Effect of Pulp Properties, Drying Technology, and Sustainability on Bath Tissue Performance and Shelf Price

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The relationship between the types of pulp, the tissue making technologies, and shelf price of bath tissue was evaluated for the North American market. Twenty-four market tissue samples (representing approximately 80% of the current market offering) were sourced and analyzed along with their nationwide price information. Pulp composition, drying technologies, market share, sustainability advertising, and tissue properties were evaluated. Tissue properties, including softness, ball burst strength, water absorbency, density, tensile strength, and tensile modulus were measured. Among all the drying technologies, creped through-air dry (CTAD) and creped through-air dry belt (CTADB) seemed to improve tissue softness most. The UCTAD maximized tissue bulk by drying the tissue web solely using a through-air (TAD) cylinder. Tissue samples with freeness between 575 to 650 mL seemed to have their properties improved more significantly through advanced drying technologies. It was found that the retail prices of these bath tissues were directly related to softness, bulkiness, water absorbency, and basis weight. A mathematical model was conducted to predict the retail price of bath tissue (based on product performance and attributes). This paper also identified the effect of "sustainability" on the retail price.

Keywords: Bath tissue; Pulp composition; Drying technology; Tissue softness analyzer (TSA); Softness; Shelf price; Market share; Sustainability

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INTRODUCTION

The hygiene tissue industry has a global $100 billion and *ca.* 38 million tons market per year, growing at 3% compound annual growth rate over the past five years (Fastmarkets RISI 2017). Previous studies in the authors' research group have quantified the effect of fiber, technology, and sustainability on the retail price for kitchen towel tissue in North America (Assis *et al.* 2018). In this paper, the authors quantified the effects of products' performance and attributes on the retail price for bath tissue.

In general terms, the performance of tissue products is related to the composition of furnish, chemical additives, and manufacturing technology (Gigac and Fišerová 2008). Virgin and recycled fibers are the two major components of hygiene tissue products (FisherSolve International 2017). Softwood and hardwood virgin pulps have been utilized in a certain ratio to make tissue products soft and strong (FisherSolve International 2017;

Assis *et al.* 2018). Softwood furnish with long fiber length forms a strong and flexible web for bath tissue (Assis *et al.* 2018). Hardwood fibers with short fiber length produce more free fiber ends on the surface, which ultimately gives a velvet feeling on the surface (Wang *et al.* 2019). Usage of recycled fibers typically decreases the bulkiness, softness, and water absorbency of bath tissue. Multiple rounds of fibrillation of recycled fibers during the refining process results in excess bonding, producing a denser and stiffer paper web (Banavath *et al.* 2011). Depending on the market segment of the tissue product, the content of recycled fiber varies.

The typical basis weight of bath tissue in the North American market is approximately 40 g/m^2, with products ranging from 15 g/m^2 to 50 g/m^2. Within bath tissue properties, softness is one of the most important (Hollmark and Ampulski 2004; Wang *et al.* 2019). Unlike the manufacturing of printing or writing paper that involves wet-pressing before drying, tissue making procedures are designed to minimize or avoid pressing, thus preserving the bulk of the tissue sheet (Kullander *et al.* 2012). There are four major types of drying process technologies being used in bath tissue manufacturing, namely light drying-crepe (LDC), creped through-air dry (CTAD), creped through-air dry belt (CTADB), and uncreped through-air dry (UCTAD).

The LDC uses a combination of gravity, vacuum, press nip, and a Yankee dryer to dry the wet tissue web (Kullander *et al.* 2012). The press nip is a roller that is set against the Yankee cylinder, which applies sufficient pressure to the paper web to remove approximately 20% of water (Kullander *et al.* 2012). The tissue web then enters the Yankee cylinder and is dried by heat. A creping blade is used at the end of the drying process to gently scrape on the surface of the tissue web (Kullander *et al.* 2012). The creping process expands the tissue web on the Z-direction, creates folds and physical ridges on the tissue web to increase the bulkiness, stretchability, and creates free fiber ends on the surface to increase the velvet feeling (Padley 2012). Such increase of bulkiness and velvet feeling is a trade-off from the loss of tensile strength.

To further increase softness and bulkiness, a thru-air drying (TAD) process was later introduced to the bath tissue industry. Instead of using light pressure to remove water, TAD uses an air cylinder for water removal. After the wet web is transferred to the TAD cylinder, a constant pressure drop and heated air (100 to 250 °C) are applied to the wet web through the honeycomb surface structure (Valmet 2014). The most common TAD dry machine is the CTAD that combines the TAD cylinder with the Yankee Dryer.

Kimberly-Clark invented the UCTAD by removing the Yankee dryer and using only the TAD cylinder to dry the web (Wendt *et al.* 1998). This process results in higher productivity because the creping speed no longer limits the production rate.

Instead of using TAD fabric in drying (CTAD), 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 (Assis *et al.* 2018). The CTADB is capable of providing bath tissue with high strength and softness, but the belt itself is expensive and less durable compared to a conventional fabric (Assis *et al.* 2018).

Much of the work related to drying technologies has focused on attempting to improve the softness of tissue sheets. Softness has historically been difficult to quantify. Panel tests are often used, in which human perception determines the softness values. To attempt to quantify softness in terms of physical behavior, a "softness analyzer" was developed. Giselher Grüner (Grüner 2016) invented the tissue softness analyzer (TSA). The instrument measures the physical attributes correlated with the softness of a paper by spinning a lamellar structure type fan on the surface of the sample. A previous study showed that TSA provides a relatively accurate quantifiable value of softness (Wang *et al.* 2019).

In this work, the authors conducted a value analysis between the shelf prices of bath tissue and their key physical properties (*e.g.*, basis weight, strength, softness, and density). Based on the results, it is possible to explore the value created by different manufacturing technologies and physical properties. Additionally, the effect of sustainability (products marketed as sustainable) on product price was discussed.

EXPERIMENTAL

Materials

Bath tissue samples

Table 1. Summary of Commercial Samples' Properties

ID	Drying Method*	Type of Brand**	# of plies	Surface Characteristics
A	UCTAD	National	1	Strong Texturing
B	CTADB	National	1	Strong Embossing
C	UCTAD	National	2	Strong Texturing
D	UCTAD	Private	2	Light Texturing
E	CTADB	National	2	Light Embossing
F	CTADB	National	2	Light Embossing
G	CTAD	National	2	Strong Embossing
H	LDC	National	3	Light Embossing
I	LDC	National	2	Light Texturing
J	UCTAD	Private	1	Strong Texturing
K	UCTAD	National	2	Strong Texturing
L	Sustainable (LDC)	Private	2	Light Embossing
M	LDC	Private	2	Strong Embossing
N	CTAD	Private	2	Light Embossing
O	CTAD	Private	2	Light Embossing
P	LDC	Private	2	Light Texturing
Q	LDC	Private	2	Light Embossing
R	LDC	National	2	Light Texturing
S	Sustainable (LDC)	Private	2	Strong Embossing
T	LDC	Private	2	Light Texturing
U	Sustainable (LDC)	Private	2	Light Embossing
V	CTAD	Private	2	Light Embossing
W	CTAD	Private	2	Light Embossing
X	LDC	Private	2	Strong Embossing

*Drying method: LDC, UCTAD, CTAD, or CTADB; A specialist in tissue paper manufacturing reviewed each sample to determine the technology used (ReiTech 2018).**Type of brand: National brands are brands owned by manufacturers, and private label are brands are owned by wholesalers or retailers (Assis *et al.* 2018), while sustainable labels are the brands that claim to use sustainable materials and/or processes

A total of 24 bath tissue samples were sourced across the US, comprising approximately 80% of the total consumer market for bath tissue. The samples were purchased in stores across the US. The shelf price for each sample, excluding any price discount, was recorded. Because the size of the packages (*e.g.*, number of rolls, number of sheets per roll, and total area) influences product prices, careful attention was paid to select packages with the approximate same total area (tissue area). Table 1 provides a description of each sample, including the drying method and type of brand. Machine technology was evaluated by tissue machine specialists (ReiTech 2018).

Experimental Design

A flow chart of the experiment design is shown in Fig. 1. The commercial products were disintegrated and reprocessed to make handsheets. Properties before and after reprocessing were measured and compared.

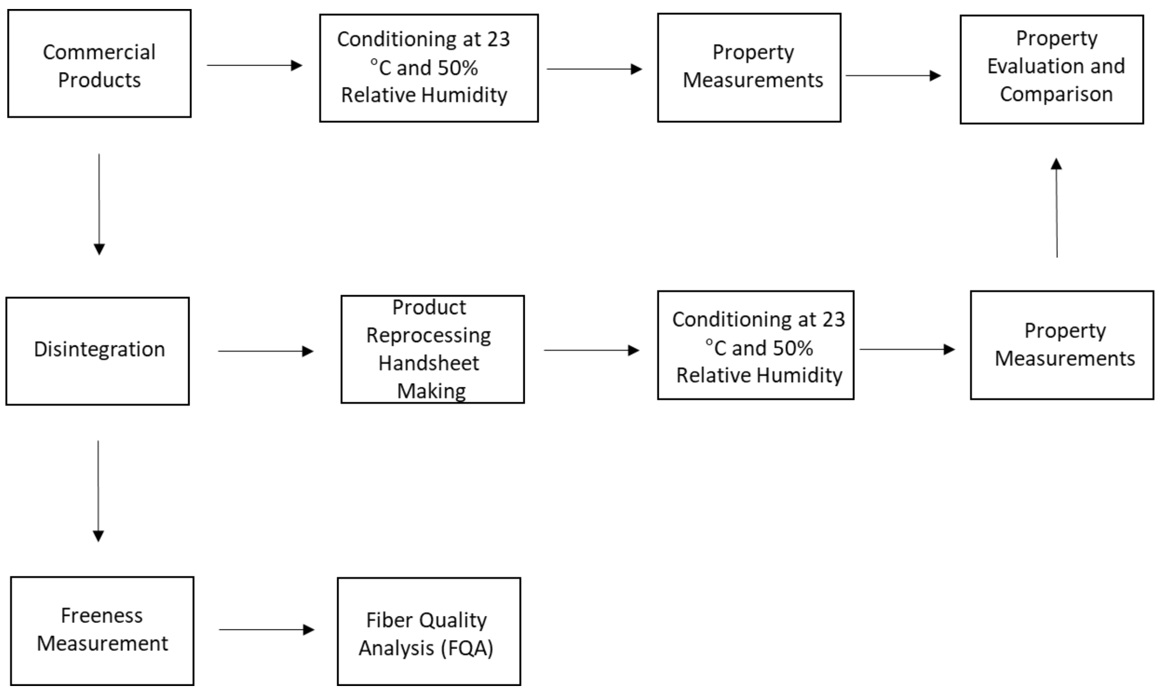

Fig. 1. Flow chart of experiment design

Physical properties

All bath tissue were conditioned in a room maintained at 50% relative humidity (RH) and 23 °C according to TAPPI T402 sp-08 (2013). The basis weight, defined as the mass of paper per unit surface area, was measured according to TAPPI T410 om-08 (2013). The caliper of the samples was measured using a 2 kPa caliper according to TAPPI T410 om-08 (2013). Density was calculated based on the result of basis weight and thickness.

Water absorbency capacity, defined as the mass of water absorbed per unit of sample mass, was measured according to ISO 12625-8 (2010).

Ball burst strength, defined as the maximum penetration force that a sample can withstand when a ball applies a perpendicular force, was measured in dry conditions (bursting force) according to ISO 12625-9 (2005). Tensile strength, defined as the maximum tensile force per unit of width that a sample can withstand before breaking in a tensile tester, was measured under dry conditions according to ISO 12625-4 (2005). The tensile strength, tensile modulus and tensile energy adsorption were measured for both directions (paper machine direction (MD) and cross direction (CD)).

Softness score was measured using a TSA (EMTEC Electronic GmbH, Leipzig, Germany). A 10 cm × 10 cm bath tissue sample was placed and clamped on the holder of the TSA. A fan with six lamellas moved vertically downward to touch the surface of the sample webs. The instrument used a TPII algorithm that correlated with a softness panel test to calculate a handfeel coefficient (HF), the results ranged between 0 (least soft) and 100 (softest). TPII was found to be the algorithm that correlated the best with the panel result (Wang *et al.* 2019).

Methods

Fiber quality analysis

Fiber length and width of each sample were measured by the HiRes fiber quality analyzer (FQA) from OpTest Equipment Inc. (LDA96; Hawkesbury, Canada). Samples were diluted to approximately 1 to 5 mg/L and disintegrated at 15,000 revolutions using a standard pulp disintegrator (Testing Machines Inc., New Castle, DE, USA). Fiber width values ranged from 7 to 60 µm. The fiber length and width distributions were obtained.

Tissue reprocessing

To study the change in the product's properties as a function of the drying technologies, it is necessary to create a control dataset that somehow isolates the effects of the drying process. To isolate the finishing and drying process effect, 24 g of each bath tissue sample was diluted and disintegrated with 2000 mL of deionized (DI) water using a standard pulp disintegrator (Testing Machines Inc., New Castle, DE, USA). The furnish was further diluted to 0.3% consistency. A total of 20 handsheets were made for each data point according to TAPPI T205 7.2, 7.3 (2006) with the following variations. After forming the handsheet, the sheet was couched onto two dry blotter papers using the couching process. A dry blotter paper was placed on the top of the handsheet. The sandwiched handsheet was dried by a heated roller dryer (Formax 12" Drum Dryer; Adirondack Machine Corp., Hudson Falls, NY, USA) at 115 °C and 20 rpm for 5 min.

Multiple linear regression

A multiple linear regression was performed using software R (RStudio, RStudio, 3.0, Boston, MA, USA) to evaluate physical properties (basis weight, caliper, ball burst strength, density, water absorbency, HF, CD tensile strength, MD tensile strength, CD tensile modulus, and MD tensile modulus), which are correlated to retailing price.

RESULTS AND DISCUSSIONS

Physical Properties Comparison

As shown in Fig. 2, the basis weight of the samples ranged from 17.4 to 49.7 g/m^2. The basis weight of TAD-dried tissues had a minimum basis weight of 30 g/m^2, whereas the basis weight of tissue dried by LDC can be as low as 15 g/m^2. The caliper ranged from 88 µm to 678 µm. The samples dried with LDC had much lower caliper than the TAD-dried samples. The density ranged from 0.073 g/cm^3 to 0.167 g/cm^3. Bath tissues dried by

TAD had an average density of approximately 0.085 g/cm^3, whereas the bath tissues dried by LDC had an average density of 0.13 g/cm^3. Through–air-drying methods increased the bulkiness of the paper, which resulted in higher compressibility and higher bulk softness (Wang *et al*. 2019). The LDC used a press nip to remove the excess water from the bath tissue and densified the sheet, which ultimately decreased the HF value of the sheet. The HF ranged from 68 to 98, where the TAD-dried tissues had much more consistent and higher softness than the LDC. The results from Fig. 2 indicate that processes involving TAD produced products that were softer, bulkier, and had higher water absorbency than products dried with LDC. The ball burst strength (BBS) ranged from 1.1 N to 3.8 N. There was no obvious relationship between the BBS and drying technologies. The majority of samples had BBS of approximately 2.5 N, which implied that the minimal requirement strength for a quality bath tissue is approximately 2.5 N. The variation of the BBS may be a consequence of fiber selections, fiber refining, basis weight, and the finish process (Kullander *et al.* 2012). Tissue dried with different technologies had a similar cross direction tensile strength. On average, the tensile strength on the MD was one fold higher than the CD tensile strength for LDC samples. The LDC-dried samples had a broad spread of MD tensile strength, which was due to the variation of the fiber resources, as explained in a later section of this work. The CD and MD tensile modulus for TAD-dried tissues were lower than the ones dried by LDC, which implied a higher stretchability of TAD tissues.

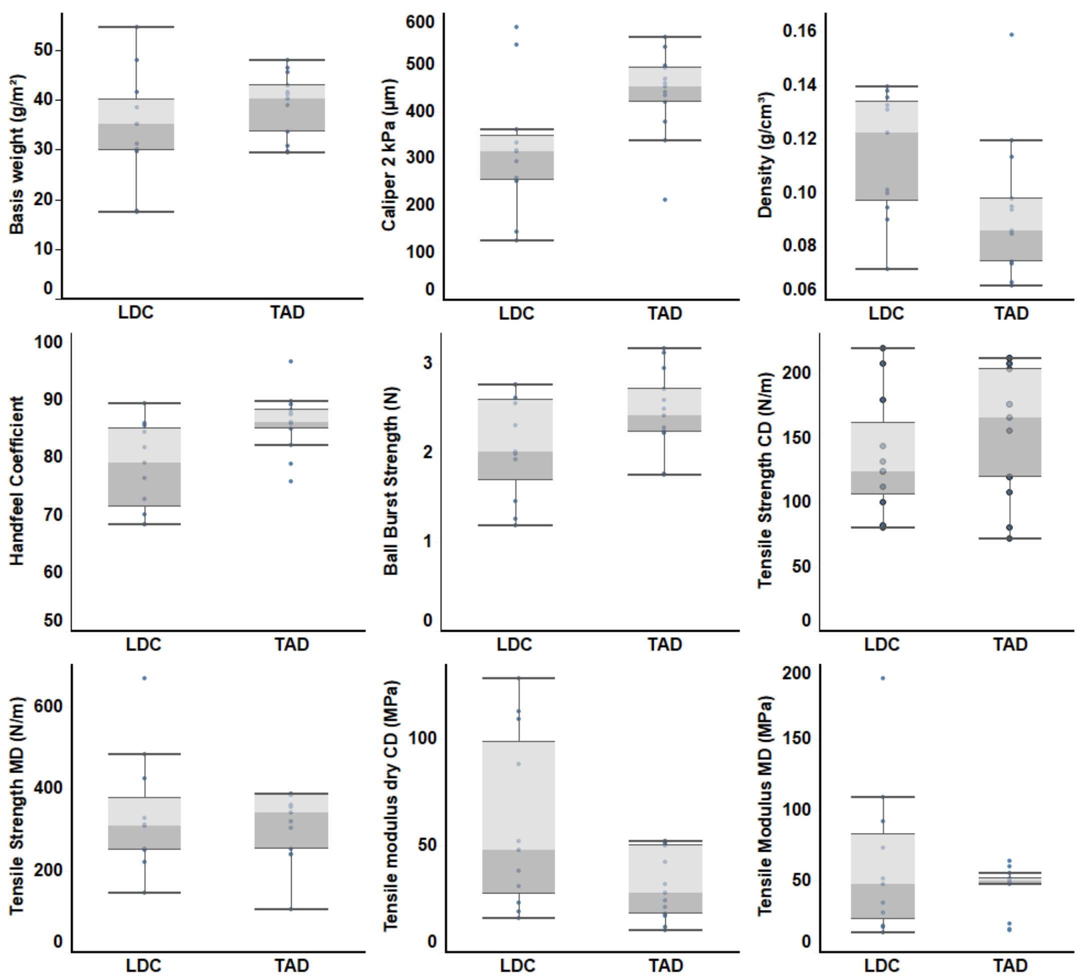

Fig. 2. Boxplots of physical properties comparison between LDC and TAD-dried tissues

Though the TAD drying process does not involve much pressing, the average strength of TAD tissues was still competitive to LDC products, even though TAD tissues had a lower modulus and thus higher flexibility than LDC tissues. This was probably due to the higher average basis weight of TAD tissue, and more importantly the usage of forming fabrics during the forming process of TAD products.

The TAD drying process does not use much pressing; therefore, the wet web needs to have an excellent formation uniformity to retain the necessary strength for the stretching on the machine direction as the web moves forward (Valmet 2014). A high mesh molding fabric is typically used in the forming section to ensure good fiber support (Patel and Herman 2007).

The materials used for weaving the forming fabric are commonly extruded polyethylene or nylon. The strand size ranges from 0.1 mm to 0.45 mm (Patel and Herman 2007). Potential strength agent, such as cationic starch or polyDADMAC, might be added to the different brands of TAD tissue as well (Miller *et al.* 2011).

As shown in Fig. 3, HF of the tissue increased with freeness; this means softer tissue samples. Higher freeness implied that there were more virgin fibers with lower surface fibrillation, fewer small fibers, and fines in the pulp (Hubbe 2007). Tissues manufactured by the TAD process typically use pulps with higher freeness. For tissue prepared using similar freeness pulps (620 to 650 mL), tissues manufactured with TAD processes were softer than LDC.

For the technology comparison of CTADB, UCTAD, CTAD, and CTADB, the CTAD products exhibited higher softness than the UCTAD, which showed the significance of creping to increase softness. The freeness had no linear correlations with BBS, cross-direction tensile strength (CDTS), machine direction tensile strength (MDTS), cross-direction tensile energy adsorption, nor machine-direction tensile energy adsorption. This was probably due to the complex and diverse manufacturing processes of the different samples.

The highest freeness correlation found corresponded to the CD tensile modulus. Lower freeness can be often attributed to the increased specific surface area of the fiber or more wet fiber flexibility. Both of these factors can lead to denser sheets with more bonding and higher tensile modulus. This also corresponded with the high CD and MD modulus values of LDC-dried tissues.

The creping process significantly decreased the MD modulus by creating the wavy structure on the tissue surface. Sample H that was dried with LDC had a competitive HF to other advanced drying technologies. This was due to a 3-ply structure used in sample H. The tissue became bulkier as more plies were added, which resulted in better softness. In contrast, a 3-ply tissue typically has a relatively high basis weight, which will result in higher cost on fibers.

As shown in Fig. 4, neither BBS, CDTS, nor MDTS had strong correlations with HF (P values were reported in Table S1). Though tissue softness is typically achieved at the cost of strength (Lavash 1985), this relationship may be inverted by the advanced manufacturing processes. The CD tensile modulus had a weak linear relationship to HF, which implies that sheet flexibility could be treated as one of the attributes to softness.

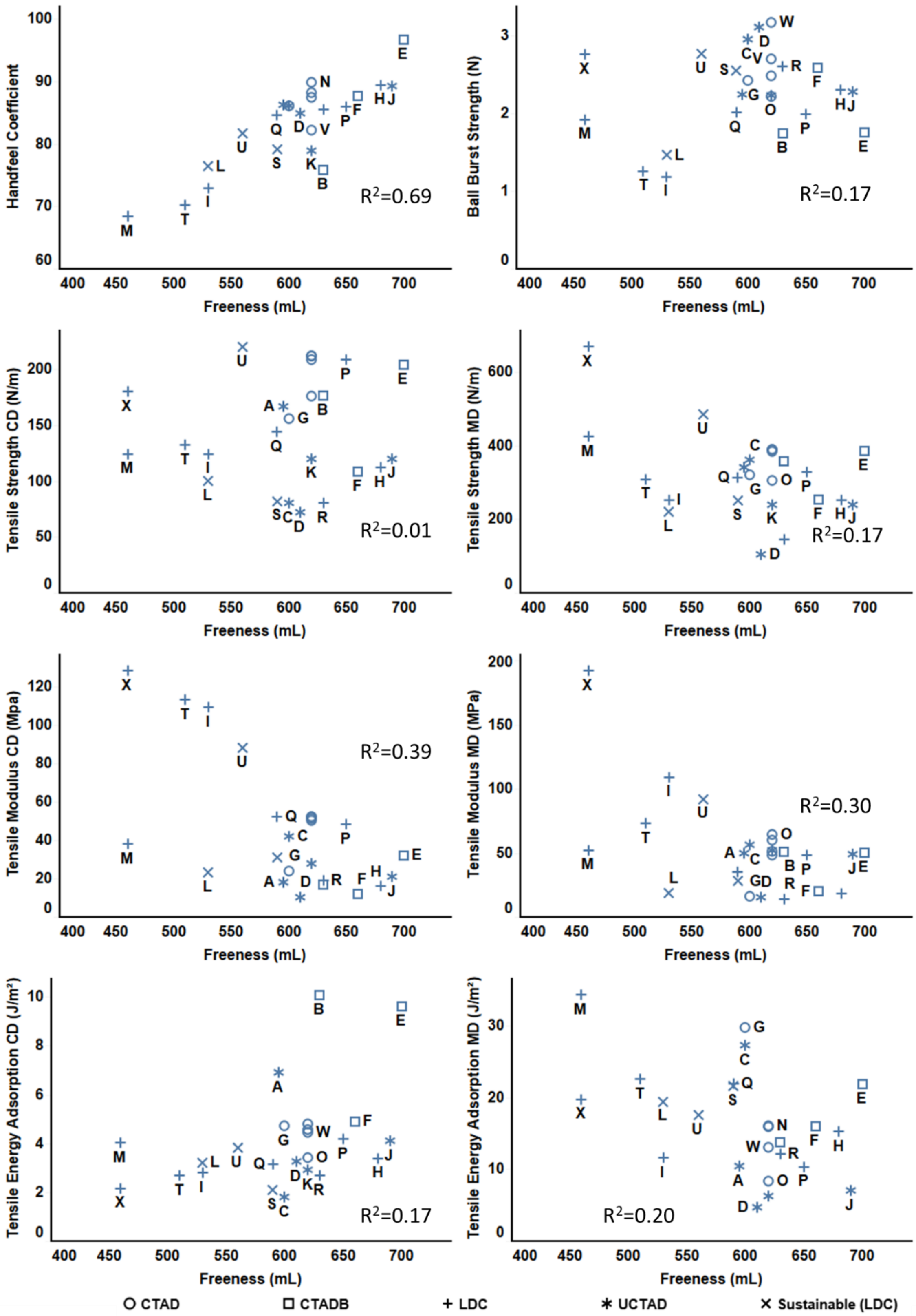

Fig. 3. Linear plot of tissue properties as a function of freeness of the reprocessed tissue samples; the letters on the plot indicate the ID of each tissue sample

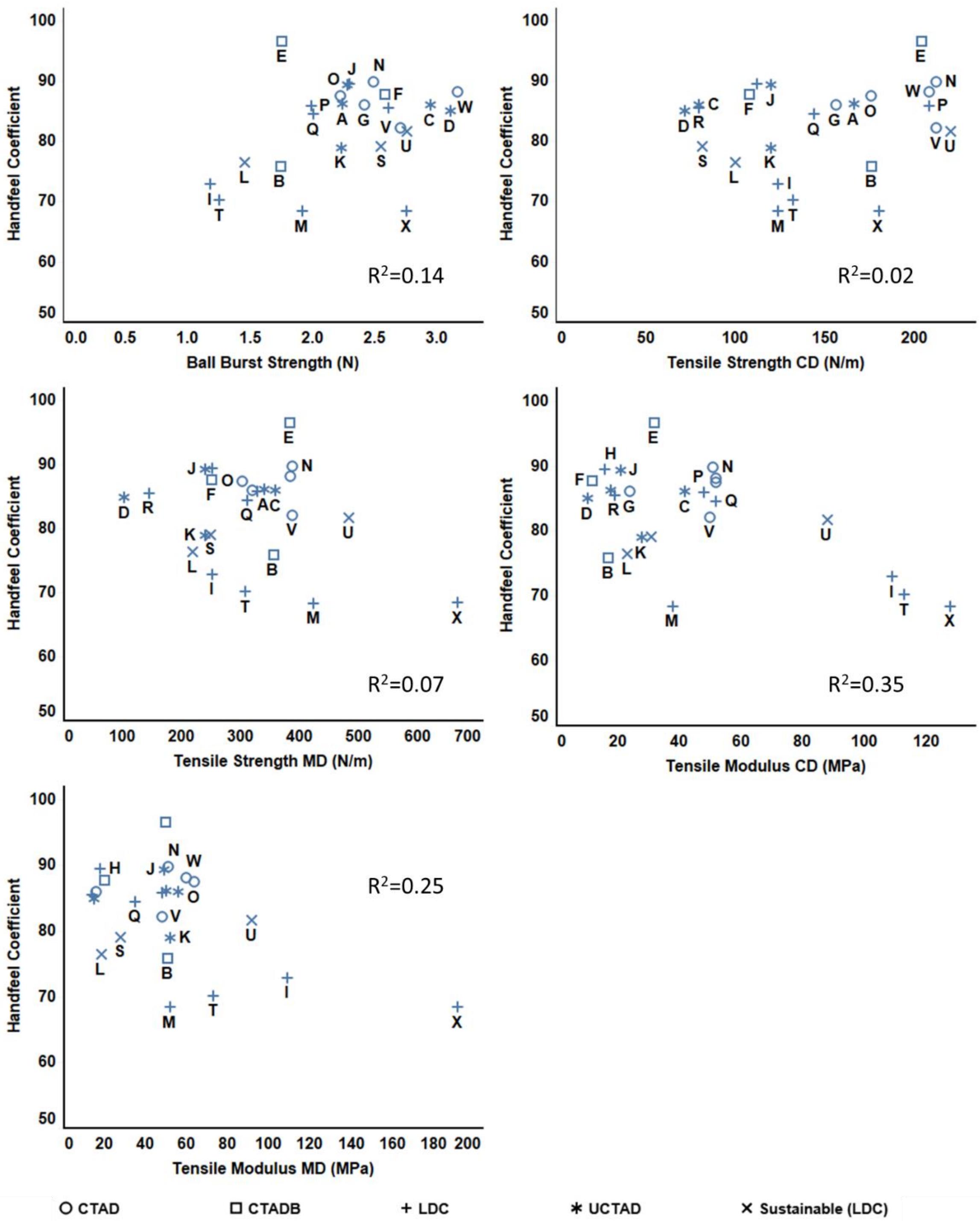

Fig. 4. Linear plot of tissue Handfeel Coefficient *vs.* physical properties

Physical Properties Comparison after Reprocessing the Commercial Tissue Samples

To further understand the effect of processing on softness, the market tissue samples were disintegrated. The resulting pulp slurry was diluted to 0.3% consistency and used to produce handsheets matching the basis weight of the original products. As shown in Fig. 5A, the handfeel coefficient of each sample dropped significantly after reprocessing.

This reprocessing eliminated the effects of creping, through-air-drying, and likely addition of wet-end chemistry to the bath tissue. It was found that the pulps with higher freeness were affected less by the reprocessing. Such differences were probably related to the level of refining and the hornification of recycled pulp (Diniz *et al*. 2004). To increase the strength of recycled fibers, a typically higher level of refining is applied (Hubbe *et al*. 2007). During the refining process, the fiber cell wall is gradually delaminated (Hubbe *et al*. 2007), and the flexibility and fibrillation of the fiber surfaces increased, which ultimately results in more hydrogen bonding opportunity between the fibers. Once the samples had been reprocessed, the bulkiness provided by creping was removed and the excessive shrinkage induced by refining further densified the sheet, which ultimately resulted in the loss of bulk softness, and thus the drop in handfeel coefficient observed.

The marketing aspect of tissue is typically categorized as economic, premium, and ultra (Assis *et al.* 2018). However, there are no clear borders for this categorization. As shown in Fig. 5A, a clear grouping was observed at freeness of 575 mL and 650 mL, interval among the majority of tissue samples was found. This interval contained tissue samples made by all four different drying methods (CTAD, CTADB, UCTAD, and LDC). The samples in this interval had their softness dropping and their ball burst strength significantly increasing after reprocessing. The samples in this interval can be categorized as premium grade.

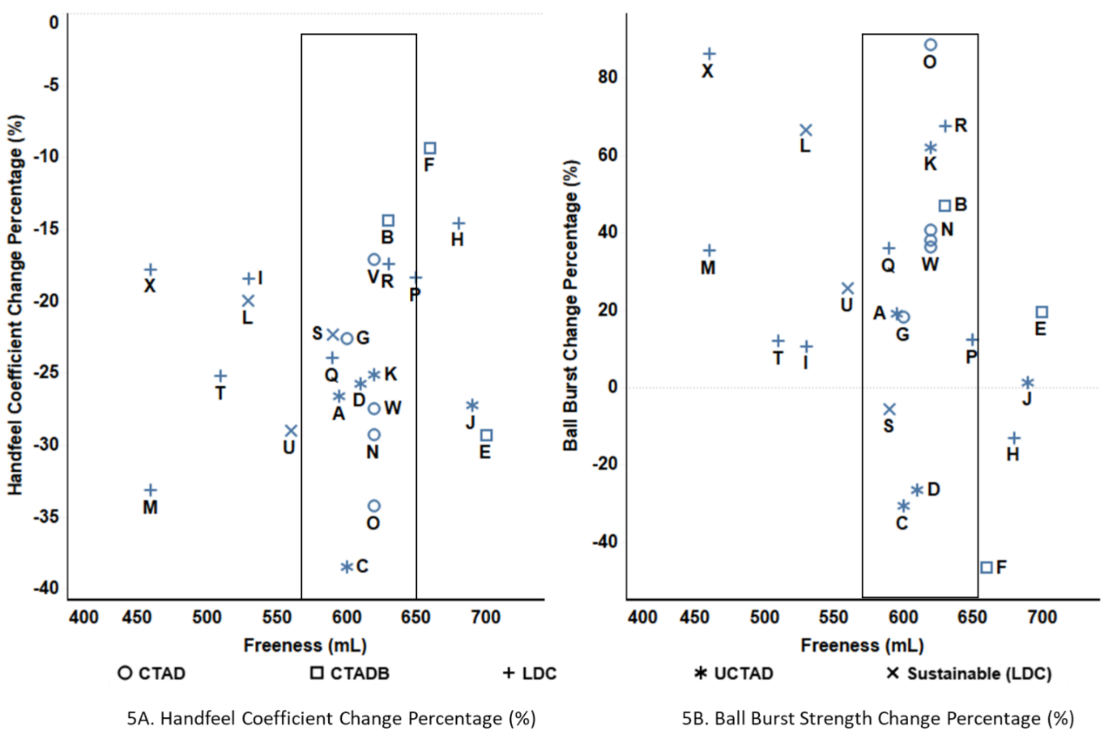

Fig. 5. A. Change of HF after reprocessing of the commercial tissue samples *vs.* Freeness of the pulp slurry; B. Change of BBS index after reprocessing of the commercial tissue samples *vs.* Freeness of the pulp slurry

For the samples that have freeness higher than 650 mL, the refining is probably only performed on the softwood fraction of the tissue-making fibers (Bicho 2018), so that the unrefined hardwood fraction in the virgin pulps was not affected by the refining process. This might explain the low extents of fiber shrinkage obtained during the reprocessing for the high freeness pulp. For tissue samples having freeness above 650 mL, the improvement induced by the drying processes became less effective, resulting in fewer changes after reprocessing. These tissue samples with freeness above 650 mL can be categorized as the ultra-grade. All the tissue samples with freeness lower than 575 mL were dried using LDC. These samples contained a significant amount (in some cases up to 100%) of recycled fibers, and their ball burst strength increased significantly after reprocessing, most likely due to hornification and densification phenomena (Diniz *et al*. 2004). The tissue samples with freeness below 575 mL can be categorized as the economy grade. As shown in Fig. 5B, sample S, D, C, H, and F had decreased BBS after reprocessing. These samples were advertised as "ultra-strong"; therefore, it is possible that a strength additive had been added during manufacturing that may have been removed during the reprocessing step (Hubbe *et al*. 2007). The property changes after reprocessing reached maximums for pulps with freeness from approximately 575 mL to approximately 650 mL This implies that the value created by processing is maximized at the pulp freeness from 575 mL to 650 mL. It should be noted that the freeness of the original stock used to make the tissue sheets, *i.e.*, before reprocessing is likely different from that found after re-processing.

Retail Price Analysis

Among all the important properties of bath tissue (*i.e.*, basis weight, ball burst strength, caliper, and softness, *etc.*), it was found that softness, basis weight, caliper, ball burst strength, and water absorbency were the properties that correlated with the shelf price of bath tissue. Figure 6 shows that as the HF value, basis weight, caliper, ball burst strength, and water absorbency increased, the price of the tissue generally increased. Basis weight, caliper, and HF coefficient had relatively higher R^2 values. The correlations between ball burst strength, water absorbency, and price were mainly backed by basis weight (as basis weight increased, the BBS and water absorbency increased). There was no obvious relationship between price and density. This was probably due to the different number of plies and different drying technologies used for different samples that highly influence the density of the commercial product. Among all the samples, the tissues dried by UCTAD had the lowest density, which indicated the high efficiency of the TAD cylinder for creating bulky three-dimensional tissue webs. The sheet basis weight had the strongest correlation with sheet price. Among all the products, CTADB-dried products exhibited the highest water uptake fraction and HF coefficient. The products advertised as sustainable products (SUS) were typically more expensive than other commercial products with similar properties.

Based on the correlations described in Fig. 6, a linear regression model with the price/m^2 as the response of basis weight and HF coefficient would be useful in predicting the price of a tissue sheet (Eq. 1). The reported R^2 value for the proposed model was 0.75, which implied that 75% of the variance within the data could be explained by the two predictors selected. Both p-values were less than 0.05, which indicated the significance of the parameters (basis weight and HF coefficient).

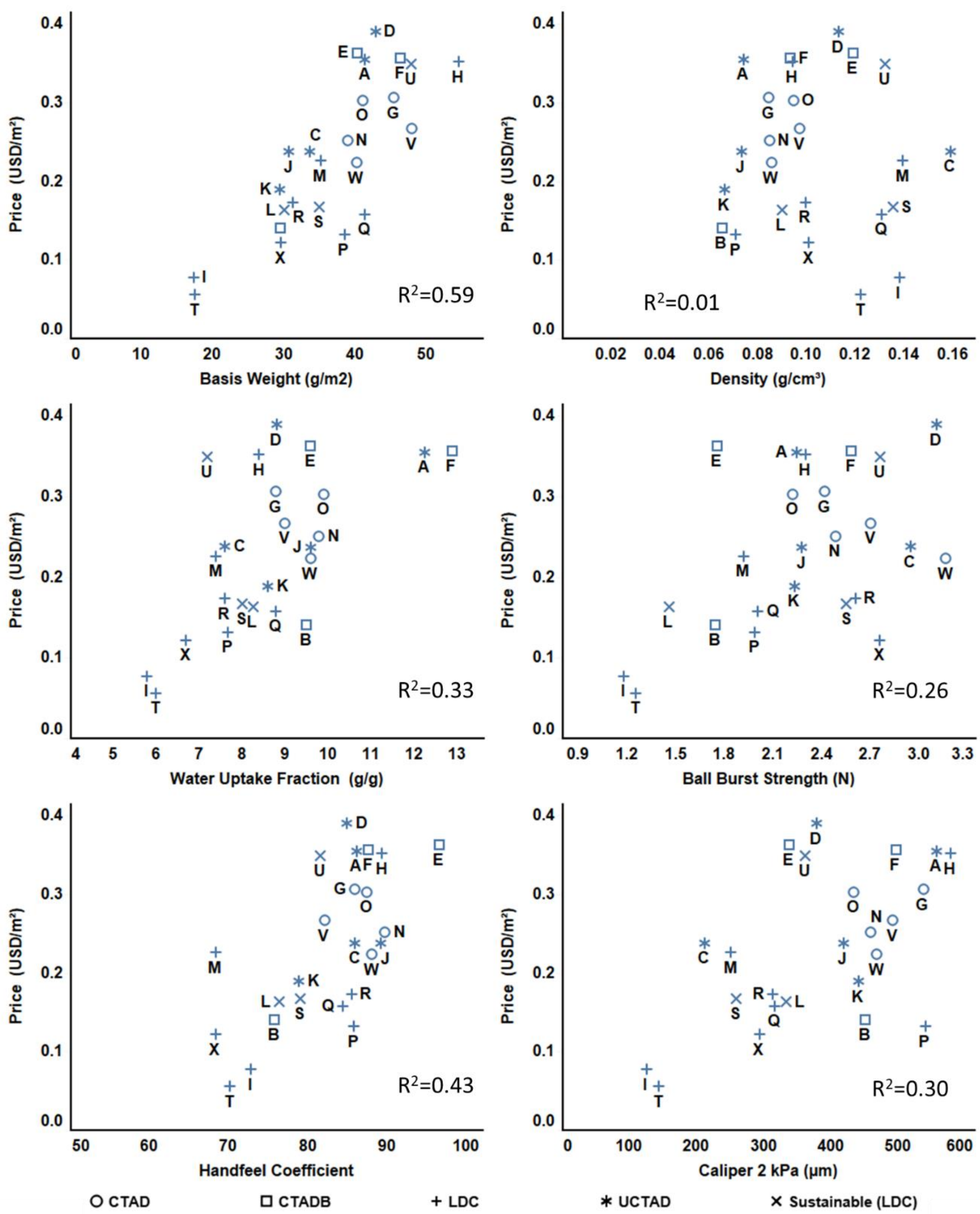

Fig. 6. Linear regression model of price/m^2 *vs.* bath tissue properties

It is possible to generate a more thorough model by including caliper, water uptake fraction, softness, and basis weight as predictors. However, these properties are highly correlated, as increasing caliper would typically result in increasing water update fraction and softness, and such a complex model would require more testing and would be more difficult for manipulation by users. The potential simplified linear regression model for price (USD/m^2) is shown in Eq. 1:

$$\frac{Price\ (USD)}{m^2} = 0.0069\frac{USD}{g} \times Basis\ weight\ (\frac{g}{m^2}) + 0.0034 \times HF - 0.305\frac{USD}{m^2} \quad (1)$$

The equation had a limited range. The basis weight and HF for consumer bath tissue are typically no less than 13g/m^2 and 60, respectively. Using the equation with inputs lower than the minimum may result in negative prices.

Figure 7 provides a product map for the North American bath tissue market. The bath tissue samples were arbitrarily classified into their different market categories based on the grouping observed from their basis weight and handfeel coefficient.

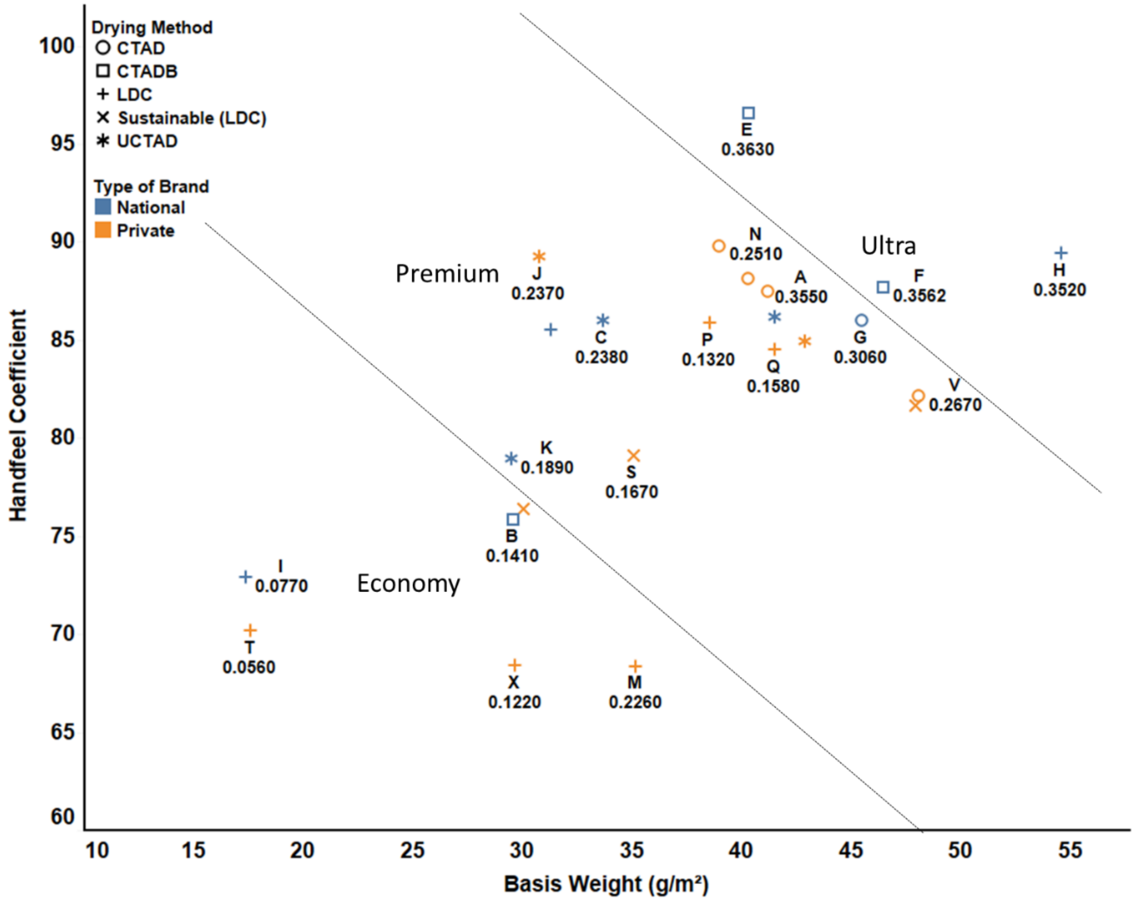

Fig. 7. Product map for the North American bath tissue market (HF *vs.* basis weight); the size data points are the shelf prices of the corresponding samples expressed on a meter square basis. The color and shape of the data points stand for the drying method and brand type, respectively.

The samples in the groups were similar to the groups in the reprocessing section (Fig. 5). This implies that the bath tissue qualities are strongly related to their fiber sources, softness, and basis weight. The economy grade had a broad spread of softness and basis weight, and relatively low price to meet specific needs in the market. The premium grade had a narrow span of the properties, where the majority of the samples stayed. The premium grades had the properties to fulfill the needs of the majority of consumers, where most of the brands tried to gain market shares. The private label brands (N, W, and O) beat national brands (D, G, and R) with better softness and lower prices in this segment. The ultra-grade remained untouchable for private labels due to possible technique and cost limitations. The results corresponded to the market share trends. The premium level nation brands were caught up by the private labels, which had lower price and possibly better performance. Consumers who prefer ultra-grade tissue could only purchase the national brands.

Another important aspect to highlight is the effect of sustainability on the retail price. Within the same market segment, the products advertised as sustainable showed shelf prices that were substantially higher compared to conventional products that showed competitive or even better performance. In fact, some of the bath tissue brands that claim to be sustainable showed poorer performance in terms of HF coefficient, caliper, and water absorbency. This reflects that today a selected group of customers is willing pay higher prices and give up part of the performance of tissue to trade for sustainability (De Boer 2003; Basu and Hicks 2008; Roheim *et al*. 2011). The market share for sustainable products is less than 1%; however, their high margins along with their low manufacturing costs (LDC processing is the technology typically used for manufacturing) and the general increasing efforts towards sustainability make these tissue products very attractive candidates for either new players entering the tissue market or existing tissue manufacturers aiming to expand their product portfolios.

To explore the relationship between fiber compositions and corresponding product performances, the fiber length distribution of samples were measured. Selective samples' fiber length distribution are shown in Fig. 8.

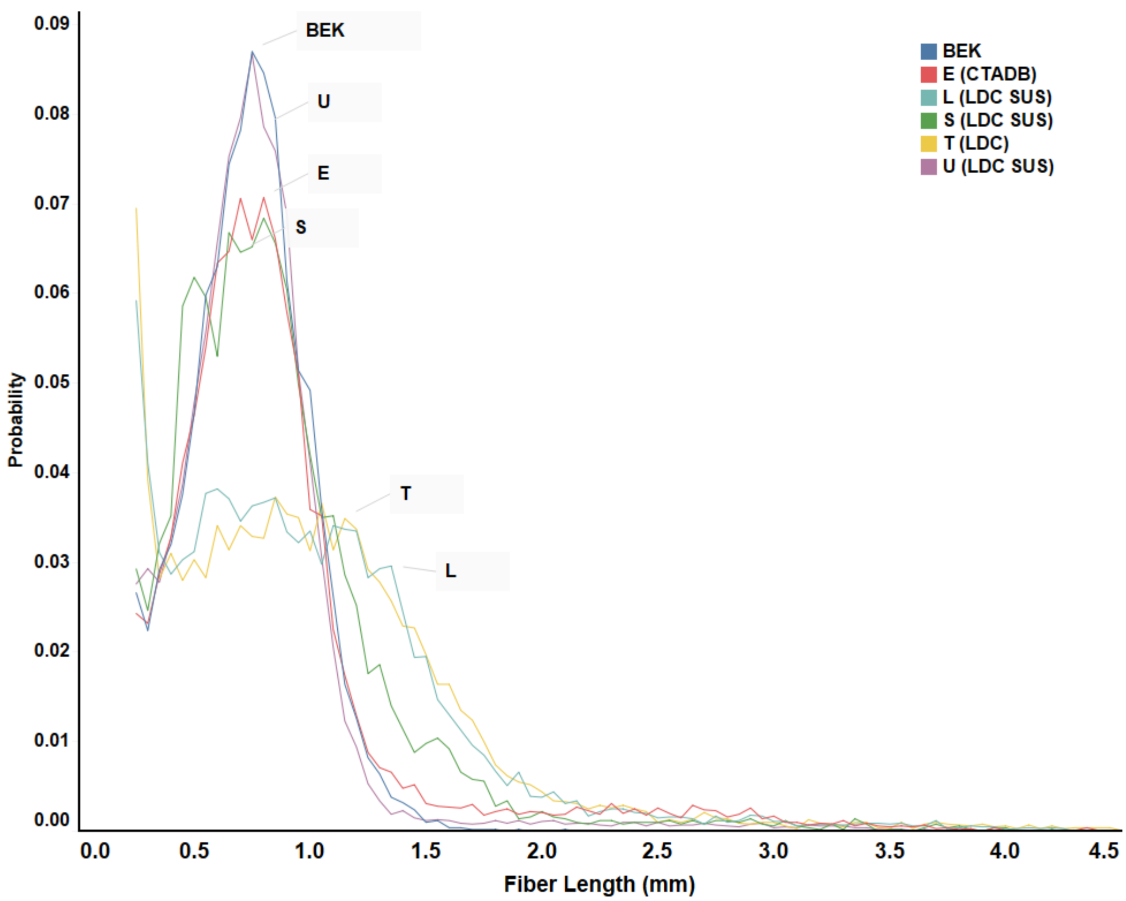

Fig. 8. Summary of distribution of fiber length (mm) for commercial tissue samples

Bleached eucalyptus hardwood pulp (BEK) was purchased from the National Institute of Standards and Technology (reference No. 8496; Gaithersburg, MD, USA). The fiber length distribution of eucalyptus was also measured as a reference. Most of the pulp samples had fiber lengths ranging from 0.5 mm to 1 mm, which confirmed the similarity of the pulp composition. Some samples contained more recycled fibers (L, T), which showed a higher number of fine particles (fiber length below 0.2 mm). To compensate for the lost strength and other important properties, a larger fraction of long fibers were added into the sample as well, as the high peak in the fiber distribution shows. The fiber distributions confirmed that the tissues manufactured with TAD methods tended to use more virgin hardwood fibers, as the fiber length was concentrated around 0.5 mm. Sample U and L that were advertised as sustainable products had similar fiber length distribution to virgin eucalyptus and deinked pulp, respectively. It is uncertain what properties make tissue product sustainable.

Based on the fiber length distribution in Fig. 10, it seems that the current sustainable concept of bath tissue is not clearly defined. The sustainable concept should be focused on reducing the environmental impact on both fiber sourcing and manufacturing, including water usage, biogenic and non-biogenic carbon footprints, *etc*. (Kuhlman and Farrington 2010).

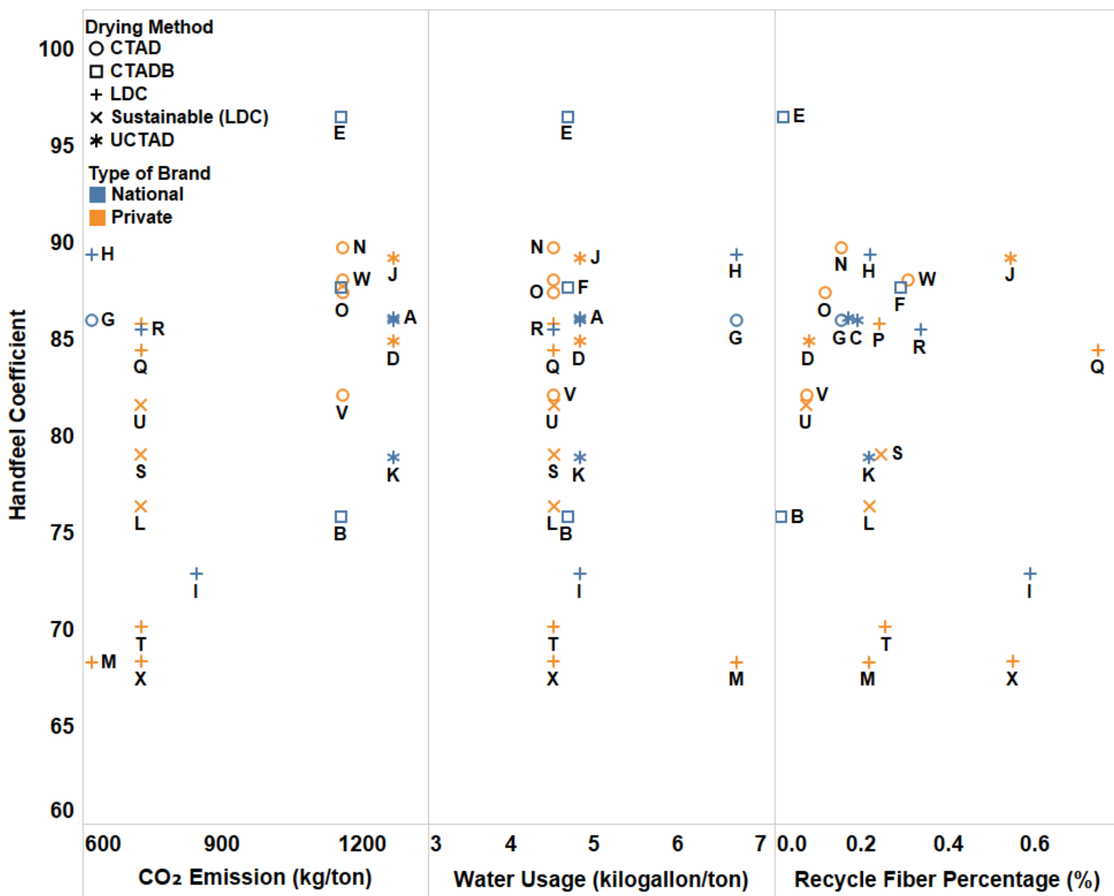

Fig. 9. The plots of HF *vs*. sustainability variables; the color and shape of the data points stand for the drying method and brand type, respectively

Because consumers are thinking highly of sustainability, the next logical step is value creation in combination with lower environmental impacts and maintain the tissue properties. To estimate the environmental impacts of the samples, the water usage and the non-biogenic CO_2 emission, including fuel, upstream, electricity, and chemical, were collected from the FisherSolve database (FisherSolve International 2017). The recycled fiber percentage was estimated by comparing the sample fiber length distribution to eucalyptus and deinked pulp. The CO_2 emission and water usage were calculated by averaging the results of all non-integrated tissue mills in North America by drying technologies, companies, and brands. Multiple brands owned by the same company were assumed to have the same water usage and CO_2 emission (FisherSolve International 2017). The water usage and CO_2 emission of private label samples were estimated by averaging the results of all non-integrated tissue mills in North America through drying technologies only. As shown in Fig. 9, other than sample H, G, and X (same company brands), the water usage for different samples were similar. The TAD samples had higher CO_2 emission due to the high energy consumption of drying. The TAD samples tended to use a high content virgin fibers to maximize the advantage of drying technologies and deliver a softer sheet. This implied conflicts between performances, technologies, and sustainability. At a certain point, it is difficult to drain more values from a low profile fiber source and low carbon footprint processes.

CONCLUSIONS

1. The properties of bath tissue samples manufactured by LDC, CTAD, CTADB, and UTAD processes were analyzed. Bath tissues made by TAD were typically softer, bulkier, and showed a higher water absorbency than LDC tissues. Among TAD technologies, UCTAD tissues had the highest bulkiness, but the lowest softness due to the lack of creping. The CTAD and CTADB tissues have competitive properties, but the retail price for CTADB tissues was higher.
2. A weak relationship was found between tissue tensile modulus and softness, even though these parameters are known to be inversely correlated. The latter reflects the strong influence that the manufacturing technology has on the final attributes exhibited by the tissue product. More study is needed to understand this relationship.
3. As the pulp freeness increased, the softness generally increased. After reprocessing the tissue samples, the softness decreased, putting in evidence the effect of the different drying technologies and creping on the product softness. The drying technologies maximized the improvement of softness at freeness values between 575 mL to 650 mL. Pulps with freeness higher than 650 mL were less sensitive to reprocessing or dry technologies.
4. The shelf price of bath tissue seemed to be predominantly positively correlated to basis weight, bulk, and softness. Tensile strength of the products did not correlate to the retail price. As long as the strength reached the minimum requirement, it no longer created any additional value.
5. Tissues with sustainability labels were mostly manufactured using LDC. These tissues sell at a much higher price compared to tissues without sustainability labels but have

similar properties. This implies that some consumers are now willing to give up part of the performance of tissue to trade for sustainability.

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APPENDIX

Table S1. Statistics Summary for Correlation Pairs

Fig. 3		
Correlation Pair	**R^2**	**P value**
HF/Freeness	0.69	<0.001
BBS/Freeness	0.17	0.299
Tensile Strength CD/Freeness	0.01	0.712
Tensile Strength MD/Freeness	0.17	0.040
Tensile Modulus CD/Freeness	0.39	<0.001
Tensile Modulus MD/Freeness	0.30	0.005
Tensile Energy Adsorption CD/Freeness	0.17	0.024
Tensile Energy Adsorption MD/Freeness	0.20	0.044
Fig. 4		
Correlation Pair	**R^2**	**P value**
HF/BBS	0.14	0.071
HF/Tensile Strength CD	0.02	0.422
HF/Tensile Strength MD	0.07	0.184
HF/Tensile Modulus CD	0.35	0.005
HF/Tensile Modulus MD	0.25	0.012
Fig. 6		
Correlation Pair	**R^2**	**P value**
Price/Basis Weight	0.59	<0.001
Price/Density	0.01	0.727
Price/Water Uptake Fraction	0.33	0.001
Price/BBS	0.26	0.014
Price/HF	0.43	<0.001
Price/Caliper	0.30	0.005