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PARAMETERIZING COTTON FIBER LENGTH DISTRIBUTION SHAPES

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ABSTRACT

The issues pertinent to the length distribution of cotton fibers are complex due the combination of factors including a strong genetic component and alterations due to fiber damage in harvesting, ginning and textile processing. As a result, the distributions have complex patterns and exhibit features that often cannot be described adequately using the usual summary statistics. Among the current parameters made available by the existing instruments, the Uniformity Index (or the uniformity ratio) represents the only commonly used shape parameter of the length distribution. Short Fiber Content (SFC) is another parameter used as an indicator of fiber damage, but was found to be inadequate in many contexts. This paper presents an alternative approach to the existing parameters. It defines the distribution's modality feature as an indicator of fiber damage and of the interaction effects that determine its shape.

KEYWORDS

Cotton fiber length distribution, distribution shape, fiber damage, bimodal distribution, DIP statistic.

1. INTRODUCTION

The industrial performance of cotton, and thus its competitiveness on the global market, is a function of its fiber properties. Although some properties are more critical than others (e.g., length), the ultimate use-value of a given cotton is determined by interactions between all attributes. For instance, there are often significant interactions among fiber strength, maturity-fineness properties, and the extent of length distribution degradation due to the impact of maturity and strength on the cotton's propensity to break (Krifa, 2006; Krifa and Holt, 2013).

Degraded cotton fiber length distributions resulting in excessive amounts of short fibers have for long been linked to significant losses in spinning performance and yarn quality (Tallant *et al.*, 1959; Thibodeaux, 2008). Over several decades, a variety of length measurement methods have been used to quantify short fibers. Different parameters were defined for this purpose. For instance, Tallant *et al.* (1960) defined the short fiber content as the percentage of fibers ⅜" and shorter. Lord (1961) used the percentage of fibers shorter than half the effective length as definition. Ultimately, all definitions evolved into a single measure arbitrarily defined as the percentage of fibers less than ½" in length, and designated as the "Short Fibers Content" or SFC.

Despite considerable advances in measurement technology, reliably quantifying the SFC proved not to be straightforward. This is in part due to the high variability of this parameter and to the sampling difficulties

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inherent to the handling of short fibers. More importantly, the definition of the SFC was questioned and its usefulness doubted in many instances. One of the most evident and recurrent critics concerns its bias against intrinsically shorter cottons, given the close relationship between staple length and SFC (Thibodeaux *et al.*, 2007). Indeed, if the current parameter were to be used in cotton pricing and commercialization, those cottons would be doubly penalized. This is due to the definition of the SFC as the percentage of fibers shorter than an arbitrary fixed length, regardless of the shape of fiber length distribution.

The length of cotton fibers is determined genetically and is thus a heritable trait that can be improved through breeding (Herring *et al.*, 2004). However, it also has a strong process-related component due to its alteration under the stresses put on the fiber in harvesting, ginning and textile processing. For instance, opening and cleaning the cotton during spinning preparation always results in a certain degree of fiber breakage because of the aggressive mechanical actions involved in those processes (Carnaby, 1984; Krifa, 2004; Krifa and Holt, 2013). Due to the combination of these effects, length distributions of cotton fibers have complex patterns and exhibit features that often cannot be described adequately using the usual summary statistics. For instance, shape features such as distribution bimodality are not provided by any measurement in use today. Consequently, the validity of the SFC parameter as an indicator of length distribution alteration due to fiber damage remains, for the least unproven; so is its usefulness as a predictor of processing performance and product quality (Robert and Blanchard, 1997; Robert *et al.*, 2000; Krifa, 2004).

This lack of valid parameterization prevents an accurate characterization of the length distribution; therefore the components of its variability cannot be analyzed. Cotton breeders need to be able to quantify the genetic contribution to this variability in order to effectively include distributions in their selection criteria. Also, ginners and spinners need to be able to quantify process-related alterations of the distribution pattern, in order to effectively optimize their mechanical processes. This research presents an alternative approach to characterizing the shape of the entire distribution of cotton fiber length. It explores the use of the distribution's modality as an alternative indicator of fiber damage during the opening-cleaning and carding processes in spinning preparation, i.e., from the bale to the card sliver.

2. MATERIALS AND METHODS

A wide range of more than 100 commercial cotton bales with targeted properties were included in the study and tested for fiber length distributions at alternative stages of the spinning preparation process (raw bale, opening & cleaning, and carding). The bales were selected to cover a broad range of the main fiber properties (staple length, length uniformity, bundle strength and micronaire) representative of the considerable diversity of possible combinations. All bales were sampled from ten layers throughout in order to ensure representativeness of the fiber samples. All raw fiber samples were tested on a High Volume Instrument (HVI 1000, by Uster) with 4 replications for micronaire, 4 for color, and 10 for length and strength. The bales were then processed through spinning preparation (Hunter Weigh Pan Hopper Feeder, Rieter Mono cylinder B4/1 coarse opener, Rieter ERM B5/5 Fine opener, AMH Blender, and Trutzschler DK 903 card). In addition to the raw samples, processed fiber samples were collected at alternative steps (card chute, card sliver) in order to evaluate the effect of mechanical handling on the length distribution features.

All samples were tested on the Advanced Fiber Information System (AFIS, by Uster) with 3 replications of 3000 fibers each. AFIS analyses provide fiber length distribution data (histograms) along with other characteristics measured on individualized fibers (maturity and fineness, as well as neps and trash content). In addition to the empirical length distribution histograms, the AFIS provides several length parameters: mean length by number (Ln), and by weight (Lw), Upper Quartile Length by weight (UQLw), length CV% by weight and by number, Short Fiber Content by weight (SFCw%) and by number (SFCn%), and length upper percentiles by number (Ln2.5% and Ln5%). Given the single-fiber nature of the measurement, the length distribution by number constitutes the source of all these parameters. The weight-biased distribution is estimated from the latter based on the assumption of a uniform fineness across all length categories and is therefore length-biased. In the following discussion, we focus on the unbiased data, i.e., AFIS measurement of length distribution by number.

In order to measure and parametrically characterize the length distribution modality, we used Hartigan's DIP test of unimodality (Hartigan and Hartigan, 1985; Hartigan, 1985; Tantrum *et al.*, 2003). The test is based on the derivation of the DIP statistic from the distance between the empirical cumulative distribution function (CDF) and the unimodal CDF closest to it. Hartigan's test for departure from unimodality was conducted using a visual basic code written based on the Fortran 66 subroutine published in (Hartigan, 1985). Mixed Weibull PDF fits and statistical analyses of the data were computed using Statistica® (StatSoft, Inc., Tulsa, OK) and Maple (Maplesoft, Waterloo, ON, Canada).

3. RESULTS AND DISCUSSIONS

Combinations of staple length, HVI strength, micronaire, and length uniformity index of the bales tested are represented in Figure 1, which shows scatter plots relating staple length and strength within different levels of micronaire and uniformity. As seen in Figure 1, HVI analyses confirm the broad spectrum of fiber property combination we have targeted.

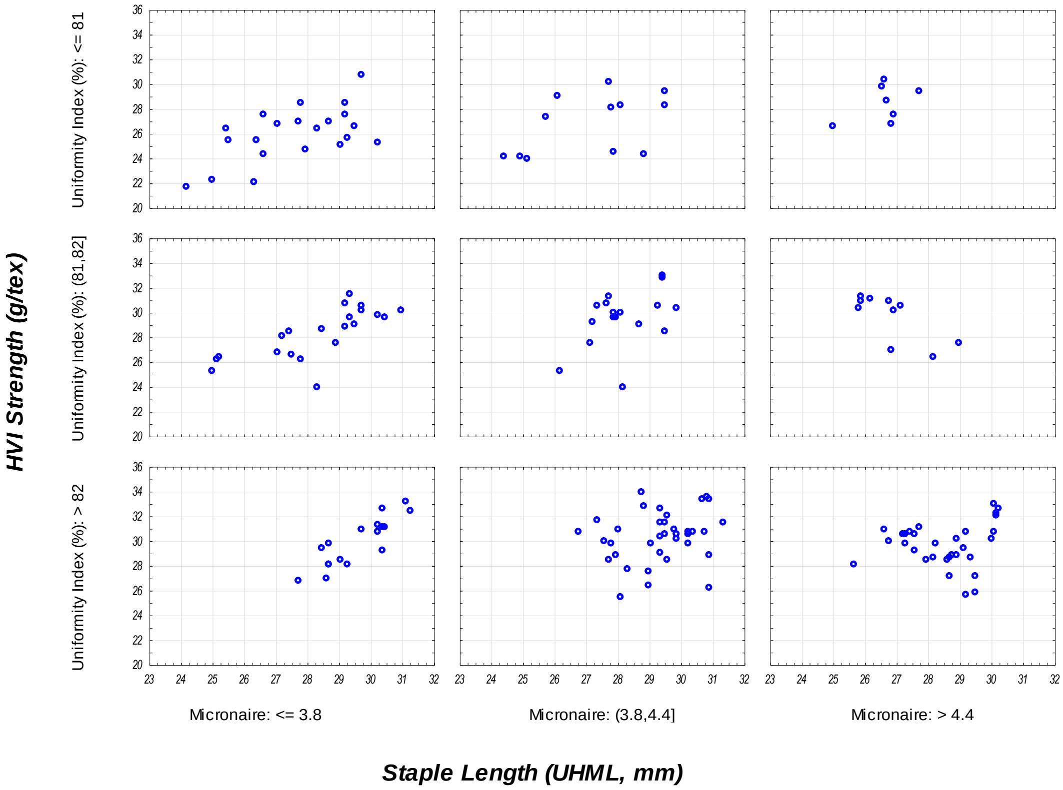

Figure 1: Combination of HVI fiber properties of the bales tested

3.1. AFIS length parameters

In the present paragraph, length parameters provided by the AFIS are examined with respect to their representativness of the potential fiber damage during the processes of preparation and carding. We selected three parameters for this analysis: the mean length by number (Ln), the 2.5% length percentile by number (L2.5%) and the Short Fiber Content by number (SFCn%). The relationship between the values of each parameter obtained on the samples from the raw bales and after the steps of opening-cleaning and carding are represented in Figures 2, 3, and 4.

It is apparent from the three Figures that the scatter plots relating the pre- to the post- opening/cleaning and carding results follow closely the equality line. This shows that for the present sample range, the three parameters did not vary to a sizeable extent after opening/cleaning and carding operations, which appears rather surprising knowing the aggressive mechanical actions involved in those spinning preparation processes. Indeed, these results suggest that the mechanical actions occurring during spinning preparation had little to no effect on the fiber length properties of the processed bales, assuming that the three parameters above are representative of the length distribution patterns. However, it appears unlikely that such aggressive mechanical handling, particularly during carding, would have so little effect on length distribution. A more probable hypothesis that could explain these results is that the three length parameters do not reflect the effects of processing on the fiber length distribution patterns. In order to confirm this statement an examination of the length distribution pattern is necessary.

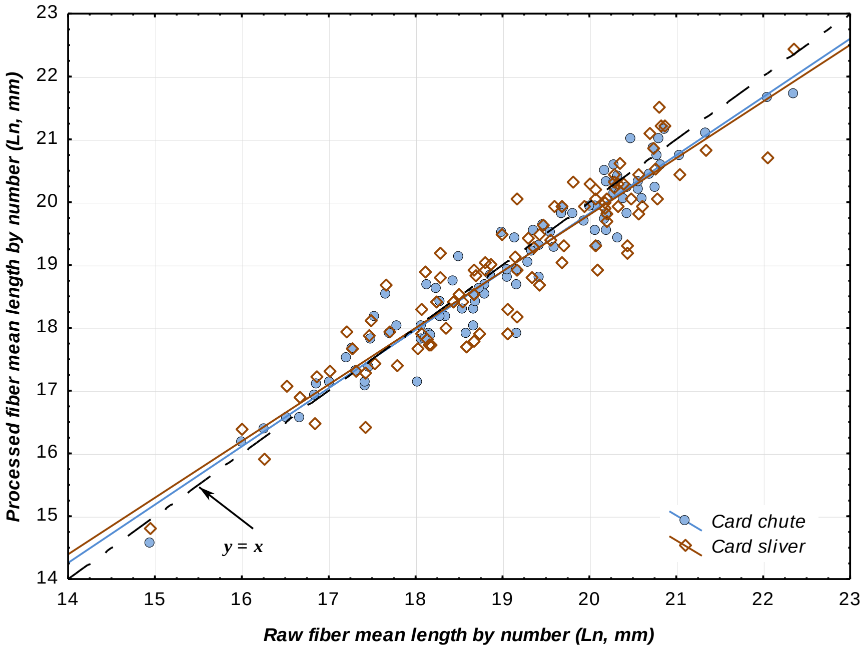

Figure 2: Effect of opening-cleaning and carding on AFIS Ln (inch)

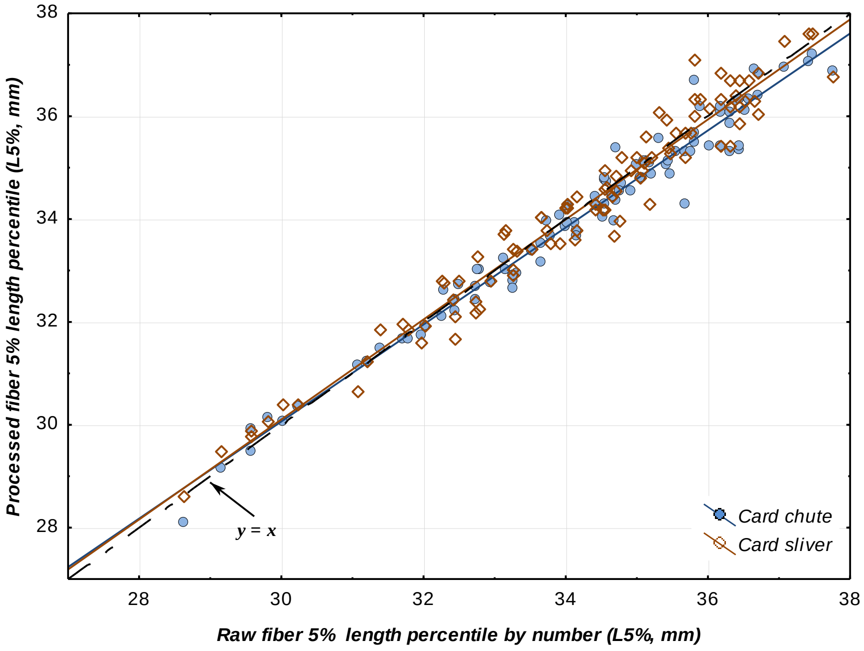

Figure 3: Effect of opening-cleaning and carding on AFIS L2.5% (inch)

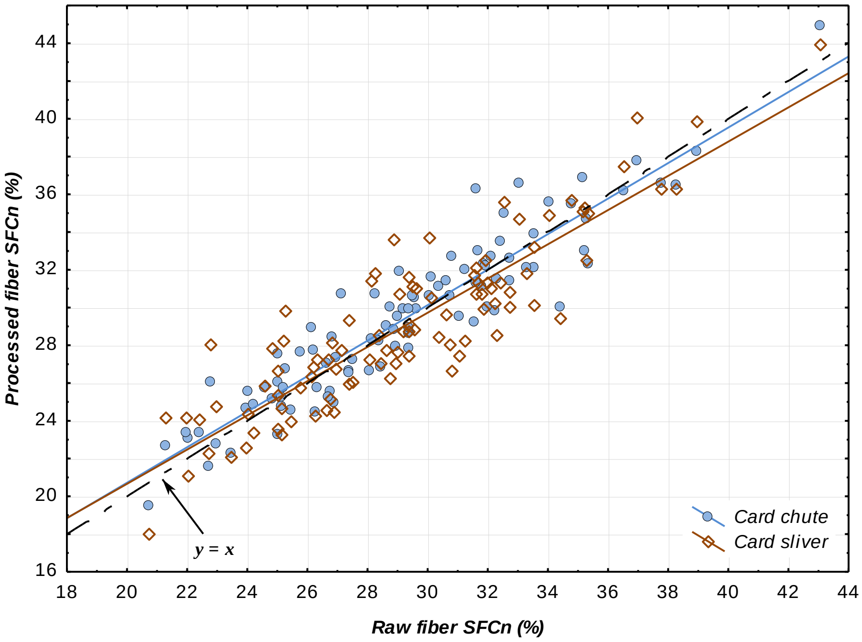

Figure 4: Effect of opening-cleaning and carding on AFIS SFCn (%)

As mentioned above, fiber length distribution analyses were conducted on all samples tested in this research. For illustration purposes we only show in Figure 5 four bales selected based on fiber maturity and strength levels. Bundle strength, micronaire and maturity ratio values for those four bales are shown in Table 1. Figure 5 exhibits the plots of length distributions observed in raw samples, after opening and cleaning (card chute), then after carding (Card sliver).

Table 1: Maturity, micronaire and bundle strength values of the bales depicted in Figure 5

Description	**Maturity ratio (MR)**	**Micronaire**	**Bundle strength (g/tex)**
A: Immature-weak	0.73	2.4	21.7
B: Low maturity, average strength	0.81	4.1	27.6
C: Average maturity, average strength	0.87	4.5	28.7
D: Mature-strong	0.92	4.2	33.4

Figure 5 clearly shows that the fiber length distributions appear slightly impacted by opening and cleaning, but is significantly altered after carding. In particular, the plots in Figure 5 show that the distribution modality changes during spinning preparation, and primarily during carding. All probability density functions observed, with the exception of the weak immature cotton, show bimodal shapes when considering the raw bale samples. On the other hand, all card sliver samples, with the exception of the strongest cotton, show unimodal shapes. Fiber breakage during processing appears to transition the distribution from a bimodal to a unimodal state. The distribution modality, and its alteration during preparation and carding, will be examined in more details in the following section. For the time being, we attempt to explain the absence of effect on the parameters represented in Figures 2, 3, and 4, and particularly short fiber content.

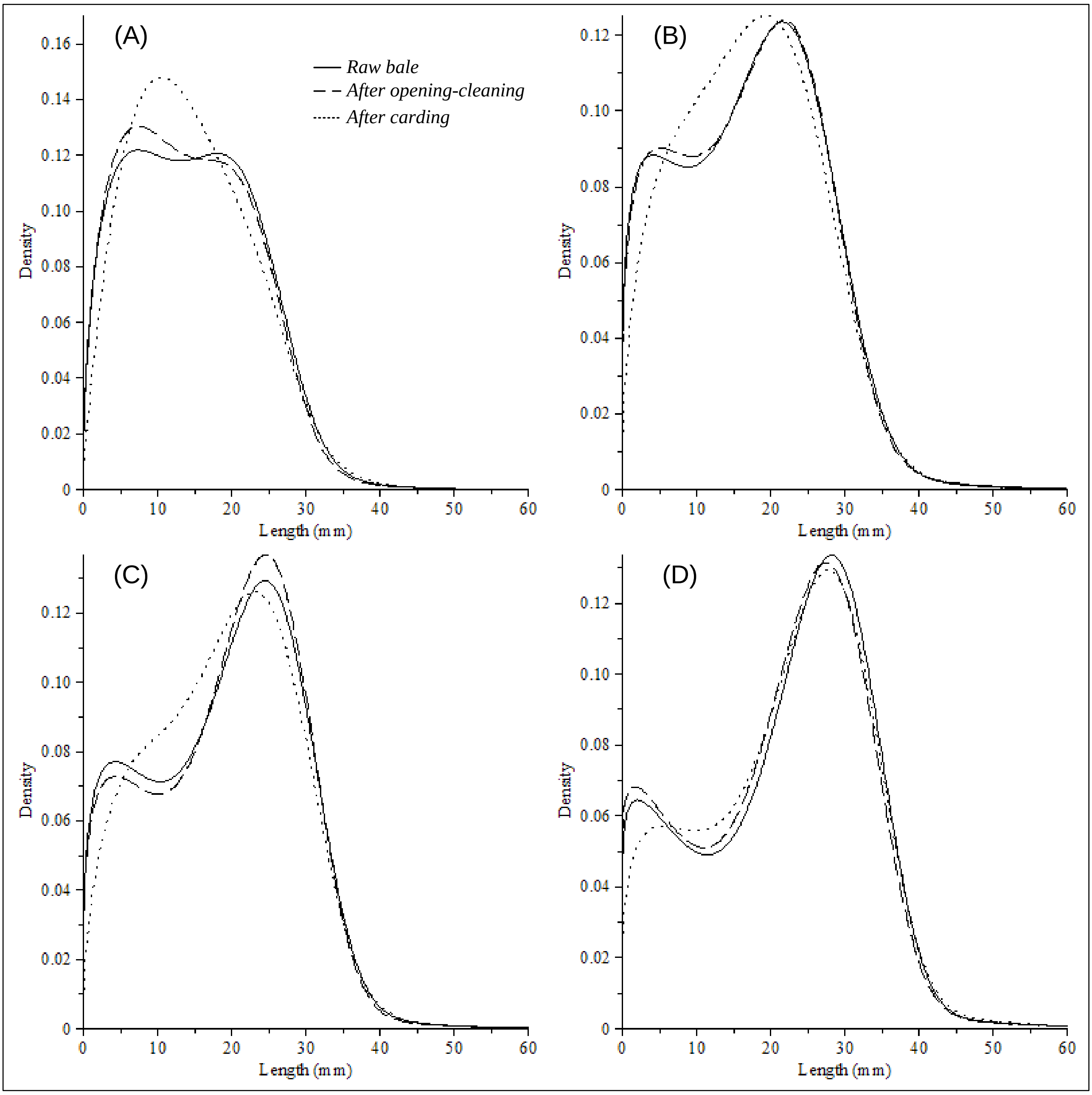

Figure 5: Effect of opening-cleaning and carding on length distribution patterns of selected bales.

Short fiber content (SFCn%) results obtained on the same four bales in raw, card chute and card sliver samples are depicted in Figure 6. The figure shows that despite the alteration seen on length distribution, the amount of short fibers (< 12.7 mm) is not affected. An example explaining the impact (or the absence of it) of this length distribution alteration on the SFCn is shown in Figure 7. In fact, the decrease in the percentage of fibers shorter than approximately 8 mm and the increase of those between 8 and 12.7 mm resulted in virtually unchanged short fiber contents. These effects were overall apparent for all the cottons examined. These results confirm that the three parameters considered in the previous paragraphs do not reflect the effects of the mechanical actions occurring during spinning preparation on the fiber length distribution.

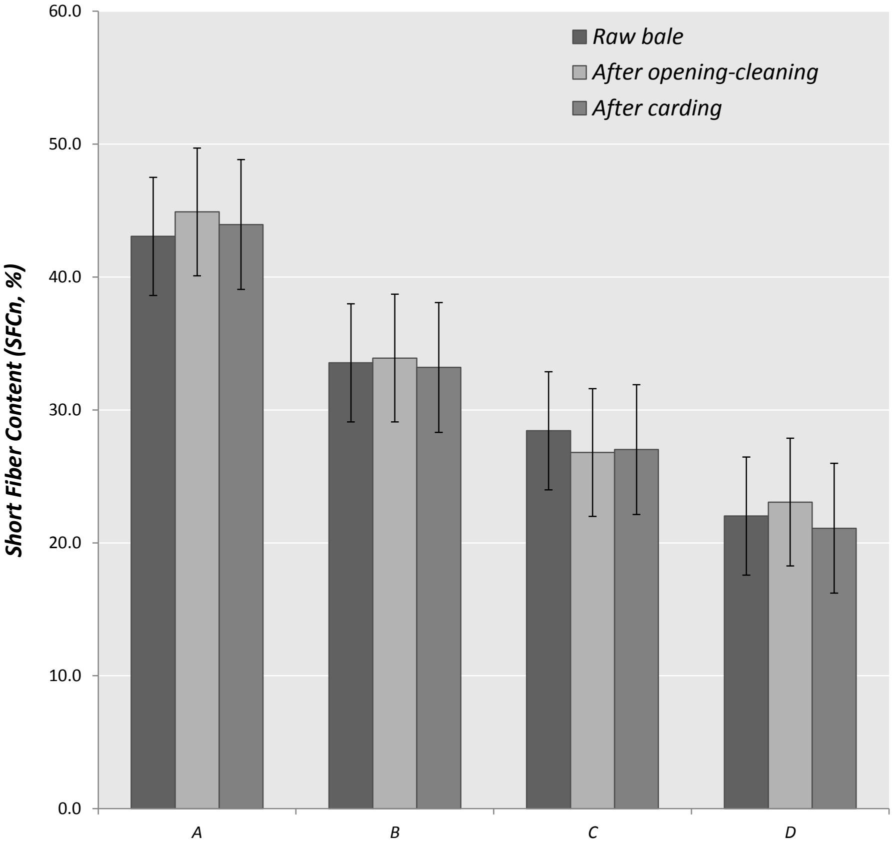

Figure 6: Effect of opening-cleaning and carding on the short fiber content (SFCn%) of the selected bales.

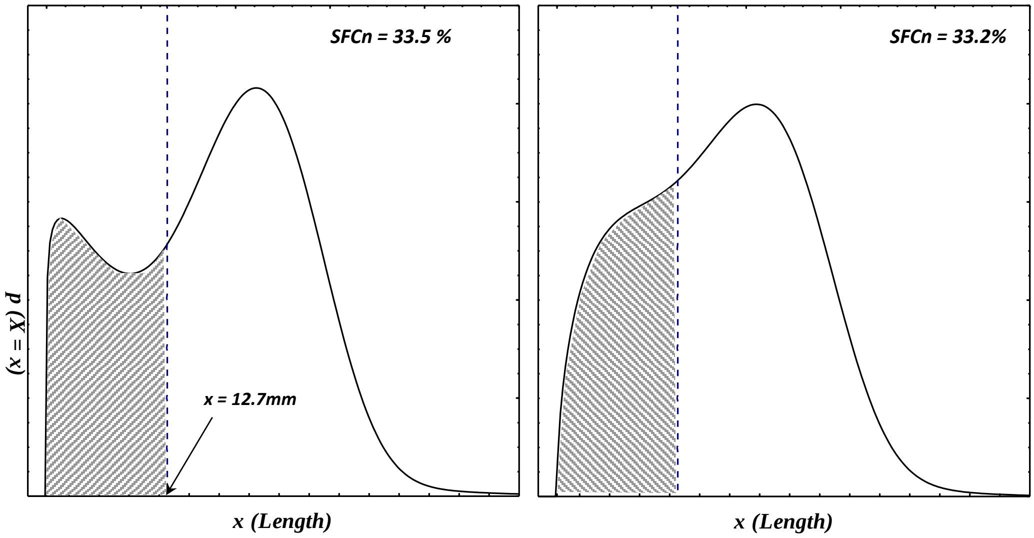

Figure 7: Length distribution is altered by the process but the SFCn% remains virtually unchanged.

3.2. Length distribution modality

Examination of the length distributions of the wide range of cottons observed revealed complex patterns with typical features and interactions with other fiber properties. As seen in Figure 5, some tested bales showed clear evidence of bimodality while others showed essentially unimodal patterns (when considering raw fiber samples). The first group (bimodal pattern) appeared to correspond to cottons with relatively high strength and maturity levels. The latter group (unimodal distributions) was mainly constituted of immature and weak cottons. Figure 8 illustrates the derivation of the DIP statistic for cotton bales from each of the two groups. In addition to the best fitting unimodal used to derive the DIP statistic, we represented on each figure the two-component mixture distribution fits corresponding to each cotton (Krifa, 2008, 2009). Obviously, the latter show a better fit to the observed data, particularly for the distribution exhibiting evidence of bimodality. However, the discrepancy between the observed distribution and the unimodal fit represents useful information since it constitutes the modality measure, i.e., the departure from unimodality or DIP statistic as defined by Hartigan (Hartigan and Hartigan, 1985; Hartigan, 1985). Figure 8 shows clearly that the distribution pattern of the immature-weak cotton (F) is characterized by a lower DIP value than the mature-strong cotton (E).

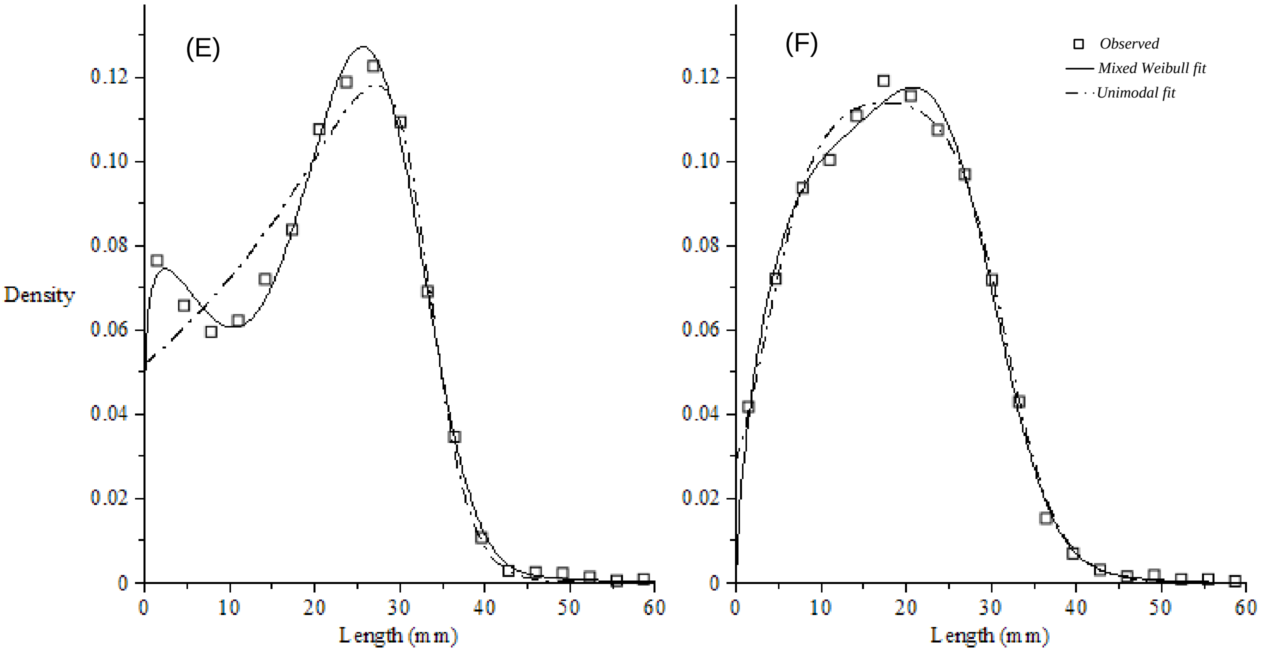

Figure 8. Examples of unimodal and mixed Weibull fits for two cotton samples with differing degrees of departure from unimodality: (E) DIP=0.011, and (F) DIP=0.0027.

Departure from unimodality results (DIP statistic) obtained on the four bales listed in Table 1 are depicted in Figure 9 for raw, card chute and card sliver samples. The results in Figure 9 show the overall tendency of the distribution’s departure from unimodality to increase with fiber strength and maturity (A<B<C<D). In addition, significant variations are also apparent within cotton and between processing stages for bales B, C, and D, more particularly when considering card sliver vs. raw and card chute fiber. Thus, unlike the short fiber content (SFCn%), the quantitative measure of the distribution modality does reflect the alteration of the length distribution under the effect of mechanical damage during carding. We confirm this result by examining the relationship between DIP results before and after processing using the entire range of cotton bales tested (Figure 11).

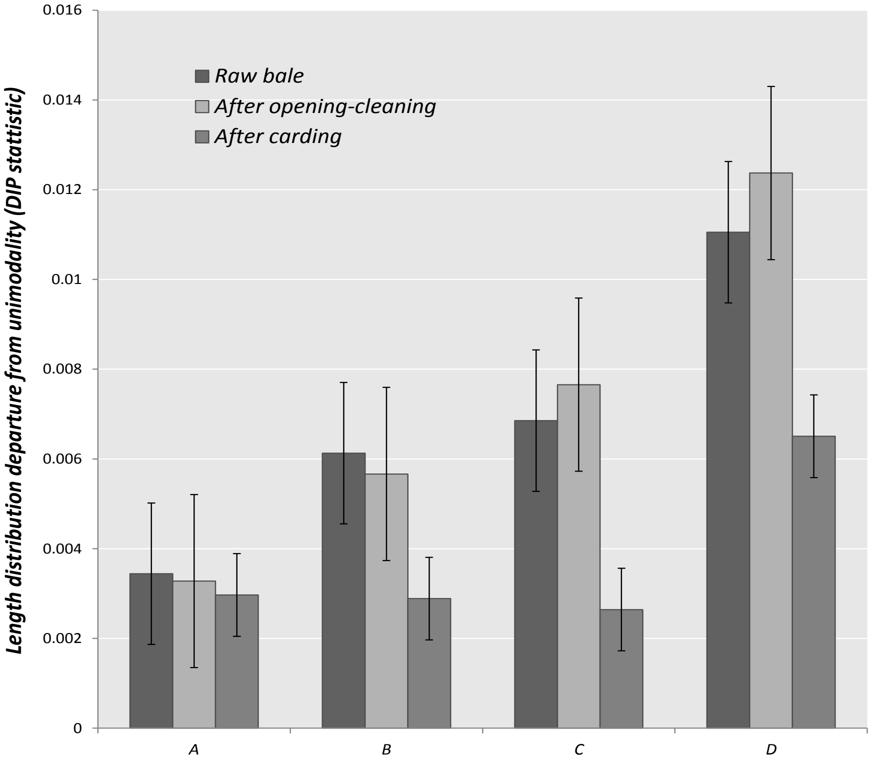

Figure 9: Effect of opening-cleaning and carding on the length distribution departure from unimodality (DIP) of the selected bales

Figure 11 shows the effects of opening-cleaning and carding processes on the length distribution modality for all the bales tested. As done previously for AFIS length parameters (Figures 2, 3, and 4), the effect of each process is represented by the relationship between the parameters measured after processing and those measured in raw fiber samples (i.e., each scatter plot represents the cumulated effects of all mechanical handling from the bale to the corresponding process).

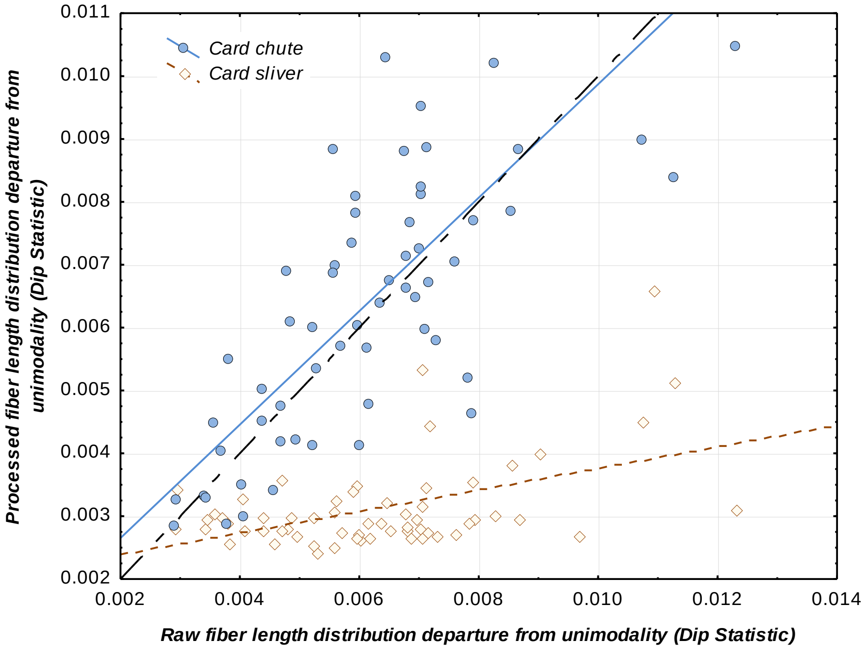

Figure 10: Effect of spinning preparation on the length distribution modality

It appears clear from Figure 11 that among the processes considered in these trials, carding is the one engendering the most substantial alteration of length distribution. The distribution departure from unimodality (DIP statistics) is representative of this alteration. Figure 11 shows a clear decrease in the DIP statistic observed after carding. Furthermore, it appears obvious that unlike the initial raw samples, the fibers in the carded samples (damaged fiber) show very small variations in the length distribution modality. These results suggest that after carding, i.e., when subjected to sufficient mechanical damage, all cottons tend to show a length distribution with no evidence of bimodality (regardless of the initial distribution modality). Therefore, depending on the point of the cotton process at which the length distribution is observed, the modality feature can be more or less discriminative between cottons. Only few exceptions, consisting of the strongest cottons (e.g., bale D above) still show a sizable departure from unimodality (DIP>0.05). The relationship between fiber strength and departure from unimodality at different steps of the process is considered in the following paragraph.

3.3. Dependence on fiber strength

Results obtained on the entire range of cotton bales we tested show a clear dependence between the modality measure and fiber strength, with mature-strong cottons showing higher DIP values when considering raw fiber samples. Figure 11 contains a scatter plot relating the length distribution modality measure (DIP) obtained on bale samples (raw cotton, bold point markers), and on card sliver samples (empty triangle point markers), to HVI fiber strength.

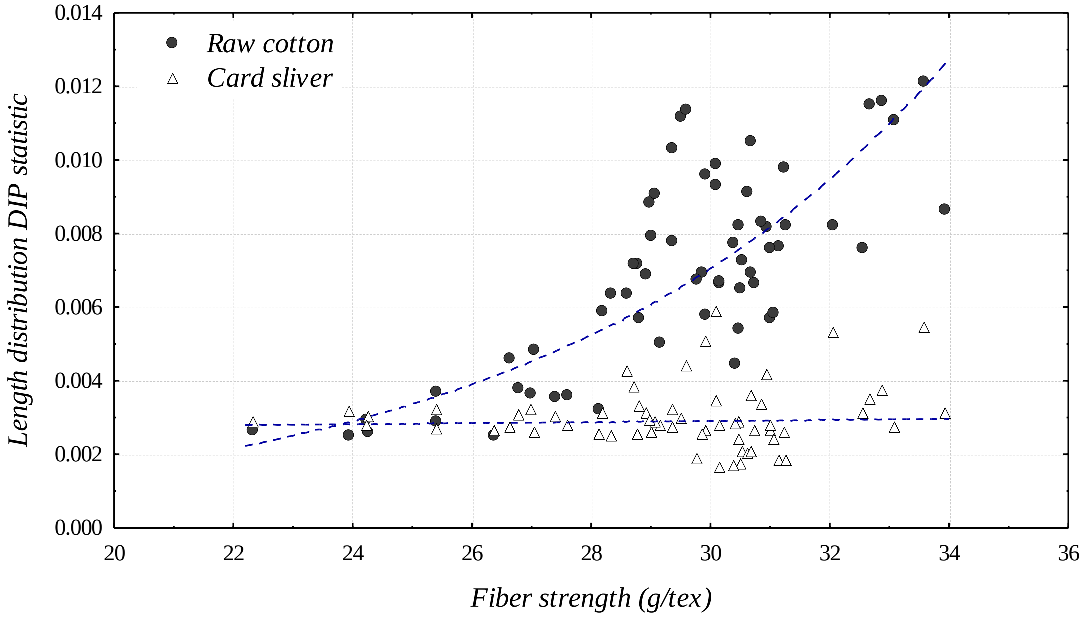

Figure 11: Length distribution modality of raw and opened-carded cotton vs. fiber strength

The scatter plot corresponding to the raw samples exhibits a curvilinear trend with a larger scatter towards high strength levels. This pattern suggests that low strength levels are associated with a fiber length distribution that is virtually unimodal (low DIP values). Cottons with high strength, on the other hand, show overall higher DIP statistic values that appear more dispersed. Figure 11 also shows that when subjected to sufficient mechanical damage, even mature-strong cottons exhibit a low DIP statistic, i.e., length distributions with no evidence of bimodality. Indeed, the scatter plots of Figure 11 show that unlike bale samples (raw cotton), fiber collected after opening-cleaning and carding (card sliver) show virtually no variation in the length distribution modality. The regression relating the DIP statistic obtained on card sliver samples to HVI fiber strength appears perfectly flat, with a slightly larger scatter at high strength levels.

It is well-established that strength and maturity are closely related to the fiber resistance to mechanical damage, and hence to its propensity to break. Thus, the observed dependence of the length distribution pattern, its modality in particular, on these properties is likely to be the reflection of fiber damage and breakage during the upstream processing stages.

4. CONCLUSION

Distribution modality appeared as a prominent feature of raw cotton fiber length. In order to characterize it during the spinning preparation process, we used the DIP statistic, which measures departure from unimodality. Unlike some common parameters provided by the measurement instruments (mean length, short fiber content) which failed to describe the alteration of length distribution, the modality measure was closely related to the degree of fiber damage: the higher the damage, and the lower the departure from unimodality, i.e., the lower the DIP statistic.

Thus, the distribution modality measured on raw cotton samples may offer a means of assessing the degree of fiber damage. On the other hand, samples observed after further processing and particularly after carding, show very small variations in the length distribution modality. Therefore, depending on the point of the cotton process at which the length distribution is observed, the modality feature can be more or less discriminative between cottons. Consideration of the length distribution modality at advanced stages of the cotton process (e.g., after carding) will not allow discriminating between cottons. On the other hand, earlier in the process (e.g., bale cotton), the distribution modality differs significantly from a cotton to another. In particular, a unimodal length distribution observed in the early stages of the cotton chain (raw cotton) is an indication of low resistance to breakage (immaturity, low strength), or/and inadequate upstream processing (ginning, lint cleaning…).

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