The Tissue Dust Analysis System: A new device and methodology to quantify dusting and linting propensity in hygiene tissue papers

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Abstract

Linting and dusting are commonly used terms to describe the tendency of a tissue web to release unbound and loosely bound fibers or filler particles during the tissue-making process or in the finished tissue product. Lint/dust generation has an overall negative impact across tissue paper manufacturing and handling operations, causing safety hazards, machine runnability difficulties, and product quality issues. To date, there are no well-established industry standards to quantify dusting/linting propensities in finished tissue products, thus evaluating the effectiveness of dust/lint control programs is challenging yet intriguing. This research aims to fill this gap by developing a methodology to characterize dusting in tissue papers. We have developed a device prototype (named the Tissue Dust Collector) and a methodology that together have been named the *Tissue Dust Analysis System* (TDAS), which aims at quantifying the propensity for tissue-grade paper products to generate dust/lint in a controlled and reproducible manner. Two samples, corresponding to commercial products with a low and high linting propensity, were tested using the proposed device and methodology, and the released particles were quantified and characterized. The device and methodology provided reproducible results for simulated consumer handling and product manufacturing scenarios. By changing the instrument's motor frequency, the force of agitation changes, mimicking/simulating consumer (60 strokes per min, spm) and producer/manufacturing (180 spm) handling scenarios (though manufacturing processes are much faster in practice). Particle counts at each level for each product showed reproducible values differentiable at different agitation levels. Adopting the proposed Tissue Dust Analysis System may help to collect, characterize and understand the mechanisms behind dusting to alleviate this issue at its various sources through dust-control strategies.

Introduction

Hygienic tissue papers, designed to reach a functional strength while maximizing softness and absorbency, include paper towels, facial tissue, napkins, wipes, and toilet paper, which serve as hygiene, comfort, and convenience products (de Assis et al. 2018). Tissues are a specific paper grade first introduced in the late 1800s that can be glazed, unglazed, or creped for different end uses (American Forest & Paper Association 2019). Tissue papers are formulated to exhibit a wide range of properties (e.g., strength, bulk, absorbency, and softness) (Batra et al. 2000), which consumers evaluate to develop an overall impression of a product and make final purchasing decisions (Barnholtz et al. 2011). The most important properties vary depending on the type of tissue product, its function, and the specific consumer's preferences (Wang et al. 2019). Softness is highly desired for bath tissue products, whereas absorbency is the primary price driver and the most desired property for paper towels (de Assis et al. 2018; Wang et al. 2019). Tissue manufacturers can alter their fiber composition, technology, and papermaking methods to attain specific properties and deploy a product with suitable consumer preference (Zambrano et al. 2020b; Zambrano et al. 2021).

A general problem arising during the tissue-making process and in the final tissue product is the tendency of the paper substrate to release fibers, leading to the formation of lint and dust (Linder et al. 2017). The

terms "lint" and "dust" are commonly used interchangeably in the paper industry (Frazier et al. 2022), although some research specifies lint as longer, larger fiber bundles of 4-5 mm in length and 500 microns in width and dust as shorter, individual fiber particles of 1-2 mm in length (Ricard et al. 2018). Dust particles are mainly made up of fibers, additives, ash, fillers, and starch, however, other particles can also be released and be described as dust, such as parenchyma cells or other fiber fragments (Campbell et al. 2020). For simplicity, the term "dusting" will be used throughout this manuscript, encompassing both lint and dust.

The generation of dust negatively impacts the entire chain of tissue paper handling, i.e., from the manufacturing stages up to the consumer. Exceptionally high dust concentrations occur during the conversion and packing processes of tissue products (Kraus et al. 2002). Hygiene tissue products with high softness and low dry tensile strength, composed of a high ratio of recycled or eucalyptus fibers, or with a high free fiber end count and low sheet moisture content will be most prone to dusting (Campbell et al. 2020).

Increasing dust release gives rise to multiple problems related to safety and health, maintenance and operation, and final product quality. Paper mill workers who regularly spend hours exposed to high levels of dust (greater than 5 mg/m³) are considered at risk of respiratory and health problems related to inhaling dust. Both intensity and length of dust exposure together have been proven to worsen health (Kraus et al. 2002). Additionally, dust that accumulates on machines during processing can potentially combust (Boyle 1970). Thus, dust must be dealt with as a waste product of the tissue-making process, costing the production facility time and resources (Campbell et al. 2020).

Products with higher dusting are less desirable because they leave behind residue on surfaces and, in some cases, on the human body. In addition, consumers indicate that it is difficult to find soft bath tissue products that do not leave residual dust (Bradbury et al. 2018).

In light of the hygienic risks and problems related to fires, explosions, and cleanliness in the end-product, the paper industry needs to find ways to combat or reduce dusting (Andersson et al. 2019). In this sense, fire protection technologies and high-efficiency dust handling systems can help prevent major deposits of already existing dust in the manufacturing facilities (Myers 2006). It becomes thus clear that developing strategies that minimize the overall dust generation by attacking its root cause may provide a more effective solution to the dusting problem.

Methods currently used to measure dusting include both paper and textile-testing methods, often particular to an application and therefore not functional over an entire industry. On the one hand, paper testing methods include dry lint rub tests, wet lint "fluff" testers, dust detection by sheet imaging, tape-pull dust analysis, motor-driven dust release, wax surface dust removal tests, and paper reflection tests, among other lesser-known methods. On the other hand, textile dust tests include sample flexing methods, tumble pilling tests, abrasion testing, and other more aggressive dust-collection methods (Frazier et al.

2022). Nevertheless, most of the existing test methods are costly, have little published data or results, or do not have a standard operating procedure.

When evaluating the methodology and the apparatuses, several tests apply a z-directional force to the paper's surface, which is not always representative of how dust is released (Yum and Bousfield 2017). Furthermore, specific methods that test through stress, bending, or rubbing may cause excess unrelated dust to be released. Finally, from ease of testing and effectiveness standpoints, some of these tests require large paper samples to be conclusive (Frazier et al. 2022). Thus, there is a need for a proficient, accurate and reproducible test that can be deployed at a lab scale, which would allow targeted research to devise dust control strategies in industry. This research aims to address this gap by developing a device and testing methodology to quantify dust particles. Thus, evaluating how dusting components change in terms of type, size, or composition at various tissue manufacturing stages is essential to further analyze and validate such a device.

This paper introduces a new Tissue Dust Collector (TDC) apparatus and methodology that combined comprise the Tissue Dust Analysis System (TDAS), which can accurately and repeatably test finished hygiene tissue products for dusting propensity. Two samples of commercial bath tissue products were selected for developing the methodology, based on their linting propensity (a high and a low-linting sample). The TDAS device and methodology include dust particle characterization, comprising both the amount of dust released and the morphological properties of such particles. Specific metrics obtained from this test method include total dust particle count, fiber and fines content, hardwood and softwood content, fiber widths and lengths, and fiber kink, achieved with a commercial image analysis-based method. Furthermore, the methodology was validated by qualitative assessment, including microscopic and Scanning Electron Microscope (SEM) imaging. Thus, major tissue brands wishing to test their product's dusting properties, consumer who wish to gain knowledge about less dusting products among buying choices, and researchers trying to understand the fundamentals behind the dusting mechanism are potential target audiences.

Experimental

The experimental is divided into two major sections. The first one includes the development of the equipment and test method. The second one includes methods to validate the Tissue Dust Analysis System.

Equipment & Materials

The experimental methodology involved in this study is outlined in Fig. 1. The types of analysis and metrics associated are also shown in the diagram. Fig. 2 shows a technical sketch of the final prototype of the TDC device. The device comprises an enclosed chamber with a hanger and a reciprocating motor, a wooden base support system, and a power source outside. The TDC device was designed to include a complete platform and support for the plastic chamber and motor to enable controlled movement,

ensuring consistent and repeatable measurements. The speed of the reciprocating motor was controlled between 60 and 180 strokes per minute. Each stroke of the motor travels a distance of 3 inches normal to the vertical chamber panel. The generated dust is collected within the enclosed glass chamber in which the reciprocating arm resides.

Depending on the motor's reciprocating stroke frequency, the agitation may represent gentle consumer handling or more aggressive handling. The conditions selected in this work are suitable for commercial bath and facial tissue products in the dry state.

Two sets of samples with a surface area totaling 8000 cm² are clipped into the device, hanging in the middle of the chamber and moved by the reciprocating motor to release particles within this chamber. In the current model, 40 sheets can be hung inside the device at one time. The particles are then collected in water and analyzed using a Fiber Quality Analyzer (FQA), HiRes FQA LDA02, to determine their characteristics relating to fiber/fines composition, fiber morphology (length, width, and fiber/fines percentages), and total particle count. This particle count metric is used to indicate dusting propensity as described in the analysis procedure section below. Particle count is calculated based on the fiber count, including and accounting for the fines percentage.

$$\text{Equation 1: } P = F / ((100 - X_f)/100)$$

Where:

P = particle count;

F = fiber count;

X = arithmetic mean;

f = % fines.

Selection of TDAS Test Materials

Two commercial products with known differences in dusting tendency were selected. The two products included one "high-linting" (referred to as Product 1) and one "low-linting" (referred to as Product 2) bath tissue. Product 1 was chosen for the "high-linting" data point since it is known to be plush, fluffy, and soft (likely to release particles). Product 2 was chosen for the "low-linting" data point since it is thin, stiffer, and less soft (less likely to release particles).

Product 1 is a two-ply product with a grammage of 48.9 g/m², uses CTADB (Creped Through-Air Dry Belt) technology, and is made of a layered hardwood/softwood mix that is not pressed. Air is passed through the sheet (Through-Air Drying), and the sheet is then dried using a Yankee dryer with creping. The

hardwood fibers are predominantly Eucalyptus, measured and reported by the supplier in excess of 70% of the furnish. The softwood fibers are Northern Bleached Softwood Kraft (NBSK). The producer is selective in the fibers used; no filler, non-wood, or recycled materials are present in the product. The product plies are held together through a water-based binder.

Product 2 is a one-ply product with a grammage of 20.3 g/m², uses LDC (Light Dry Crepe) technology, and is also made of a softwood and hardwood fiber blend, though these are combined uniformly rather than layered. The fibrous structure is lightly pressed, then dried on a Yankee dryer, followed by creping. Similar to Product 1, the supplier reported that the hardwood fibers are mostly Eucalyptus, although at a lower percentage (as low as 50%). The softwood fibers in Product 2 are mainly NBSK as well. The producer of this product does not use recycled fiber or filler.

Additional testing was done on 19 other bath tissue products with the highest market share in the North American market to validate the difference between products in terms of dusting propensity (determined by the number of particles released). Tests also included basis weight (ISO 12625-6 2005), softness (TSA softness), tensile strength (ISO 12625-4 2005), water absorption capacity (ISO 12625-8 2016), bulk (ISO 12625-3 2005), and TDAS tests. Additional variables such as drying technology (Through-Air Drying, Creped Through-Air Drying, Un-creped Through-Air Drying, Light Dry Crepe, energy efficient Through-Air Drying, Creped Through-Air Dry Belt, Advanced Tissue Molding System), tissue paper grade (hygiene tissue, printed paper, paperboard), type of brand (economy, ultra, premium), and fiber and fines content (fines percentage) and properties (average fiber length) were also measured for these samples.

Test Criteria (Parameter) Selection

Several device parameters had to be determined to create a standardized, accurate, and repeatable testing procedure. Parameters included motor speed (number of strokes or revolutions per minute), time (duration) within the container, sample quantity determination, and collection method.

The following criteria were considered for establishing testing conditions of the dusting device:

- Clear differentiation between products with different levels of dusting
- High resolution for low dusting products
- Minimization of testing time

The motor speed testing range was based on the MB11 Toilet Paper Drop Powder Rate Tester, which ranged from 60 to 180 repetitions per minute (UTS International Co., Ltd.). Thus, the speed increments for testing the new device included 60, 120, and 180 revolutions per minute, described as "strokes per minute" (spm).

Time duration increments of 1, 2, 4, and 8 minutes were selected, and preliminary tests confirmed that the particle counts were differentiable among these time increments even in the "lower-linting" product.

To ensure comparable results, the amount of sample used in each test was standardized. The quantification criteria was normalized by standard surface area rather than a mass basis, given that most of the dust particles were released due to the friction between sheets when the motor was running and agitating the sample. The total surface area tested per experiment was 8000 cm² (assuming negligible width), which equates to the total surface area of 40 10x10 cm sheets. A set of twenty sheets was clipped to each of the two hangers in the chamber.

The criteria were validated by a design of experiments at each speed level: 60 spm, 120 spm, and 180 spm, with each time duration: 1, 2, 4, and 8 minutes, for both products. Three replicates for each product were tested at each combination of conditions. For example, for Product 1, three replicates of tests were done at: (i) 60 spm for 1, 2, 4, and 8 minutes, (ii) 120 spm for 1, 2, 4, and 8 minutes, and (iii) 180 spm for 1, 2, 4, and 8 minutes. Three trials of the same testing criteria were done for Product 2.

Testing Method for Dust Particles

The procedure used for generating and collecting dust particle samples is described in this section. Tests were done on commercial products tested as-received, as well as the dust coming from these products (Fig. 6). The standard operating procedure for the TDC device (following sample conditioning) begins with sample preparation by cutting or carefully tearing the number of samples for 8000 cm². This cutting or tearing step is done inside the chamber to capture these particles since the unrolling or tearing of a sheet from the roll releases a measurable amount of dust, even before agitation. Both sets of samples are clipped to the hanger attached to the motor, which is run for the specified time and speed. After the motor is stopped, the chamber is sprayed down with a water bottle to transfer all the particles from inside the chamber quantitatively. This water-particle mixture is poured into a cylinder and filled to 500 mL with DI water, then mixed five times to improve distribution. 100 mL from this mixture is poured into a smaller cylinder, and this sample is run through the FQA. Two 100 mL samples of the original 500 mL water-particle mixture are tested in the FQA, and results are averaged. If the standard deviation between the two measurements is less than 10%, this average value is multiplied by five to calculate the total particle count. If not, additional 100 mL samples are tested until the standard deviation condition is met. Two different dust samples, taken directly after the creping doctor on beams and supports at a tissue-making facility, were supplied for testing. The associated product roll was sent along with each creping dust sample. Sheets from this roll were also tested in the FQA to compare the fiber compositions of dust from creping operations to those of the final commercial product.

Fiber Analysis of the Whole Product

In addition to analyzing the dust released from the supplied commercial products, disintegrated sheet particles representing the composition of the final product were also analyzed. In order to test the bath tissue roll, a sheet was removed from the roll, and a small piece from the edge was cut (~ 1 cm² square).

This piece was disintegrated into its fibrous components. The fiber-water dilution, filled to 500 mL, was placed into the FQA for unagitated product sheet testing.

Quantitative and Qualitative Analysis Using TDAS Method

After the dust had been collected, both quantitative and qualitative analyses were performed. Quantitative procedures are part of the TDAS methodology and include recording various fiber properties from the FQA. Measurements of softness, tested with a Tissue Softness Analyzer (TSA, Emtec Electronic GmbH), and tensile strength (ISO 12625-4 2005), tested using an Instron® model 4443, were also taken to observe property relationships between dusting characteristics and these properties. Qualitative assessments are not a part of the standard procedure created in this study but were done as a validation step to help support numerical data. Qualitative methods included both optical and scanning electron microscopy. The steps for these analysis procedures are outlined in the following sections.

Microscopic Imaging

Product 1 and Product 2 were each run through the TDC at 120 spm for 8 minutes. The longer duration of eight minutes was chosen in order to create more dust particle release for examination. Dust was collected from the TDC chamber for each sample in a water solution. Samples of the dust particles in water were run through a centrifuge to remove excess water to make them more concentrated. Samples were dyed red with saffron to increase contrast and then viewed and imaged under the microscope.

SEM Imaging Procedure

SEM imaging was done on four samples (one control and one agitated sheet for each) on their surfaces and cross-sections. To evaluate the sheet surface prior to agitation, a sheet of Product 1 and Product 2 were taken directly from their respective rolls and placed carefully into sealed and labeled bags. For generating a surface after agitation, Products 1 and 2 were run through the TDC at 120 spm for 8 minutes. A sheet of Product 1 and Product 2 were taken after agitation and carefully placed into sealed and labeled bags. Imaging was performed using a field emission scanning electron microscope (FEI Verios 460L), which can image at high resolutions without conductive coatings. Cross-sectional samples were cut under liquid nitrogen.

Validation of the Methodology

The final product is not the only part of papermaking that releases dust. More dust accumulates in operational processes such as converting and creping (Frazier et al. 2022). Therefore, it is necessary to evaluate the fiber characteristics of this operational dust as well as that of the final product to shed light on the composition of dust across various processing steps.

The TDAS test method was validated with a creping comparison test using dust released from commercial products in a manufacturing facility. Two separate dust samples, taken directly after the creping doctor on beams and supports at a tissue-making facility, were supplied for testing. For both creping dust samples received, the collection location was the same, and the associated product roll was sent along with each creping dust sample.

Various metrics and analyses were considered when validating the TDAS with creping dust. For the two supplied products, three samples were obtained for each: dust collected from creping, dust collected from testing with the TDC, and final unagitated sheet testing of the bath tissue product roll. These six samples were all tested in the FQA, and fiber length, width, and content characteristics were obtained from these tests. The results of these FQA tests were compared to each other in various combinations. Results comparing the fiber compositions of these tests can be seen in Table 1.

Ultra-premium layered Through Air-Dried (TAD) creping dust, and the matching bath tissue roll samples were obtained from a commercial contact. The roll was made hours after the dust was collected from the operation. The composition was specified as a ~30% NBSK and ~70% BEK (Bleached Eucalyptus Kraft) fiber furnish. The creping moisture was low, approximately 2.5%. This product was ultra-premium, high grade, and "high-linting," similar to the Product 1 previously described. From this point on, this ultra-premium TAD operation dust will be referred to as Product A. Product A has a basis weight of 40.4 g/m².

A commercial "low-linting" 1-ply recycled fiber product, similar in basis weight and tensile strength to lab-tested Product 2, was provided by a tissue producer. Creping operation dust, as well as the associated product roll, were provided. Although similar in type and quality, this product was made with 100% recycled materials, so it may not be directly comparable to Product 2. Its creping moisture was moderate, approximately 5%, and the product was made using a non-layered conventional nip press process. This 1-ply recycled fiber "low-linting" product will be referred to as Product B. Product B has a basis weight of 31 g/m².

Hardwood and Softwood Approximate Determination

Hardwood and softwood contents were calculated based on known or measured fiber properties of base fibers (i.e., length, width, coarseness). The following assumptions were followed to calculate the hardwood/softwood ratio: (i) BEK are hardwood fibers with length weighted fiber length of 0.82 mm, coarseness of 73 mg/km, and fiber width of 16.4 micrometers, and (ii) NBSK are softwood fibers with length weighted fiber length of 2.34 mm, coarseness of 135 mg/km, and fiber width of 28.4 micrometers (de Assis et al. 2019). These base values are input values for the calculations. Arithmetic fiber length values are used as well and can be obtained from the FQA data. The "Goal Seek" function in Microsoft Excel is used to back-calculate a mass fraction value for hardwood or softwood fibers, and then the mean fiber length is set equal to the sample's mean fiber length by changing that mass fraction. Finally, the goal seek function is used to obtain the final mass fraction estimate.

Results And Discussion

Understanding how tissue paper dusting originates and what causes a higher dusting propensity is crucial. Thus specific tissue paper properties must be examined, including but not limited to: fiber content, softness, strength, additive content, drying technology, and processing stage.

Effect of Frequency and Duration on Dusting Propensity

This initial testing of samples examined the two main variables that can be adjusted in the instrument, namely the oscillation frequency and the duration of the test.

Products 1 and 2 were agitated using the TDAS procedure at each testing iteration. The particle counts for each of the products were quantified and are presented in Fig. 3. All combinations of frequency and time are displayed as well as a comparison of products by the number of strokes and frequency at a constant time. The number of strokes represents a calculated value based on the frequency of repetitions per time.

The frequency and duration of the test affect dust generation (Fig. 3a and b). The effective acceleration applied to the sheets (i.e., the dusting force) increases by changing the oscillation frequency. Changing the duration of the test indicates how the tissue sheets "wear" or resist dusting.

Higher frequencies generated more dust for both products. Also, as the agitation time was increased, more dust was generated, indicating that the release of dust in this test is progressive, either due to "wear" or due to the ability of trapped dust particles to be released with increased time. If wearing of the sample is taking place, this means that it does not simply remove free fibers from the surface of the tissue. Overall, Product 1 showed a higher dusting tendency than Product 2.

The particle count (Fig. 3) also shows that the chosen sample surface area is sufficient to generate a measurable amount of dust that enables differentiating varying frequencies, times, as well as dusting propensities between products.

The same results can also be examined in terms of the number of cycles completed. Fig. 3c shows data plotted in terms of the total number of strokes the sample was subjected to in the instrument. Although it is less evident for Product 2 due to scaling, the effect of the cycles seemed to be cumulative, and the number of particles released with an increasing number of strokes followed a different path depending on the frequency. This assertion implies that the higher frequencies have a different effect on the mechanism of dust released from the tissue. Therefore, frequency and duration should be considered as independent variables.

Testing with the dusting device and proposed methodology has shown that the device is sufficient in distinguishing the dusting tendencies of commercial products (based on the total number of particles released from the tissue samples during testing).

Based on the mechanism of particle release and methodology proposed, the following advantages of the testing method herein developed compared to pre-existing test methods are expected:

- Identification of localized dusting, which may not be detected by pre-existing methods given their surface integrity approach for dust testing (i.e., Dry Lint Sutherland Rub Tester, Wet Lint Tester, IGT Pick Test). Localized dusting occurs when a tissue web's surface is prone to dusting and easily frees surface fibers, even when the bonding underneath the surface is sufficiently strong and not prone to dusting (Donner 2008).
- Quantification of particles released when the tissue product is unrolled or sheets are torn apart from the roll, considering that a significant amount of dust particles are released from punctured/perforated lines separating the individual sheets.

Evaluation of Particles

The FQA analysis allows studying the source of dusting in the tissue product, i.e., detecting if the dust collected is primarily composed of fines or fibers. Further analysis of the fiber fraction in the dust collected will explain its predominant composition, e.g., short or long fibers.

Dust Composition

The fines content of the two products was analyzed for each of the various experimental speeds and times. The percent fines content is a meaningful element of fiber morphology and must be considered for a comprehensive evaluation of dust particle characterization. Similar to the fiber length, the number of particles increases with speed. The following data, displayed in Fig. 4, shows how the particle characteristics change in terms of percent fines composition as a function of agitation time and frequency.

For Product 1 at lower speeds, most dust is concentrated in fines, and with increased time, fines generation increases or stays constant at these lower speeds. At higher speeds, mostly fibers are released, not just fines (Fig. 4a). Note that if fibers measure less than 0.2 mm, they will be counted as fines by the FQA, meaning any fibers that may have been broken during creping and have been released may be counted as fines particles.

For Product 2, more fibers are released at the shortest duration and lowest speed (60 spm) and with increased time at 120 spm, but more fines at the highest speed (180), especially at shorter durations (Fig. 4b).

Fiber characteristics are dependent on the time at the lowest frequency but not higher frequencies. The type of particles released at higher frequencies (120 and 180 spm) is essentially the same: fewer fines and more fibers.

Fiber Content

This section will cover fiber composition in the dust component of the products. The two known commercial products (1 and 2) were characterized by average fiber length, an important feature of fiber morphology, as part of the characterization of the dust particles (Fig. 5). This average fiber length was tracked over different time and frequency parameters to evaluate the factors that affected length for both products, and if so, what the effect was. The TDAS-produced dust was tested at different speed conditions (60 and 120 spm) but constant time conditions (4 minutes). These frequencies were chosen because the difference between dust components at 60 and 120 spm was much more significant than those at 120 and 180 spm. The results for 120 and 180 spm showed very similar trends to each other.

The number of particles still increases with speed, but with these visualizations, it becomes clear how the particle characteristics (not just quantity) change in terms of composition.

Agitation time has little to no impact on average fiber length for Product 1 (Fig. 5a), but the frequency shows a large difference. In Product 2, longer fibers are released at longer durations at the lowest frequency (Fig. 5b), while slightly shorter fibers are released at the higher frequencies.

By observing the particle size distribution, it can be seen that higher frequencies release more short fibers while lower frequencies release fewer short fibers. The average fiber length of the dust components of each product was graphed over a change in frequency at a constant time duration (4 minutes) to see the effect of a single variable on dust composition (Figs. 5c and 5d). The results of this were similar to that of Figs. 5a and 5b, which include time as a variable as well.

Product 1, at 60 spm, released more short fibers, with a peak around 0.2 mm (right at the fines cut-off). At 120 spm, most fibers released are slightly longer, suggesting the frequency makes a more considerable difference in the type of fiber released for this sample. At a lower agitation force, the particles released from the web are comprised mainly of small loosely bonded particles (primarily fines). As the agitation force increases, fibers (either short hardwood fibers or long fibers broken during the creping operation) begin to be released from the paper web.

Product 2, at 60 and 120 spm, showed the highest peaks at approximately the same fiber length, around 0.2 mm. Most fibers released at both these frequencies (and time) are shorter fibers. The reason for this difference between Product 1 and 2 is likely the different layering structures of the fibers in the sheets for each product. Product 1 hardwood and softwood components are layered, whereas Product 2 hardwood and softwood components are combined uniformly, which would affect which fibers are released and how easily they are released. Thus, from this average fiber length data, it should be concluded that frequency and duration of testing can affect the dust properties and that average fiber length can sometimes be affected by broken fibers.

Comparing Fiber Components of Dust to Finished Products

The fiber content of the dust component (produced using the TDC at conditions of 120 spm and 4 minutes) was overlayed on the product (from the package, unagitated) (Fig. 6) to see how similar or different the final bath tissue is compared to the dust that comes off that finished product.

Dust from Product 1, collected from the TDC, was very similar in fiber length and characteristics to its product roll, whereas dust from Product 2 showed a significant difference. Most fiber lengths for Product 1 are concentrated just below 1 mm, and the dusting component has only a slightly higher concentration of shorter fibers (and percent fines content). Therefore, it can be concluded that for Product 1, TDAS dust closely imitates the components of the final bath tissue product.

When examining the dusting components of Product 2, most fibers are concentrated at the shortest fiber length (fibers start at 0.2 mm), whereas in the final bath tissue, most fibers are of longer lengths than the dusting component. Product 2 mainly releases loosely bonded particles, which tend to be fines and short fibers. Considering that this is not a layered product, and that the longer softwood fibers have more bonding points and are more interlocked in structure, this result makes sense.

Morphological Analysis of Dust Components

Tissue sheets are expected to exhibit a higher number of free fiber ends and a higher level of exposure of fibers from the surface to be more prone to dusting (Campbell et al. 2020). Analysis of SEM images of the creped tissue sheets were performed to analyze a possible correlation between the crepe structure and the dusting propensity.

Image analysis of samples from Product 1 and 2, including optical microscopy and SEM, is shown in Figs. 7, 8, and 9. Released dust particles from TDAS testing as well as control (before) and agitated (after) sheet samples were imaged for evaluation of hardwood and softwood components and fractured or damaged fibers.

Several microscopic images highlighting dusting components from Products 1 and 2 are depicted in Fig. 7.

The dust sample collected from Product 1 (Fig. 7a) showed softwood tracheids, hardwood fibers, and vessel elements. This imaging proves that the dust testing mechanism releases not just a single fiber type. Fiber elements seen in these images were identified using Ilvessalo-Pfäffli's Fiber Atlas Identification of Papermaking Fibers (1995).

The dust particles from Product 2 were mainly individual fibers or fiber bunches, and imaging showed evidence of both hardwood and softwood fibers. Based on differences in diameter, both hardwood fibers and softwood tracheids can be distinguished in the images (Fig. 7e). Fig. 7f shows crossfield pitting and a smooth ray tracheid, suggesting that this is likely a spruce fiber. Bordered pits and rays can also be seen.

SEM images showing structural features of Product 1 before and after agitation are depicted in Fig. 8. SEM imaging was used to verify if fibers were damaged or broken, which was less obvious under a standard optical microscope. Moreover, cross-sectional SEM images made obvious the free fibers protruding from the surface of the sheets.

In SEM images of the Product 1 sample agitated in the TDC, free fibers on the surface were present and evident in the cross-sectional view (Fig. 8a). In the surface view, when comparing the control sample sheet to the agitated sheet after testing, the agitated sheet appeared to have more separated fibers (Fig. 8c) and was potentially more damaged overall. Similar to the imaging under an optical microscope, the SEM imaging showed evidence of both hardwood fibers and softwood tracheids (Fig. 8d). However, with SEM imaging, free or potentially broken fiber pieces were also distinguishable (Fig. 8e). Thus, since there is no pressing in the manufacture of Product 1, the short fibers are more exposed and come off more easily when agitated. SEM images of Product 2 can be seen in Fig. 9.

Product 2 differs from that of Product 1. In the SEM surface images of Product 2, it appears that the control sample sheet (Fig. 9a) is much more compressed and dense compared to the agitated sheet, which has holes and empty spaces, indicating damage (Fig. 9b). At high magnifications, softwood tracheids and hardwood fibers could be distinguished. From the cross-sectional views of Product 2 before and after agitation, there is no indication of major structural changes occurring in the sheet during the procedure (Fig. 9c and d). This result is likely due to this product's interlocked and pressed structure, keeping more fibers from protruding from the surface.

From both microscopic and SEM images, softwood and hardwood presence can be confirmed in both Product 1 and 2's TDAS dust particles and whole sheet samples. Eucalyptus hardwood fibers and possible spruce or pine hardwood fibers were observed, as well as evidence of fiber damage or breakage in surface and cross-sectional SEM images. There was a similar representation in both samples. The differences in SEM imaging between Products 1 and 2 helps validate the differing quantitative results obtained with the FQA.

Proposed Dust Release Mechanism

A dust release mechanism can be proposed for tissue products based on the experimental results previously described. The dusting mechanism (Fig 10a) shows how dust is released from a hygiene tissue sheet according to speed, time, and product type. This mechanism evaluates how dusting components change in terms of type, size, or composition over various levels of agitation.

There are two major regimes for dust release as depicted in Figure 10. The first is the high dusting regime, which describes a high frequency (e.g., 180 spm) agitation. At short durations (e.g., 1 min) in both products tested, this high regime releases loose particles from a tissue sheet that have fiber lengths measuring near 0.8 mm, and with additional time (e.g., 8 mins), this average fiber length does not change much at the high frequency (Fig. 5). However, at longer durations (e.g., 8 mins), the sheet experiences

wear, during which more fibers begin to protrude from the surface and bonding is reduced, allowing more dust overall to be generated (Fig 3a and b).

The second regime, the low dusting regime, describes a low frequency (e.g., 60 spm) agitation. Although the data in this study shows differences by product, for both products tested, the transition from short to long durations (e.g., 1 min and 8 mins, respectively) reflected increases in percent fines content of the dust. Similar to in the high dusting regime, longer durations (e.g., 8 mins) tended to reflect an overall increase in particles released, though not as significant as the high dusting regime.

Validation of the Methodology with Dust Produced in the Creping Operation of a Tissue Machine

Comparison of Creping Dust and TDAS dust

Dust collected from the creping operation in a tissue paper manufacturing process and dust produced and collected with the TDC device was tested for validation purposes. The goal was to collect dust using the TDC and evaluate if it was representative of dust from tissue mill operations, such as creping. This type of experiment would provide insights about the translation from bench-scale to commercial-scale of dust control strategies. Also, such a study might reveal if dust differs in terms of its morphological features at different stages of papermaking.

Product A, ultra-premium TAD creping dust at 2.5% creping moisture, and Product B, 1-ply economy creping dust at 5% creping moisture, were tested and compared to Products 1 and 2.

Table 1 summarizes fiber metrics for Products A and B. Each product's roll, creping dust, and TDAS dust were tested, and the results are displayed below. Refer to Fig. 6 for data on Products 1 and 2 for comparison.

Table 1: A summary table of Products A and B that specifies average fiber length and percent fiber and fines content for different process stages.

	Property	Product A	Product B
Final product roll	% Fibers, Lw ^[a]	90.9	85.7
	% Fines, Lw	9.1	14.3
	Hardwood Content	38.8%	70.8%
	Softwood Content	61.2%	29.2%
	Avg Fiber Length (mm)	1.17	0.93
TDAS lab-produced dust	% Fibers, Lw	92.8	71.2
	% Fines, Lw	7.2	28.8
	Hardwood Content	52.8%	40.6%
	Softwood Content	47.2%	59.4%
	Avg Fiber Length (mm)	1.04	1.15
Creping dust	% Fibers, Lw	97.6	45.7
	% Fines, Lw	2.4	54.3
	Hardwood Content	96.6%	100% ^[b]
	Softwood Content	3.34%	0%
	Avg Fiber Length (mm)	0.83	0.41

^[a] Length weighted fiber and fines values were used for all measurements.

^[b] The hardwood content of the creping dust is a calculated estimate and may not be exactly 100%.

As mentioned previously, the hardwood and softwood calculations shown in Table 1 were done assuming that the hardwood fibers are BEK and the softwood fibers are NBSK. The TDAS testing conditions for these tests were 120 spm and 4 minutes.

Product A, with low moisture creping and higher creping intensity (as specified by the producer), shows a slightly lower percentage of fibers in TDAS dust (particles with lengths exceeding 0.2 mm) compared to that of the creped sample (Table 1). More fines (determined by length) are counted in the product roll and the TDAS dust than the creping dust, but the fibers (> 0.2 mm) that are released during creping are shorter on average than those that release during TDAS testing or from the product roll.

Product B, with moderate moisture creping and low creping intensity, shows a fiber percent higher than the creped fiber percent in TDAS dust (Table 1). As expected, more fines (determined by length) are present in creping and TDAS dust compared to the final product roll, but the fibers (> 0.2 mm) that are

released during creping are much shorter than those that come off in TDAS testing. It is possible that the rubbing and peeling of the surface during testing may account for such a difference.

The length weighted fines content in Products A and 1 is fairly low. Considering that these are virgin products, whenever dust is released, essentially the same composition of particles as the roll is being released. In contrast, products made of recycled fibers are more concentrated in fines, and these are the particles that come off more easily during testing.

These results suggest that a higher creping intensity with lower moisture during creping might cause more fibers to be released, while a lower creping intensity and higher moisture during creping might cause less fines to be released. In addition, the layered nature of Product A increases the likelihood of the short fibers present on the outer surface of the sheet being released during creping. In contrast, in Product B, since its structure is interlocked, only loosely bonded particles (such as fines) are released from the sheet.

Furthermore, the previous results indicate that the dust produced and collected from the TDC lab device can closely replicate or predict the fiber characteristics (specifically fiber percentage and length) of operation dust for high linting or high creped and low moisture creped products such as Product A and 1. There is more difference between the TDAS lab-produced dust and the operating dust for lower-linting or less creped and higher moisture creped products such as Product B and 2. The differences that are seen between lab-produced dust using the TDC and operation dust from creping are likely due to the more aggressive nature of creping compared to simple agitation. A mechanical force is applied during creping that causes breakage of some fiber-to-fiber bonds that is much less likely to occur during TDAS lab tests.

In summary, creping dust and TDAS dust evaluations seem to indicate that the type of layering and technology used for tissue-making can affect which fiber types are released and when they are released in the process. Based on these preliminary results, collected TDAS dust may be able to predict which types of fibers will be released more during various forms of agitation (whether that is a creping stage or a consumer handling stage). Knowing this information may help manufacturers combat the issue of excessive dusting. In addition, by elucidating the dusting mechanisms, it could become clearer when and how dust is released at different speeds or times (i.e., phases of processing), so a manufacturer may be able to locate dusting at its source, and thus create a specialized dust-control strategy based on this information.

Validation of the Methodology with Commercial Products

It is helpful to correlate dust propensity and characteristics with known properties of hygiene tissue products. This is performed in order to determine which properties relate to the highest or lowest dust values and which do not seem to correlate with dust propensity. In this work, dust particle propensity has been related to softness, tensile strength, and technology.

Twenty-one market tissue products (representing about 80% of the existing US market offering) were tested and analyzed. The products were analyzed with the TDC at a frequency of 120 spm for 4 minutes. Thus, products were ranked according to dusting propensity, using total particle count as the ranking metric. Fig. 11 shows the results.

Fig. 11 shows that both tissue products in the market can be distinguished using particle count, tested with the TDAS. It was hypothesized that since Product 1 had a higher likelihood of particle release compared to Product 2 based on product properties (specifically higher levels of softness and lower levels of strength), results from testing using the TDC device and standardized methodology would validate these assertions. These results confirm that Products 1 and 2 represent higher and lower dusting products (respectively) compared to other products in the market. This conclusion validates the use of them for the major comparative experimental data. This visualization of particle count might also be valuable for producers trying to gauge their products with regards to linting propensity in the marketplace or even for consumers looking for a lower-linting product.

Since softness has been proposed to be related to dusting propensity, it was used as validation. A lower TS7 softness value indicates a softer product. The particle counts for the 21 commercial products tested are quantified and compared to these products' softness profiles (Fig. 12).

Although the correlation between TS7 softness and particle count for this set of commercial products is not strong, a positive relationship between higher softness and greater dust propensity does exist. This correlation may be less strong due to the number of variables involved, such as fiber composition, machine technology, and embossing, among others. In general, softer products have a higher tendency to generate dust. It has been found that when paper sheets are treated with a spray softener, the accumulated dust content on the creping blade is higher than usual (World Paper Mill 2020). It has also been suggested that mechanical pulps with high fines content tend to give rise to dusting problems due to the increase in tissue paper density (Axelsson 2001).

Tensile strength was also measured on the commercial products. Increasing the surface strength of paper has been proposed as a way in which to decrease the dusting tendency of paper during printing (Song et al. 2010). Similarly, for tissue-making, if the bonding strength of the sheet can be increased, dust formation can be decreased (Sheridan et al. 2005). Improvement of tissue dusting is highly dependent on the paper web's ability to maintain integrity during creping, which would decrease fiber fragmentation without greatly reducing softness (Sheridan et al. 2005).

The particle counts for the 21 commercial products tested are quantified and compared to these products' tensile strengths (Fig. 13).

This data shows little correlation between tensile strength and dusting propensity. A product could be very strong based on fiber selection (i.e., virgin fibers) but be layered, making the product dustier. However, using Product 1 and 2 as examples (noted in Figs. 12 and 13), it can be said that in general products with lower TS7 values and lower tensile strengths tend to have higher dusting propensities.

Another variable that could influence the dusting tendency in tissue papers is the tissue drying technology. The 21 commercial products tested in this study are displayed below with their corresponding dusting propensities and technology types (Fig. 14).

Tissue-making technology type would likely influence dusting propensity, and this research is the first to publicly shed light on the impact of machine technology on dusting.

Technologies consistently displaying higher dusting propensity according to these results include UCTAD (Un-Creped Through-Air Drying) and ATMOS (Advanced Tissue Molding System), followed by CTAD (Creped Through-Air Drying). It has been found that TAD processes tend to orient fibers in the z-direction, exposing fiber ends at the surface, which may increase dusting tendency, but additional research in this area would be beneficial for making more substantial conclusions.

Conclusions And Future Implications

Tissue paper linting and dusting is a rising concern in the paper industry for manufacturers, producers, and consumers of commercial products. There are health, safety, and quality issues related to heightened dust levels. Without proper equipment and a standard method of evaluating such dust, these issues cannot be efficiently solved or controlled. The Tissue Dust Collector apparatus and the Tissue Dust Analysis System developed in this research allow testing of dusting propensity and characterization of the dust particles produced. The results from the Tissue Dust Analysis System were validated by looking at dust particle counts over several commercial products, comparing dust from creping to final product dust, and observing correlations between product properties and dusting tendency. The device and methodology described herein sufficiently test tissue paper dust so that it can be characterized and critical information can be gathered to potentially implement dust control strategies. Testing of commercial bath tissue from the North American market shows that dust content differs among products, and fiber/fine composition in the dust may also vary, depending on technology, creping intensity, moisture content, etc.

This work motivates research and development surrounding dust reduction in paper products. Further research could include studying ways to combat dust while maintaining desirable softness and strength properties. Solutions could range from wet-end or reel additives, Yankee coatings, or sprays, to name a few. Different wet-end chemistry strategies (retention aids) could be evaluated and compared in terms of dusting propensity across the manufacturing process and finished products. Tissue paper produced without retention aids could be used as controls. Different types and dosages of retention aids could be added to the furnish to evaluate fine retention and dusting propensity effects. Analyzing the results obtained in this research work, among the dusting reduction strategies, the most prospective would be:

- Chemical additive treatment which could include crepe control technology, sprays, dry strength additives, or cationic functional promoters, to name a few (Campbell et al. 2020). Starch, clay, or phosphate esters are examples of additives that could affect paper dusting.

- Cellulose nanofibers (CNFs) from residues have also been suggested for dusting improvement, specifically for higher dusting recycled paper (Balea et al. 2017). The higher filler content of recycled paper typically yields low strength and worse dusting properties. However, CNFs tend to be costly and negatively impact softness and absorbency in tissue papers (Zambrano 2020a), so this may not be the best method for dusting improvement.
- Mechanical treatments can also increase the bonding of ray cells and, therefore, reduce dusting (Balea et al. 2017). Improved web strength and decreased porosity will yield a lower linting product.

Additional considerations include making adjustments to papermaking machinery or processes to reduce dusting during processing or converting steps. All of these possible methods to reduce dusting must also consider the tradeoff in other properties such as softness, strength, or absorbency that may result from the dust control program.

Declarations

Competing Interests

The authors declare that they have no competing interests.

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Compliance with Ethical Standards

The authors did no tests on humans or animals to write this work.

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Figures

Figure 1

Experimental design for testing and analysis. Product 1 represents a “high-linting” premium bath tissue, Product 2 represents a “low-linting” economy bath tissue. Product A represents the ultra-premium creping dust sample and roll, Product B represents the low-linting creping dust sample and roll from a recycled product. FQA: Fiber Quality Analyzer, HW: Hardwood, SW: Softwood

Figure 2

(a) Final device prototype schematic of Tissue Dust Collector (TDC) (b) Movement diagram showing movement of the motor and how dust is released

Figure 3

(a) Product 1 Trials and (b) Product 2 Trials at varied conditions; (c) Particle count of Product 1 and 2 by number of strokes, with error bars corresponding to the standard deviation

Figure 4

Graph of average % fines of Product 1 (a) and Product 2 (b) TDAS produced dust at different conditions; The remaining percentage corresponds to the fiber fraction

Figure 5

Average fiber length of dust components (a) Product 1 and (b) Product 2. Particle size distribution of TDAS dust produced at different frequency conditions but constant time for (c) Product 1 and (d) Product 2

Figure 6

(a) Fiber length distributions of Product 1 bath tissue product roll and dusting component of the bath tissue from TDAS testing at 120 spm and 4 minutes overlayed; (b) Fiber length distributions of Product 2 bath tissue product roll and dusting component of the bath tissue from TDAS testing at 120 spm and 4 minutes overlayed; Note that fiber lengths are defined as having lengths greater than 0.2 mm and are weighted (Lw) values

Figure 7

Product 1 - (a) Hardwood fibers and vessel elements along with a softwood tracheid, (b) Vessel element pitting and simple perforation plates, likely Eucalyptus; Product 2 - (c) An individual hardwood fiber, (d) A fiber bunch, (e) Hardwood and softwood fibers, (f) Potential Spruce fiber

Figure 8

Product 1 SEM images of (a) Cross Section, agitated at 250 μm (b) Surface, control at 100 μm , (c) Surface, agitated at 100 μm , (d) Surface, control at 50 μm , and (e) Surface, agitated at 25 μm

Figure 9

Product 2 SEM images of surface and cross sections of unagitated and agitated sheets

Figure 10

Proposed dust release mechanism for hygiene tissue products including the effect of agitating tissue sheets with the TDC device at various forces and durations to show the dusting regimes associated

Figure 11

Comparison of Dust Particle Counts of the top 21 market share products. Product 1 and Product 2 are pointed out to show relative dusting propensities

Figure 12

Visualizing softness against particle counts

Figure 13

Visualizing Tensile Strength against particle counts

Figure 14

Visualizing dusting propensity of commercial products based on their drying technologies

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