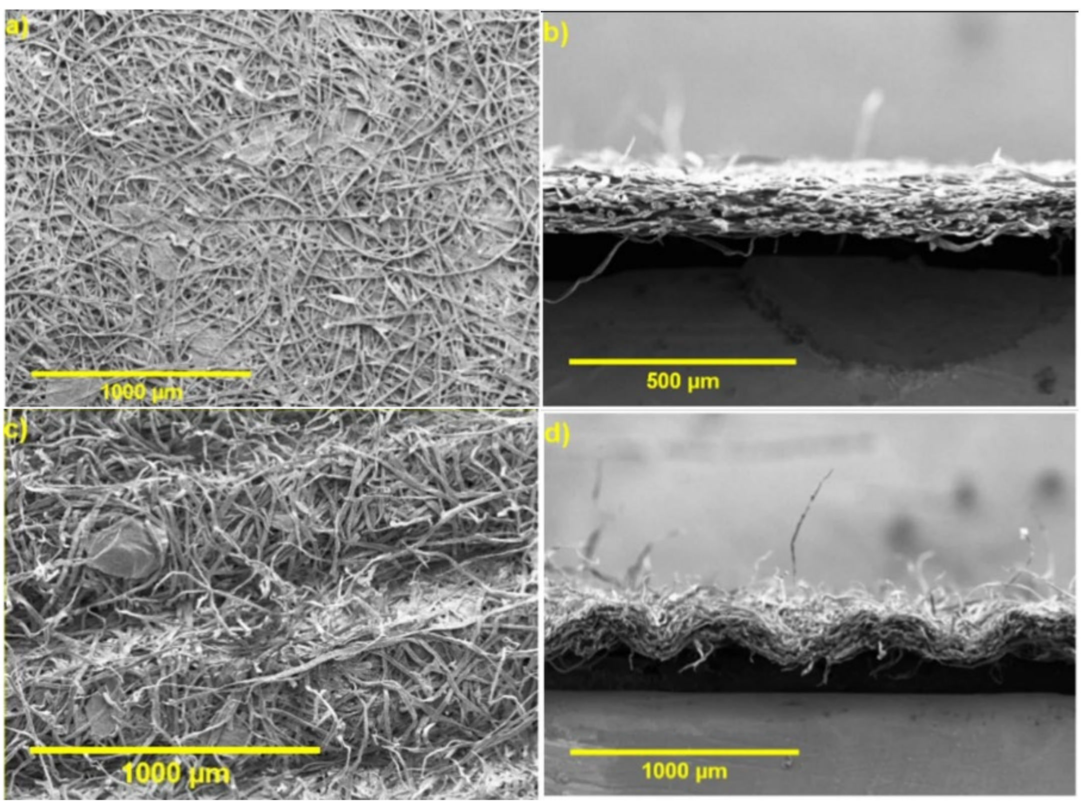


Fig. 13. Scanning electron microscopy (SEM) images of surface and cross-section of uncreped (a,b) and creped handsheets(c,d) for bleached eucalyptus kraft pulp. Figure adapted from de Assis *et al.* (2020)

Converting

Converting is the final step in tissue paper manufacturing. This process is defined as a set of procedures (*e.g.*, unwinding, embossing, printing, perforating, rewinding, cutting, and packaging) performed on paper. Converting provides finished products with important functional properties that add value when placed into the commercial market (Oliveira Mendes *et al.* 2020; Vieira *et al.* 2020b).

Embossing mechanically sculptures tissue paper to improve the visual appearance, lower density, and increase softness. Embossing also improves haptic and abrasive properties (Vieira *et al.* 2020b). Moreover, this process involves tissue sheets with two or more plies, where a higher number of plies also improves tissue strength and softness (de Assis *et al.* 2018, Vieira *et al.* 2020b). The tissue plies are pressed together completely or just at the edges during the embossing process (de Assis *et al.* 2018). The embossing process involves compressing individual plies with a pattern of indentations and holding them together into a final laminate (Spina and Cavalcante 2018). Embossing typically compresses the sheets together at distinct points. The process can be used to add aesthetic graphic elements to tissue products. Occasionally, it is used for the purpose of identifying and distinguishing products (Stefani 2020).

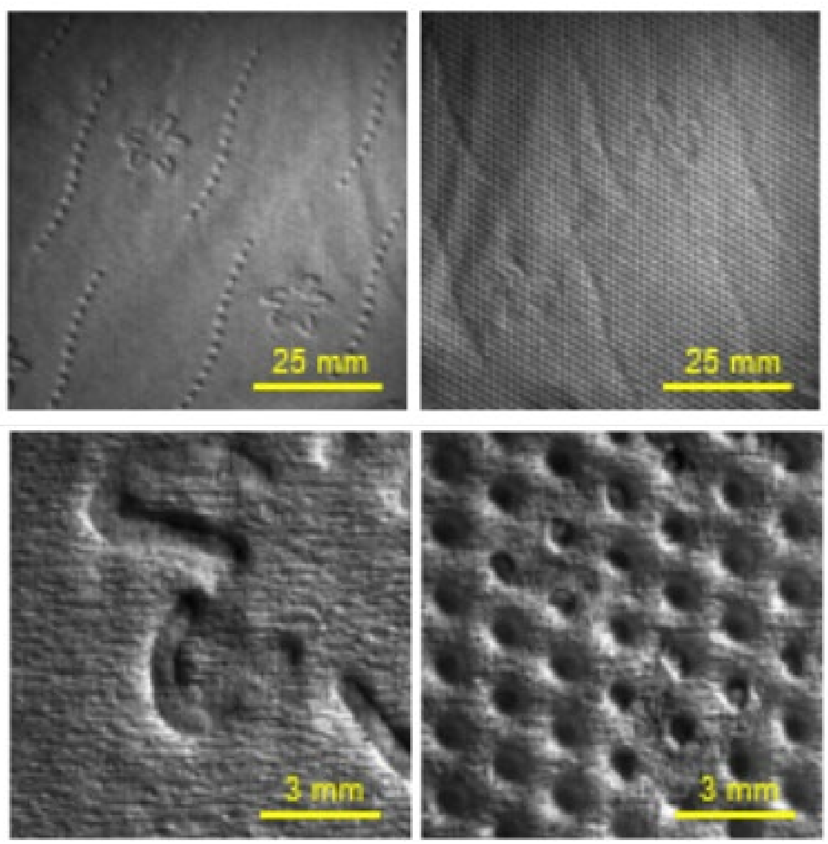


Fig. 14. Global (a,b) and magnified views (c,d) of the embossed tissue surface. Figure adapted from (Vieira *et al.* 2020b)

Paper is pressed with a metal roll with a specific image pattern in this process. The embossing die pattern is molded into the paper using pressure and heat, as can be seen in the high-relief image Fig. 14 (Vieira *et al.* 2020b). Patterns may depend on product lines (*e.g.*, premium, non-premium), customer requirements, and applications (*e.g.*, towels, toilet paper, *etc*.). The premium products normally have a more elaborate pattern to delight consumers (Spina and Cavalcante 2018). The embossing machine design and embossing roll influence tissue properties such as tensile strength and softness (Enderby and Straten 2001; de Assis *et al.* 2019; Stefani 2020).

It has been reported that both embossing technology and embossing patterns can have significant effects on tissue softness and other properties (Spina and Cavalcante 2018; Stefani 2020). Two major embossing technologies are used: “nested” and “knob-to-knob” (de Assis *et al.* 2018). In the first process, the embossing projections of one ply are placed between the embossing projections of the other ply. On the other hand, in the “knob-to-knob” technology, the embossing patterns of both plies are aligned to each other. The knob-to-knob embossing promotes higher bulk, absorbency, and compressibility (Enderby and Straten 2001). Another technology, the “top sheet embossing,” is used when two TAD plies are combined. Space is formed between the plies, which enhances water absorbency capacity and rate due to the creation of inter-ply channels, allowing higher water storage and lower water flow resistance (de Assis *et al*. 2018; Vieira *et al.* 2020b). Further details about the embossing process and its effect on softness can be found in previous works (Spina and Cavalcante 2018; Stefani 2020).

Chemical Additives that Promote Tissue Paper Softness

Several chemical additives are applied in the manufacturing process of tissue paper to improve the quality and performance of these products (Liu 2004; Gashti and Adibzadeh 2014; Tang *et al.* 2017; Mazzon *et al.* 2019). The main additives used in tissue making are softening and debonding agents. Other additives include lotions, antibacterial additives, and enzymes (Igarashi *et al.* 2016; Park *et al.* 2019; Morais *et al.* 2021; Xu *et al.* 2021).

The tissue and textile industries use several softeners and debonders synthesized for these industries (Liu 2004; Igarashi *et al.* 2016; Tang *et al.* 2017). The application of softener agents, which are generally surfactants, modify the cellulose surface chemistry. The adsorption of these materials is depicted in Fig. 15. As the chemical is adsorbed, the lipophilic chain of the adsorbed chemical promotes a lubricating effect, translating into a softer sensation. These additives are applied in the wet end as a debonder or later in the process (*e.g.* dry end or converting) as a lotion (Park *et al.* 2019). Among softener types, cationic ones have been reported to have the best performance (Shore 2002). On the other hand, non-ionic softeners provide high lubricity and are stable under extreme conditions (*e.g*. pH and heat). Additionally, silicone softeners have been reported to give very high softness, crease recovery, abrasion resistance, and tear strength (Schindler and Hauser 2004).

Softening agents can also be ionic surfactants (*e.g.* anionic, cationic, or amphoteric). Their hydrophilicity, nature of hydrophobic side chains, and molecular weight significantly impact tissue properties (Parvinzadeh 2007; Parvinzadeh and Najafi 2008). The cellulose fiber surface has a negative apparent surface charge (Brønsted base, due to the dissociation of a proton from -COOH groups). In this sense, it could interact with the softener through electrostatic interactions and hydrogen, dipolar, or Van der Waals forces. Most of the ionic softeners are based on quaternary ammonium salts, of which *N,N*-distearyl-*N,N*-dimethyl-ammonium chloride (DSDMAC) products are common, as well as esterquats (Mishra 2007; Patanwala and Dorugade 2010). Moreover, the use of tetradecyl-trimethyl-ammonium bromide (TTAB) has been reported as a softening agent (Corrente *et al.* 2021).

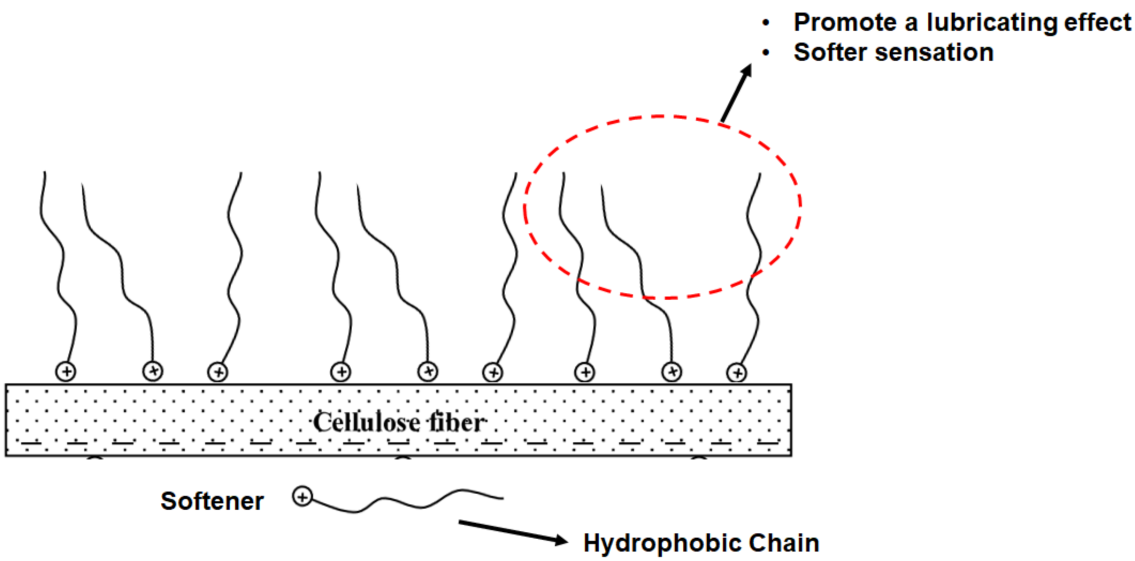


Fig. 15. Scheme based on the softener mechanism to improve the tissue softness. The mechanism is based on the softener adsorption on cellulose surface (Park *et al.* 2019).

Besides ionic softeners, non-ionic compounds have been recently used as softeners for textiles and tissue paper manufacturing. Ultratex FSA New (FSA), Ultratex FH New (FH), Turpex ACN New (ACN), and Ultraphil DCW New (DCW) are commercial softeners based on emulsions with functional polysiloxane and polyalkylene that have shown outstanding performance on cellulosic surface softness (Tang *et al.* 2017). Silicone-based softeners and lotion have also improved tissue softness (Mazzon *et al.* 2019; Park *et al.* 2019).

The application of debonding agents has been effective in improving the softness of tissue products and increasing the wet strength of the paper (Liu 2004; Fatehi *et al.* 2010). The traditional cationic debonders usually are quaternary ammonium compounds (Liu 2004; Fatehi *et al.* 2010). In practice, the long fatty alkyl chain in the debonder structure plays an important role, as it disrupts the fiber-fiber bonding, which reduces the tissue sheet strength and increases the sheet bulk (Liu 2004). Softrite® 7516 was found to have a significant positive effect on the softness of tissue handsheet paper, as the fatty chains of the debonder impart a lubricating feel to the fibers (Liu 2004). Additionally, ester-type debonders are commonly used since they are biodegradable and capable of reducing sheet dry tensile strength and improving tissue softness (Liu 2004). In this context, palm stearine diester has been used as a debonder agent to significantly improve tissue sheet softness (Liu 2004). Recently, a multibranched long-chain alkyl quaternary ammonium has been reportedly used as an antibacterial-debonding agent for softening. As a result of the treatment, the softness was improved proportionally with the length of alkyl chains and the number of long alkyl chains on the side chains (Xu *et al.* 2021).

When enzymes have been used in a fiber biorefining process, it has been discovered that they contributed to changes in the tissue properties of kraft and sulfite industrial pulps (Morais *et al.* 2021). The enzymatic treatment of pulp led to more efficient fiber fibrillation. Consequently, a lower level of refining was required, the formation of fines decreased, and the fiber bonding was improved. Additionally, the enzymatic treatment for both pulps helped to maintain the strength and increase the softness for the kraft and sulfite pulps, respectively (Morais *et al.* 2021).

FIBER RESOURCES USED FOR TISSUE MAKING

Tissue paper is primarily composed of wood fibers, although non-wood fibers are becoming more common. These fibers can be categorized by their origin (virgin or recycled), process (chemical, mechanical, bleached, unbleached), and source (hardwood, softwood, non-wood). All these variables contribute to the final performance of the bath tissue (de Assis *et al.* 2018; FisherSolve International 2017). Manufacturers experiment with the combinations and attempt to determine the formula that gives the lowest cost but highest performance products.

Kraft Virgin Wood Pulp

Though more and more non-wood fiber products are coming to the market, the dominant source for making tissue is wood fiber. Wood is composed of ~ 45% cellulose, ~20% hemicellulose, ~30% lignin, and some minor extractives. The composition varies by species and layers of the cell wall (Sjöström and Westermark 1999). The cell wall consists of the lumen, middle lamella, primary cell wall (P), and secondary cell walls (S1, S2, S3). The wood fibers may be liberated from the wood through a pulping process. There are a variety of pulping processes, including groundwood (GW), refiner mechanical pulping (RMP), chemi-thermo mechanical pulping (CTMP), semi-chemical pulping, and chemical pulping. While all of the pulping methods may be used to create fibers for tissue and toweling, the most common type of pulping is chemical pulping (*e.g.* kraft pulping). In addition, recycled chemically pulped fiber from mixed office wastes is used for tissue and towel manufacturing.

Wood fibers produced from angiosperms are categorized as hardwood fibers. In the United States, angiosperm species from the north and south regions are different. They can be classified as Northern Hardwood (NBHK: aspen, maples, birches, beech, *etc.*) and Southern Hardwood (gums, oaks, poplar, ash). Hardwood fiber is relatively short (1 to 2 mm) and thin (10 to 20 μm). Depending on the species used to produce the fiber and the climate the tree has grown in, the fiber dimension of hardwood market pulp might vary significantly. *Eucalyptus* species, including *grandis, urophylla, globulus*, *etc*. are hardwood species mainly imported from South America. Fibers produced from eucalyptus plantations are more uniform and are regarded as the best fiber to make tissue (Nanko *et al.* 2005; FisherSolve International 2017; de Assis *et al.* 2018).

Gymnosperms are trees that are typically known as softwoods. Softwood fibers are relatively long (3 to 5 mm) with widths in the range of 30 to 50 micrometers. The high aspect ratio of the softwood fibers provides good tensile and tear strength. Such properties improve the runnability of the paper machine, since the paper web of softwood can withstand higher stretch force in the machine direction. Northern bleached softwood kraft (NBSK) pulps are produced from pines, spruces, hemlocks, *etc*. Southern bleached softwood kraft (SBSK) pulps are produced mainly from pines (*e.g.* loblolly pine). Hardwood fibers are shorter and less flexible, but they provide good formation and a smoother surface. Though softness is often the most important property of tissue, it is typically inversely related to strength (Nanko *et al.* 2005, de Assis *et al.* 2018). A minimum strength of tissue is required for daily usage; hence, softwood and hardwood are commonly used in a ratio to maximize hardwood without hurting strength significantly. NBSK is relatively thin, long, and has low coarseness among softwood fiber choices, which is highly desirable as the source of tissue strength (Byrd and Hurter 2013). Eucalyptus fibers are uniform, thin, and low coarseness, which serves as the best candidate for softness (Hall 1983; Pavan 2011). The ratio between softwood and hardwood fiber can range from 50:50 to 90:10, depending on the product grade. Typically, this ratio stays around 30:70 (Nanko *et al.* 2005; Zou 2017). Coarseness, which is defined as the weight per unit length of the fiber, has been indicated to have a critical impact on tissue softness. Lower coarseness contributes to improved softness (Park *et al*. 2020)

Mechanical Pulp

Mechanical pulps are not used as often as kraft pulps for tissue and toweling. Depending on the grade of the tissue, some mechanical pulps can be added into the kraft pulp mixture without hurting the performance significantly (Nanko *et al.* 2005; Yuan *et al.* 2016). Mechanical pulp is attractive to manufacturers because of its low cost and high yield. Kraft pulping removes the lignin from the fiber and degrades the hemicellulose and cellulose, which are the desirable parts of the fiber. The kraft pulp yield is around 40% to 50% (Colodette *et al.* 2002). Mechanical pulping uses mechanical energy to separate fiber from wood, and it has a high yield of up to 97%. However, mechanical pulping does not remove lignin from the fiber, which results in shorter, stiff fibers, leading to low-strength papers (Colodete *et al.* 2002). The mechanically pulped fibers are also fragile, brittle, and less durable. Due to its rigidity and stiffness, mechanical pulp can be used to improve bulk and water absorbency (Nanko *et al.* 2005; Yuan *et al.* 2016). Variants include Thermo-Mechanical Pulp (TMP), which uses heat to improve fiber liberation, and Chemi-Thermo-Mechanical Pulp (CTMP), which uses chemicals, heat, and mechanical energy to liberate the fibers. These pulps are occasionally utilized for tissue making (Kramer *et al.* 2009). However, the overall usage of mechanical pulps in absorbent paper products is low.

Recycled Pulp

Recycled pulp is also a source for tissue manufacturing. The most common recycled pulp comes from mixed office waste papers (MOW). These waste papers are processed to remove inks, fillers, and small fibers. The resulting dinked pulp (DiP) has significantly lower amounts of filler than the waste paper and fiber composition of ~25% softwood and 75% hardwood, which is suitable for making tissue. Depending on the grade of the tissue, some recycled pulps can be added into the kraft pulp mixture without hurting the performance significantly (Nanko *et al.* 2005; Yuan *et al.* 2016). There are physical and chemical challenges associated with using recycled pulp. Chemically, recycled pulps are produced from waste papers. These papers have a different purpose, and the corresponding pulps are treated differently in chemical processes. It is expected that recycled pulp still contains some wet-end additives, fillers, strength additives, sizing agents, *etc.* These chemicals can potentially damage tissue performance, including water absorbency, softness, and strength (de Assis *et al.* 2018). Physically, the recycled fibers become shorter and more ribbon-shaped after rounds of refining. The lumens of the fibers collapse completely after excessive refining and pressing processes. This collapse results in an irreversible loss of swelling and a decrease in water absorbency. Tissue products made from recycled pulps have lower softness at the same tensile strength when compared with sheets made with virgin fibers. The various waste paper sources used to make recycled pulps dictate fiber dimensions. Compared to mechanical pulp, the usage of recycled pulp is higher. Recycled pulps are commonly used for producing lower-performance tissue products that can often be found in public facilities.

Non-Wood Pulp

Though non-wood pulp is a minority fiber source for papermaking (6.5% to wood pulp production) (FAO 2017b), non-wood pulps can be used as an alternative. Non-wood pulps such as wheat straw, bagasse, and bamboo have a much shorter harvest period compared to wood pulps. For people seeking more environmentally friendly products, non-wood pulp based tissue papers are perceived as more environmentally friendly and have a market (Byrd and Hurter 2013; Phillips *et al.* 2015; Zou and Liu 2016). The challenges of using non-wood materials as the sources for papermaking come from the difficulties of processing and the resulting products' poor performances. Non-wood pulps such as wheat straw and bagasse have high fines content, which undermines the drainage and runnability of the papermaking process. The non-wood biomass is bulky and decays fast, which makes the storage more challenging. Non-wood fibers have a wide range of dimensions. Wheat straw and bamboo fiber are the two non-wood fibers with similar fiber dimensions to hardwood and softwood (Byrd and Hurter 2013; Phillips *et al.* 2015; Zou and Liu 2016, de Assis *et al.* 2018).

The problems with wheat straw pulp are the non-uniformity of fiber length and high fines content. The wheat straw fiber length in its leaves, nodes and internodes is around 1.2 mm, 0.79 mm, and 0.65 mm, respectively (Singh *et al.* 2011; McKean and Jacobs 1997). It would be costly to separate them before pulping, but non-uniform fibers would produce non-uniform paper webs. On the other hand, wheat straw fiber has a high slenderness ratio, high rigidity, and high Runkel ratio, resulting in a bulky structure in the paper web (Singh *et al.* 2011). The wheat straw also contains a higher content of hemicellulose, which brings more strength to the paper. Using wheat straw fiber properly would increase the water absorbency and strength of the paper web (McKean and Jacobs 1997).

Bamboo can produce comparable pulp to hardwood and softwood as a high growth rate biomass. The average bamboo fiber length and width are ~2 mm and 18 μm, respectively (Nanko *et al.* 2005; Cao *et al.* 2014; Phillips *et al.* 2015). The fiber dimension variation of bamboo is high due to the difference between the bamboo fibers acquired from nodes and internodes. The fibers obtained from nodes contain excess fines and short fibers, significantly affecting the overall product properties. Bamboo fiber also has a relatively higher content of hemicellulose, which could potentially provide better strength to the paper. With additional attention and processes during pulping, bamboo fiber can be used as an alternative to wood fibers. Bamboo fibers combine the advantages of hardwood and softwood fibers, and they could be a candidate for producing soft and strong tissue paper (Nanko *et al.* 2005; Cao *et al.* 2014; Phillips *et al.* 2015; Zou and Liu 2016).

SUMMARY/CONCLUSIONS

- Softness is a perception that combines complex physical interaction with the skin and inputs related to sight, smell, and sound to create a complete sense of softness. The sense of touch involves specific physical interaction, including compression, vibration, and stick-slip phenomena.

- The measurement of softness has focused primarily on the physical and topographic properties of the tissue sheet. These properties include surface roughness, tensile strength, stretch, friction, density, acoustic transmission, *etc.* These measurement techniques are separated into two broad categories. The first uses existing measurement techniques and combines the measured properties into an algorithm to predict the softness. The second category uses custom-made equipment to correlate the measurement with softness.
- Recent advances in softness measurement use an approach using both a custom piece of softness measurement equipment and integrated algorithms. This equipment has been shown to work effectively for characterizing softness, especially after calibration with standards.
- Tissue-making operations have been designed to enhance the softness of tissue while maintaining required strength properties. The evolution of the processes has primarily focused on the dry end of the paper machine, where creping and through-air drying has become an important development in creating soft tissue.
- Embossing patterns provide a marketing effect to tissue and provide an improvement in perceived tissue softness. Moreover, multiple plies have been reported to improve tissue softness.
- Several fiber types can be used to make tissue paper. Most of the fibers are bleached kraft hardwood and softwood fibers. By usage, non-wood fibers represent a relatively small fraction of the total fibers used. Still, they are becoming increasingly important as consumers assign a higher value to tissue made from these fibers. Recycled fibers are often used for commercial products and are typically made from de-inked market pulp coming from Mixed Office Waste (MOW).
- Additives are also used to enhance the softness of tissue. These additives include de-bonders that increase bulk and reduce the strength of the tissue as well as lotions that change the surface friction. This method for enhancing tissue properties is worth exploring in more detail.
- Tissue softness and its measurement continue to evolve, and accurate measurement of tissue properties is critical for developing new manufacturing technologies and fiber sources.

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