Improvement of the cotton fiber length measurements using High Volume Instrument (HVI) fibrogram

by

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ABSTRACT

Within-sample variation in cotton fiber length is an important parameter to consider when explaining variation in yarn quality. However, the most widely used cotton fiber length parameters, Upper Half Mean Length (UHML) and Uniformity Index (UI), provided by the High Volume Instrument (HVI), do not characterize the total within-sample variation in fiber length. HVI fiber length measurements are based on the fibrogram principle where a fiber beard is scanned over a beam of red light from 3.81 mm away of its base to the tip and a detector is used to measure the amount of light attenuated across the fiber beard which generates a curve called the fibrogram.

Fibrogram curves are not reported in regular HVI output. However, it can be exported from native HVI software as vector graphic images when samples are measured in module testing mode. A method was developed to extract the data that were used to generate the fibrogram curve. This allows statistical analysis to be performed on the whole fibrogram curve, without loss of information.

Initial investigation of UHML and UI was conducted using 19,628 commercial bales. Obtained results reveal that the typical HVI length measurements are not characterizing unique types of length variation in the fiber beard. Fibrogram measurements taken from a subset of 538 of commercial samples were used to identify independent types of fiber length variation characterized by the fibrogram that are not currently being characterized by UHML and UI. The results obtained suggest that the HVI fibrogram does capture additional within-sample variation in fiber length that is not being currently reported. Two additional sets of samples were then used to evaluate the importance of this currently unused information about length variation. Partial Least

Square Regression (PLSR) models were used to determine the importance of this new information as a tool for explaining variation in yarn quality. The four PLSR models were designed as follows: the first model contains only non-length HVI parameters, the second model contains the current HVI length parameters along with all the non-length HVI parameters, the third model contains fiber length variation captured by the fibrogram along with non-length HVI parameters and the fourth model contains fiber length variation captured by the Advanced Fiber Information System (AFIS, length by number) along with non-length HVI parameters. The results presented here suggest that the additional variation captured by the fibrogram provides better yarn quality prediction (Model 3) than current HVI length parameters (Model 2) and are comparable to the results obtained using the AFIS length distribution by number (Model 4). The PLSR models were then validated using a leave-one-out cross-validation and they show that the models built with information extracted from the fibrogram are better at predicting yarn quality than models with the most commonly used HVI length parameters. These results suggest that the information from the fibrogram is at least as good as the AFIS length distribution by number when characterizing variation in yarn quality.

While the additional information provided by the whole fibrogram could provide a new tool to breeders for selecting their breeding lines and spinners for purchasing cotton bales, fibrogram measurements are not calibrated to be used across cotton industry. In this study, a method of correcting the whole fibrogram curve across HVIs using a set of 529 commercial samples was developed. Validation of the correction procedure was also investigated by using an independent set of 932 commercial samples. The results obtained show that it is possible to bring the fibrogram curves measured by

multiple instruments into an agreement through multivariate correction. It indicates that it may be possible to use the whole fibrogram to improve HVI fiber length measurements across the cotton industry.

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CHAPTER 1

INTRODUCTION

1.1. Cotton production

Cotton is the dominant natural fiber used by the textile industry worldwide. The genus Gossypium contains 49 species; among them, four species were domesticated independently in different regions of the New World (*G. barbadense and G. hirsutum*) and Old World (*G. arboreum and G herbaceum*). Early domestication of these four species focused on their lint producing characteristics. Cotton seeds are also a source of high-quality vegetable oil for human consumption and a source of proteins and fibers for animal feed (Wakelyn and Chaudhury, 2010). G. barbadense, a New World species, produces long, strong, and fine fibers that are ideal for high-quality end products (yarns and fabrics). However, this species contributes low amounts to the world cotton production (less than 5%). Due to the agronomic superiority, and higher quality fiber, *G. hirsutum* has supplanted the other domesticated cotton species. It accounts for more than 95% of the total cotton production in the U.S. (Fang et al., 2016; USDA ERS, 2019).

Commercially, cotton is grown in more than 80 countries. Among them, China, India, The United States, Brazil, Pakistan, Turkey, Australia, and Uzbekistan are the cotton-producing countries with the largest production. The United States of America, China, and India together provide two-thirds of the total world cotton production (USDA, 2019). In the 2018 production year, China produced 6,040 thousand metric tons, India 5,350 thousand metric tons, and the U.S. 3,999 thousand metric tons (ICAC, 2019) (Figure 1. 1).

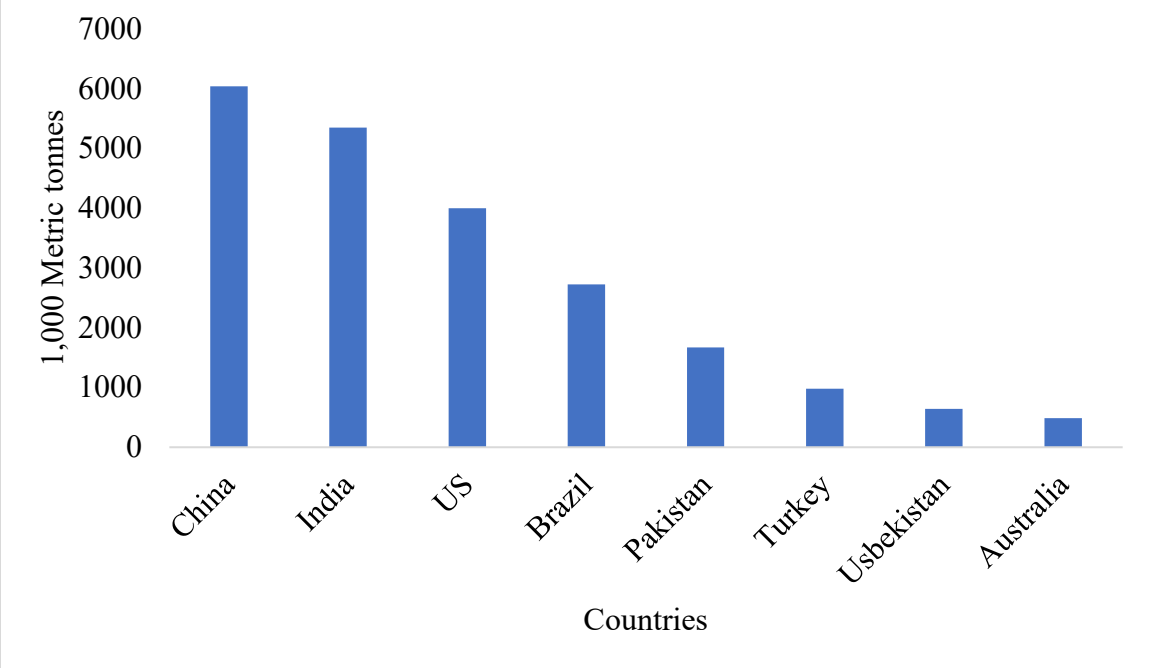

Figure 1. 1: Leading cotton producing countries in 2018/2019 (ICAC, 2019)

Many countries (~150) are involved in cotton production, exports and imports. The United States is the number one cotton exporting country followed by Brazil and India (ICAC, 2019). In the 2018 crop year, the US exported 3,214 thousand metric tons. Brazil, the second-highest cotton exporting country, exported 1,446 thousand metric tons that year (Figure 1. 2).

Asian countries import most of the cotton produced worldwide. China, Bangladesh, and Vietnam are the leading cotton importing countries in Asia. Though China is the leading cotton-producing country, it imported 2,100 thousand metric tons of cotton lint in 2018, making it the largest importer. China is followed by Bangladesh, which imported 1,544 thousand metric tons the same year (Figure 1. 3) (ICAC, 2019).

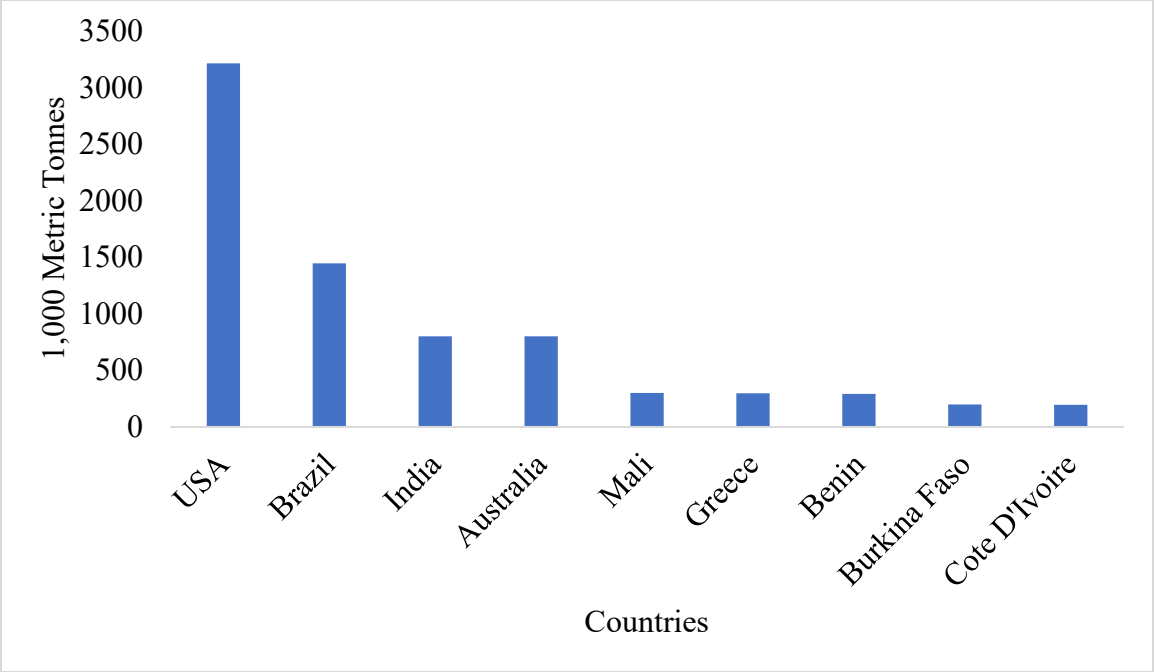

Figure 1. 2: Leading cotton exporting countries in 2018 crop year (ICAC, 2019)

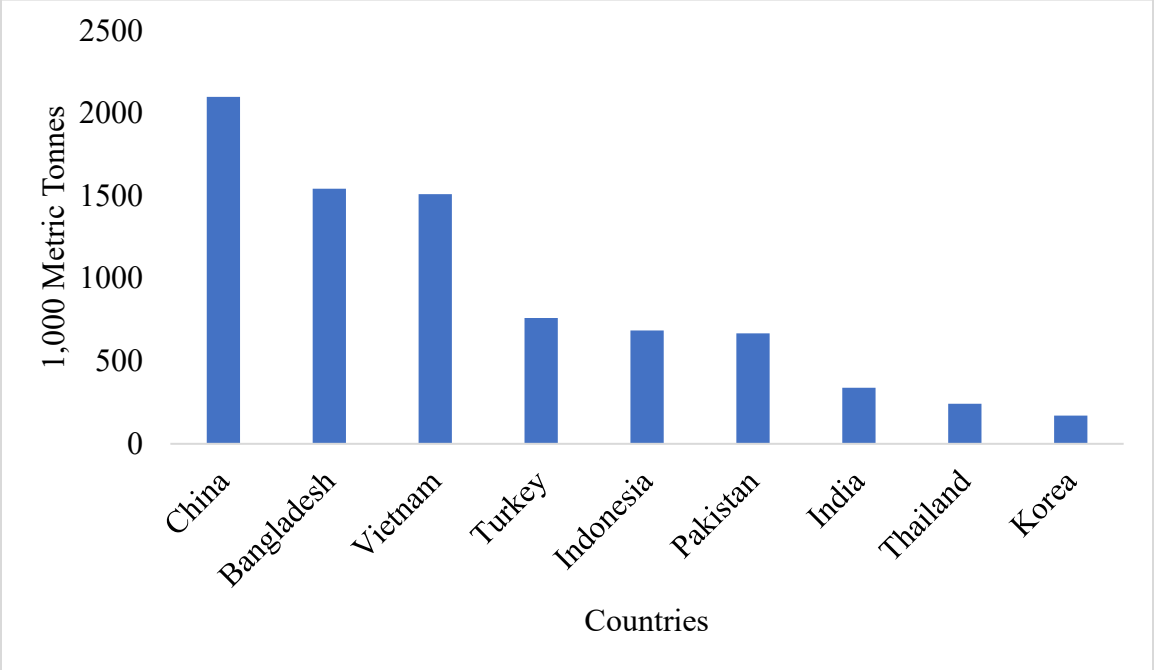

Figure 1. 3: Leading cotton importing countries in 2018 crop year (ICAC, 2019)

1.2. US cotton production

Cotton is among the most important cash crops in the U.S., generating more than $21 billion a year and over 125,000 jobs from farms to textile mills (USDA ERS, 2, 2019). Each year, 15 to 20 million cotton bales are produced in the U.S. Texas produces the most cotton of total U.S production followed by Georgia and Mississippi among 17 cotton-producing states in the U.S.

In 1997, at its peak, the U.S. textile manufacturing consumed approximately 11 million bales of cotton, most of which were grown domestically. The textile industry in the U.S. was predominantly focused on rotor spun yarn. Due to the decline of the U.S. textile industry, domestic cotton consumption declined. At its lowest point in 2011, the consumption of cotton in the U.S. was 3.3 million bales. Reduced use of cotton by U.S. domestic textile mills led to an increased reliance on the international market for US-grown cotton. In the 2018 production year, the U.S. exported 3,214 thousand metric tons (81.79%) of cotton while it produced 3,999 thousand metric tons (Figure 1. 4) (ICAC, 2019; Cotton outlook, Feb 2019). In order to be competitive in the international marketplace, the U.S. cotton growers must produce cotton with a quality profile suitable to meet the demand from their targeted textile industry (Kelly et al., 2015).

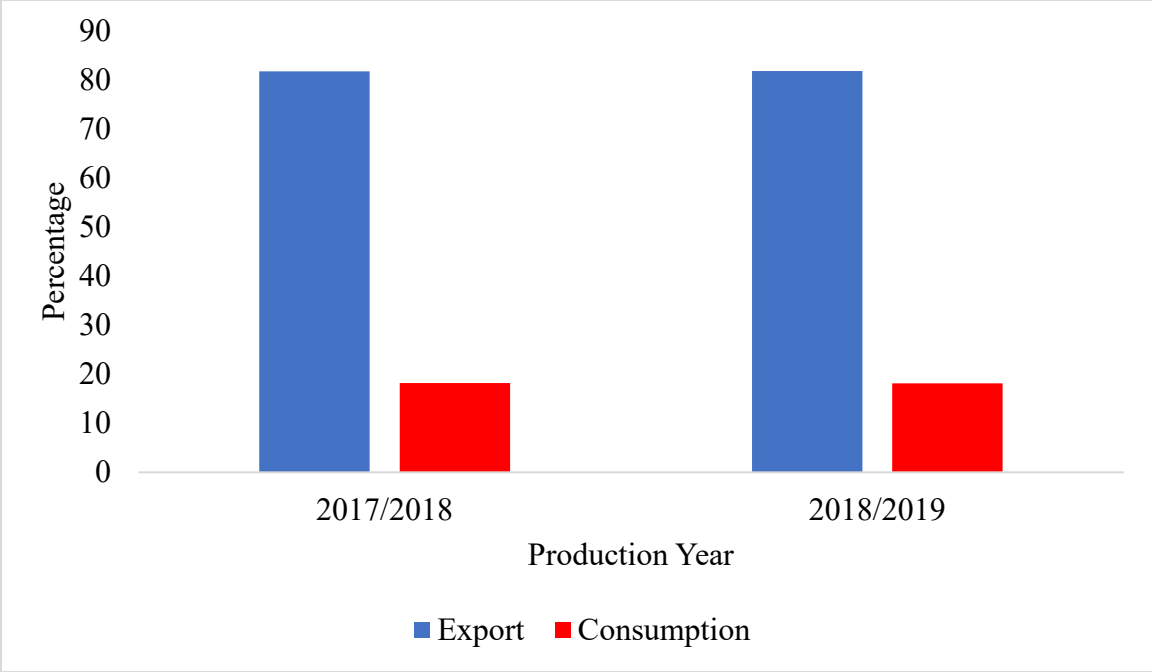

Figure 1. 4: U.S. cotton situation showing the percentage of domestic consumption and international exports.

Reliance on international markets resulted in different requirements for fiber properties. In the global market, ring spinning is dominant, which requires a certain fiber quality profile to produce finer and stronger yarns. Ring spinning requires higher quality cotton than rotor spinning. For example, ring spinning is more sensitive to short fiber content than rotor spinning (McCreight et al., 1997). The base for fiber quality, which includes length, length uniformity, strength, micronaire, color, and trash, is higher in the international ring spinning market compare to the U.S. base (Estur, 2004). Therefore, to be competitive, the U.S. cotton growers should focus on producing fiber quality that meets the demand of the international market.

Developing cotton germplasm with improved fiber quality that meets the demands of the textile mills is a responsibility of the cotton breeder. For many years, the High

Volume Instrument is being used as the primary instrument to determine the price of cotton. While HVI is the sole source of fiber quality data for many cotton breeders, other instruments are available. Fiber quality testing instruments such as Advanced Fiber Information System (AFIS), Cottonscope, FAVIMAT, and fiber cross-section image analysis provide important measurements that help determine the potential processing performance and yarn quality of the fiber (Kelly and Hequet 2012; Rodgers et al., 2012; Thibodeaux et al., 1999). For example, the complete fiber length distribution is among the most crucial fiber quality parameters, because it impacts almost all yarn quality parameters (El Mogahzy, 1999; Kelly, Hequet and Dever, 2012; Kelly and Hequet 2012).

While the AFIS length distribution is an important measurement that illustrates the importance of measuring within sample variation in fiber length, it is slow and too costly for many breeding efforts. The HVI is a faster test but does not provide the distributional fiber length measurement. As a result, within sample variation in fiber length is often not a consideration in germplasm improvement or marketing.

1.3. Cotton fiber development

Cotton fiber, or cotton lint, originates from a single epidermal cell on the surface of the ovule that undergoes the following developmental stages (Wilkins and Jernstedt 1999; Abidi et al., 2010; Stewart, 2010; Haigler et al., 2012):

- Differentiation,
- Initiation,
- Elongation,
- Secondary cell wall formation,

- Maturation

Together, these developmental stages typically last at least 50 days and have a direct impact on cotton fiber quality characteristics.

1.3.1. Initiation

Fiber initiation starts on the day of anthesis when the flower is open for pollination. The initiation stage lasts only a day for each fiber. However, the overall initiation phase could last for 5 to 6 days post-anthesis (DPA) because of several waves of fiber initiation (Stewart, 1975; Lee et al., 2007). The second series of fibers initiation results in fuzz fibers (Basely, 1977). Fuzz fibers are short fibers left on the surface of the cotton seeds after separating the lint from the seeds by ginning. While these fibers are an important source of cellulose, they are not spinnable and are not a focus of this research.

1.3.2. Elongation

The second stage of fiber development is elongation. The fiber elongation phase starts from 2 to 3 DPA and lasts until 18 to 24 DPA (Ruan et al., 2004; Abidi et al., 2008). The fiber elongation rate, and ultimately fiber length, depend on both environmental and genetic factors (Basra 1999). The maximum rate of fiber elongation occurs between 6 DPA to 12 DPA (Meinert and Delmer, 1977; Basra and Saha, 2000). Meinert and Delmer found relatively constant primary cell wall thickness until 12 DPA, after that the cell wall thickness increases gradually (Meinert and Delmer, 1977).

The elongation phase is strongly affected by the turgor pressure surrounding the vacuole (Naithani et al., 1982; Gokhani and Thaker, 2002; Seagull, 1992; Wilkins and Jernstedt,

1999). Surrounding temperature also has a significant influence on the final fiber length of a cultivar (Wanjura and Barker, 1985; Cotton Physiology today, 2001).

The initial fiber diameter is set up at the time of fiber initiation, though it may increase a little bit through the elongation phase. Thus, the elongation phase not only includes the extension of fiber length; it can include an increase of fiber diameter (Boylston et al., 1990; Bradow et al., 1996; 1997).

1.3.3. Secondary cell wall formation

Cellulose then begins to be deposited on the internal surface of the primary cell wall forming the secondary cell wall (SCW). The composition of SCW begins even before the elongation phase ceased, but the elongation phase does end shortly after the SCW development begins (Benedict et al., 1973). Typically, SCW thickening starts around 18 DPA to 24 DPA, but it varies from variety to variety and continues until the boll opens (50 to 60 DPA).

The developing fibers from 24 to 44 DPA consist of highly organized beta-1,4-glucan chains called cellulose microfibrils (Kim et al., 2017). This is an almost pure source of cellulose (Haigler, 2010). Cellulose deposition changes its direction periodically to form twisted reversal regions (Seagull, 1992; Haigler, 2010). The percentage of cellulose in the fiber cell can double in one day, Meinert and Delmar found this occurring between 16 and 17 DPA (1977). The final thickness of the cell wall can reach 10 μm.

1.3.4. Maturation

Most of the US-grown upland cotton reach their full fiber maturity from 40 to 50 DPA (Kim et al., 2017). The cylindrical fibers collapse after boll opening due to the removal of lumen fluid and intermolecular water in cellulose (Basra and Malik, 1984). This desiccation causes the cellulose molecules to form intermolecular hydrogen bonds (Ingram, 1974; Hsieh, 2007). These intermolecular hydrogen bonds cause irreversible morphological changes that increase the molecular strains and reduce chain mobility.

1.4. Mechanical processing

Cotton fiber quality is highest on the day of boll opening. After that day, weathering, harvesting, ginning, and storage conditions can negatively impact fiber quality, which ultimately reduces the profits for the cotton producers as well as for the textile mills (Armijo et al., 2006; Hughs et al., 2013).

1.4.1. Harvesting

The traditional way to remove seedcotton from plant is hand harvesting. Hand harvesting is better at preserving fiber quality than most harvesting methods and incorporates lower amounts of unwanted materials (Sui et al., 2010). However, this technique is time-consuming and cannot be applied for commercial production in large acreages in the United States. Stripper machine harvesting and picker machine harvesting are two popular harvesting techniques used across the cotton industry in the industrialized world.

Picker harvesting removes the seedcotton from the open bolls with a rotating spindle that snares the fiber. Because only the fiber is caught, this method results in less unwanted materials in the harvested seedcotton compared to mechanical stripping. Picker

harvested cotton can include from 5 to 10% foreign material (Faulkner et al., 2011a; Wanjura 2012). As a result, picker harvested cotton requires less cleaning, resulting in a better fiber quality profile with reduced short fiber content, neps, foreign matter, and increased micronaire, length and length uniformity (Wanjura, 2012, 2017, 2019; Faulkner et al., 2011b)

Cotton stripper harvesting removes both mature and immature bolls using a combination of brushes and bats that knock the plant material into the harvesting mechanism. Unopen bolls and any leaf that are left on the plants can be incorporated into the harvest, resulting in an excessive amount of unwanted materials (Tupper, 1996; Wanjura, 2019). Stripper harvested cotton can contain from 15 to 25 % trash and will require higher level of cleaning during ginning. Cleaning processes are aggressive and break fibers, resulting in a poorer fiber quality profile compared to picker harvested cotton (Faulkner et al., 2011a; Wanjura 2012).

1.4.2. Ginning

Ginning is the process of preparing marketable bale fibers and seeds for oil extraction and/or animal feed from seed cotton. Ginning is not simply a process of removing fibers from a seed. Ginners need to remove the foreign matter from the lint, which may negatively impact lint value through fiber breakage.

While aggressive lint cleaning will remove most of the foreign matter from the lint, it will break the fibers and produce a high level of short fibers in the sample, which will result in profit loss for growers (Armijo et al., 2019). Aggressive lint cleaning will also improve the visual appearance of the fibers but will damage fiber quality and reduce the bale weight due to the removal of some fibers with waste (Mangialardi, 1985;

Anthony, 1988; Hardin et al., 2018). On the other hand, a low level of cleaning could leave the fibers with an excessive amount of foreign matter that could ultimately impact yarn quality. Therefore, proper practice of cleaning during ginning is required to preserve the fiber quality such as length and length uniformity and also clean the lint at an acceptable level.

1.4.3. Storage

Excessive moisture content in the cotton lint during storage impacts the fiber properties and visual appearance (Chu and Anthony, 2004). Due to increased activity of microbial organisms during storage at a high level of moisture, fibers could become more fragile. During further processing, these fibers will break more frequently and impact yarn quality (Chu and Anthony 2004).

1.5. Yarn Processing

Spun yarn quality is determined by the fiber quality and the type of spinning process being used (Moghazy et al., 1990; Ethridge and Krifa, 2004). The production of spun yarns from raw cotton fibers requires a series of steps.

1.5.1. Sliver preparation

Sliver preparation is necessary in all three dominant spinning technologies: ring spinning, open-end rotor spinning, and vortex or air-jet spinning. Sliver preparation includes several steps such as opening, blending, carding, and drawing. Sometimes, combing is done in order to remove short fibers to produce high-quality textiles. After sliver preparation, roving is required only for the ring spinning system. The main difference among the spinning technologies is how the fibers from the sliver are twisted.

1.5.1.1. Opening and blending

Spinning mills purchase many cotton bales which are contaminated by different types of foreign materials such as trash and motes. Spinners blend multiple bales generally from 30 to 80 bales to form a laydown, but cotton fiber quality varies among the bales and within a bale in a laydown. Efficient yarn production requires a high throughput of consistent fiber quality. Therefore, to minimize the within-sample variability, cotton bales in a laydown need to be well blended (El Moghazy and Chewning, 2001; Wakelyn, 1997; Szaloki, 1976).

A certain number of bales are identified using the EFSTM (Engineered Fiber Selection) software (or a similar software) and mixed to produce a given yarn quality (El Moghazy and Chewning, 2001). Bale ties are removed 24 hours prior to arrange them in the laydown. A bale plucker continuously picks small tufts of fibers from each bale and a series of machines are used to clean and blend these loose fibers delivered by the plucker.

1.5.1.2. Carding

After cleaning and several rounds of blending, cotton fibers are delivered to the carding machine for further processing. The carding action is composed of three wire-covered cylinders and a flat series of wire-covered bars. Lint cleaning by the carding machine is the final cleaning stage before yarn formation if no combing is used. The carding machine makes a thin web of fibers with a low variation in mass that is passed through a trumpet, or highly polished cone, creating a sliver. The slivers are temporarily stored in a can for transport to other processing stages (Kelly et al., 2015; Lawrence, 2007).

1.5.1.3. Drawing

The slivers in the cans are transported to the drawing frame to improve the uniformity in mass and make the fiber parallel to the axis of the sliver. Generally, several cans of slivers are drafted and blended together to produce single slivers with straightened fibers. This sliver is then again stored into cans for the second stage-drawing, or finisher-drawing, if needed. The drawing process improves the sliver evenness that will eventually reduce the thin and thick places in the yarn (Hunter, 2007; Oxtoby, 1987).

1.5.1.4. Roving

The weight per unit length of the sliver is reduced (typically one-eighth of the original sliver) to produce a package of fibers that are suitable for delivery to and processing through the ring spinning frame (Seagull and Alspaugh, 2001). Three drafting rollers, similar to the ring spinning drafting zone, are used to make roving bobbins. The fibers from the slivers are slightly twisted just to hold the fibers together and transferred them to a roving bobbin.

1.5.2. Spinning

Spinning is the process of converting fibers from the loose slivers, or roving, into twisted fine and stronger yarn. The consumer's demand for high-quality apparel increases while textile mills want to reduce the production cost in order to be competitive in the market. However, mills face increasing labor costs and high raw material costs. These factors force mills to adopt newer technologies to produce high-quality yarn with a higher production rate. Increased production rates can result in higher levels of stress on fibers and yarns during processing. While fiber quality requirements depend on the type of

spinning system to be used and on the type of yarn that will be produced, mills generally require fibers that are longer and stronger with a better length uniformity (Suh and Sasser, 1996). Table 1. 1 shows the most important fiber properties for different types of spinning technology (Suh and Sasser, 1996).

Table 1. 1: The spinning system and required fiber properties

Ring	**Rotor**	**Air-jet**
Length	Strength	Length
Strength	Micronaire	Strength
Micronaire	Length	Length Uniformity
Length Uniformity	Length Uniformity	Micronaire

The most dominant spinning technologies for cotton are ring and rotor spinning. These two spinning systems together account for more than 90% of the total global yarn production (ITMF, 2014). Ring spinning alone contributes approximately 73% of the global short staple yarn production while the rotor accounts for 23% (ITMF, 2014).

1.5.2.1. Ring Spinning

In ring spinning, the slightly twisted fibers from roving are fed into the ring spinning frame drafting zone. The speed of the drafting zone is determined based on the yarn count that will be produced. The desired twist needed to produce strong yarn is provided by the spinning spindle. A small piece of metal or ceramic that spins around the ring, a traveler, controls the orientation of the yarn between the spindle and the ring

(Kelly et al., 2015). Figure 1. 5 shows a typical ring-spinning frame at the Fiber and Biopolymer Research Institute, Texas Tech University.

Ring spinning systems produce the highest quality of yarn with a wide range of yarn counts (EI Moghzy and Chewing, 2001; Shao et al., 2019). For any given yarn count, longer and stronger fibers will efficiently produce higher-quality yarns as they require less twist (Kelly 2015). Poor fiber quality can also contribute to imperfection and processing problems.

Figure 1. 5: Ring spinning frame (Suessen Fiomax 1000) at Fiber and Biopolymer Research Institute, Texas tech University.

The cost is higher for ring spinning because it requires significantly more human participation than any other technology and is lower throughput than many modern alternatives. Therefore, ring spinning mills often focus on the production of finer, higher-value yarns (EI Mogahzy, 1995).

1.5.2.2. Open-end rotor spinning

Rotor spinning is almost fully automated and is used to produce coarser yarns such as denim yarns (Cheng and Murray, 2000). It does not have the same material demands as ring spinning in terms of fiber quality, and the spinning technology has a higher throughput than ring spinning (Huh et al., 2002).

Slivers from the drawing frame are directly used for the production of rotor spun yarn. This spinning system does not require roving or winding. Figure 1. 6 shows an open-end rotor spinning frame at the FBRI, Texas Tech University. The Rotor spinning provides more even yarns compared to ring spinning and neps problems are less prominent (Kelly et al., 2015). However, rotor spun yarns are generally weaker than ring-spun yarns (Manohar, 1983; Cheng and Cheng, 2004).

Figure 1. 6: Open end rotor spinning frame (Rieter R20) at Fiber and Biopolymer Research Institute.

1.5.2.3. Airjet/Vortex Spinning

Due to the increase in labor cost even in Asia, textile industries are looking for an alternative spinning technology to lower the production cost. Airjet spinning is an automated spinning technology (Figure 1. 7) that provides a high quality of yarn, similar to ring spinning with a greater production rate (Ortlek et al., 2004; Erdumlu et al., 2009, 2012). But this spinning system requires long, strong and very uniform fibers to be processed (Gordon, 2002). The development of cotton germplasm with improved within-sample variation in fiber length is required to fit the raw material needs of mills using this technology.

Figure 1. 7: Airjet spinning frame (Muratec, Vortex II 870) at Fiber and Biopolymer Research Institute, Texas Tech University.

1.6. Cotton fiber quality

1.6.1. Fiber length

Cotton fiber length was the first fiber quality parameter used to understand how cotton will perform during yarn processing (May, 1999). Cotton fiber length is considered as the main contributor to yarn strength and processing performance, and has been used since mechanical spinning frame development (Brown, 1938; Perkins et al., 1984; May, 1999). Given all other fiber quality parameters being equal, longer fibers require less twist resulting in stronger yarns than yarns produce from shorter-staple fibers (El Mogahzy and Chewning, 1990; Azzouz et al., 2008; May 1999). A premium is paid for bales with longer staple lengths (CCC, 2019). Thus, it is among the most important fiber quality parameter in both marketing and processing (Brag and Shofner, 1993).

Breeders utilize cotton fiber length to select breeding lines and ultimately produce varieties that fulfill the demands of textile mills (Kelly et al., 2013) while spinners use fiber length to get the bales that best meet their demands from the market and to determine the proper settings for the mill equipment (Moghazy, 2001). During yarn manufacturing, the distance between rolls for drafting is set based on fiber length (Behery, 1993).

It is not just the longer fibers in a sample that contribute to the quality of the end-product. The complete within-sample distribution of cotton fiber length contributes to a cotton's processing performance and, ultimately, the quality of yarn produced (Wakeham, 1955; Hequet & Ethridge, 2000). The changes to the longer fibers are not reliable indicators of fiber damage, while short fibers are better indicators of fiber damage due to breakage (Cui et al., 2000). Greater amounts of short fibers are found in weak and immature cotton and require excessive cleaning that can lead to fiber damage (Krifa, 2006; Thibodeaux, 2008). If there are more short fibers, then it is likely to produce yarns with more thick places and thin places. Short fibers can also slow mill throughput and lower profitability by increasing work stoppages due to ends-down.

1.6.1.1. Characterizing fiber length variation

The cotton industry has been using fiber length for evaluating fiber quality and uses length measurements in cotton marketing and research (Perkins et al., 1984). Before the development of instrumental measurement of fiber length, it was evaluated by cotton classers. Over time, several fiber length parameters have been used by the cotton industry (Cai, 2013). The influence of different fiber length parameters on yarn quality varies based on how they are measured and what types of fiber length variation are captured

(Cai, 2013). Because of the importance of fiber length, scientists are continuously working on devising instruments for accurate and quicker evaluation of cotton fiber length.

The fibrogram fiber length measurement developed by Hertel is one of the major steps towards the development of a faster fiber length measurement system (Hertel and Zervigon, 1936; Hertel, 1940). In 1936, Hertel and Zervigon developed a method for measuring the length of seedcotton fiber (Hertel and Zervigon, 1936). Later in 1940, Hertel developed a method for measuring the length of lint cotton fiber (Hertel, 1940).

Hertel's fibrograph fiber length measurement system made two major assumptions which are: 1) sampled fibers for fibrogram measurement are biased to its length, 2.) fibers are randomly clamped. Hertel's first assumption was valid for the fiber beards produced using a sliver sample (Krowicki, 1987; Zeidman, 1991). Fiber beards prepared from raw cotton using the fibrosampler are not length biased (Chu and Riley, 1997).

Fiber length measurement with Hertel's original fibrograph method was performed manually. Several developments had been done in order to automate the fibrograph measurement (Tallant 1952, 1958). To facilitate the direct readings of the measurement, Rouse (1958) coupled two dial gauges to the fibrograph. Hertel's original method was designed to measure Upper Half Mean Length (UHML) and Mean Length (ML) of the scanned sample (Hertel, 1940). Later, Hertel and Craven (1960) proposed a method of measuring span lengths with a digital fibrograph. Hertel designed a fibrosampler for sample preparation to eliminate the operator error and provide a faster

sampling method. The development of the digital fibrograph made the fibrogram measurement faster.

In 1969, the fibrograph was integrated with other fiber quality evaluating instruments in the design of an automated instrument named High Volume Instrument (HVI). The HVI allowed the cotton industry to quickly measure samples for several fiber quality parameters such as UHML, Uniformity Index (UI), Strength, Elongation, Micronaire, Color, and Trash.

The cotton industry needs detailed fiber quality information to implement new technologies for harvesting, ginning, and textile manufacturing in order to meet the demand for high productivity and high-quality end products. The interest in fiber length parameters went beyond the measurement of UHML and UI. There is also an ever-growing interest in the measurement of the percentage of fibers shorter than half an inch (Short Fiber Content). Currently, the HVI determines the length of the longest fibers in a sample. In 1993, the Advanced Fiber Information System (AFIS) was developed to measure individual fibers rather than fiber bundles or beards (Bragg and Shofner, 1993). AFIS provides the complete fiber length distribution along with some other important fiber quality parameters such as fiber maturity, fiber fineness, visible foreign matters (VFM), standard fineness, mean length (by number or by weight), upper quartile length (UQL by weight), short fiber content (SFC by number or by weight).

1.6.2. Fiber tensile properties: Fiber strength and elongation

HVI fiber strength is the measurement of the weight normalized force required to break the bundle of fibers and is reported in grams per Tex (g/Tex). Fiber strength is highly related to cellulose deposition and its organization during secondary cell wall

development (Seagull, 1992). The structural reversal of the secondary cell wall is the preferred location of fiber breakage due to mechanical stress (Ball, 1928; Wakeham, 1951).

Higher fiber strength results in higher yarn strength (Zhang et al., 2003; Farag and El Mogahzy, 2009). Cotton fiber strength may be measured on single fibers or a bundle. The Pressley cotton fiber strength tester was developed to rapidly determine cotton fiber strength (Pressley, 1942). A small bundle of fibers is inserted in the tester and a load is applied using a roller weight. The measurement of the load required to break the bundle is recorded manually. It is then expressed as Pressley Index (P.I) (ASTM D1445, 2012).

A flat bundle method of fiber strength testing system or Stelometer (strength and Elongation tester) was introduced in 1953. It was immediately accepted by the cotton industry due to its ease of use, speed, and ability to provide for the first time both strength and elongation. At first, the strength of cotton was measured with zero-gauge length and the result as expressed as Pressley Index (P.I). Later on, it was demonstrated that strength measured with a finite gauge length shows a better correlation with yarn strength (Worley et al., 1966). Therefore, the fiber clamping device was modified to include a gauge length of 3.2 mm (1/8 inch) on both the Pressley and the Stelometer. HVI, the U.S. cotton classing instrument, uses the Stelometer principle to measure fiber strength. The HVI is calibrated using the strength measurement from the Pressley tester because both HVI and Pressley measurements are based on constant force.

Elongation is the ability of a fiber or a bundle of fibers to stretch before it breaks due to mechanical stress. Fiber elongation directly impacts yarn elongation and yarn

work-to-break (Faulkner et al., 2012). Higher bundle elongation results in better yarn quality if all the other fiber qualities remain equal (Backe, 1996).

Due to the negative correlation between fiber elongation and fiber strength, cotton breeders did not show much interest in improving cotton fiber elongation (May and Taylor, 1998). Later on, Benzina and co-authors explain in detail the importance of simultaneous improvement of fiber strength and elongation (Benzina et al., 2007). They explained that the fibers with lower tenacity and elongation break more during ginning as well as during opening and carding, resulting in higher short fiber content. The stelometer is used to measure cotton fiber elongation. However, the current HVI system is not calibrated for elongation measurement, making it challenging to use in a research programs or cotton classification.

1.6.3. Fiber maturity

Fiber maturity is the determination of the cellulose deposition during secondary cell wall formation and its organization. A mature and open cotton boll could contain fibers with a wide range of fiber maturity (Feng et al., 2011). The variation in fiber maturity could occur within a single seed, within a boll, and due to an indeterminate growing habit of a plant (Feng et al., 2011).

Variation in fiber maturity negatively impacts textile products such as yarns or fabrics. Mature fibers are strong and break less during processing, while immature fibers produce short fiber content by breaking during processing. The presence of immature fibers in a sample causes uneven dye uptake and white specks in the fabric (Smith, 1991; Hequet et al., 2006).

1.6.4. Micronaire: maturity-fineness complex

Micronaire is the combined measurement of fiber maturity and fineness (ASTM D1448). The micronaire measurement is based on Darcy's law, where a laminar airflow passes through a plug of cotton fibers of known weight (Darcy, 1856; Kelly et al., 2015). Micronaire measurement is inversely proportional to the square of the specific surface area (Kozeny, 1927). The specific surface area of cotton fibers depends both on maturity and fineness (Lord, 1956).

Cotton fibers with the same micronaire values could have very different maturity values as well as different fineness (Hequet, 2007). This can happen if one sample contains immature and coarse fibers, while the second sample contains mature and fine fibers. Cotton with mature and fine fibers will perform better than cotton with immature coarse fibers.

1.6.5. Color and Trash

Cotton color degradation in the field shows the impact of weathering after the bolls open. Due to the indeterminate growth of the cotton plant, cotton bolls at different nodes form and open at different times (Feng et al., 2011). Farmers harvest cotton when most of the bolls are open. The cotton bolls which are opened earlier would be impacted more by the weather.

Variation in cotton color could be an indication of the problems caused by microbial deterioration. Several factors, such as rainfall, freezing, cotton plant leaves fragments, and fungal activities could impact cotton color. Differences in cotton color among bales in a laydown may affect dye uptake of yarns and fabrics. The HVI

colorimeter uses the Nickerson-Hunter diagram to report cotton fiber color (Nickerson, 1951).

Trash and contamination are unwanted foreign matter left within the cotton lint after ginning. The difference in trash content between samples could result from variation in harvesting practices and genetic differences such as leaf hairiness (Faulkner et a., 2011; Morais et al., 2020). The presence of excessive trash particles in a sample could impact the measurement of other fiber quality attributes (Peirce and Lord, 1939; Lord, 1955; Morais et al., 2020).

1.7. U.S. cotton classification and marketing

In 1907, a group of cotton industry representatives recommended a resolution to establish a uniform cotton standard which would eliminate the price differences among markets and put the cotton farmers in a better bargaining position for their production (Cotton Inc., 2015). In 1909, the United States Department of Agriculture (USDA) first developed two cotton standards for fiber length and color (Gordon, 2007). Before USDA cotton classification, cottons were sold based on the regional reputation.

Later, the U.S. cotton future act of 1914 set the rules for the standard cotton classification, which become mandatory in 1923 (Brown, 1938; O. May, 1996). Cotton was classed using length, color, preparation and non-lint content. Initially, cotton classification was performed manually by a cotton classer.

The development of instrumental fiber quality assessment systems allowed the cotton industry to measure several important fiber properties, which are essential to predict yarn quality. During the 1900s, several instruments were developed to measure

cotton fiber quality which includes the fibronaire for micronaire, the fibrograph for fiber length measurement, the colorimeter for reflectance and yellowness, and the Stelometer for fiber strength and elongation measurements (Hertel, 1936, 1940 and 1953; Perkins, Ethridge and Bragg 1984, Sasser and Moore, 1992). To facilitate cotton classification, the measurement principles used in these instruments were combined to engineer a high-speed testing instrument named the High Volume Instrument (HVI). Currently, USDA cotton classification is based on HVI which consists of the measurement of fiber length, length uniformity, strength, micronaire, color, leaf and cotton classers call on extraneous matters. All the cotton bales produced in the U.S. every year are measured with HVI for these fiber quality parameters.

The Commodity Credit Corporation's (CCC) loan chart provides base price, premium and discount information to the cotton market based on HVI fiber quality parameters provided by the classing report. The CCC loan schedule is formulated based on the average of the first seven months of Daily Spot Cotton Quotations (DSCQ) and the CCC loan value of the last year (Brown et al., 1995; Ethridge and Hudson, 1998). Farmers should produce cotton with higher length, higher strength, less yellowness, adequate micronaire, and the minimum amount of extraneous materials in order to get a premium based on the CCC loan chart.

1.8. Measurement of cotton fiber quality

It is important to measure cotton fiber quality to understand where a certain type of cotton could be used more efficiently. Cotton fiber quality is directly related to yarn quality (EI Mogahzy, 1990, 2001). The type of spinning technology being used is based on fiber quality. Several instruments are used to evaluate fiber quality for different

purposes. The standard test method for cotton fiber length is the Suter-Webb array method (ASTM, 2019). This method is obsolete. The two most common instruments, HVI and AFIS, are used by the cotton industry to evaluate fiber length along with other important fiber quality parameters.

1.8.1. High Volume Instrument (HVI)

HVI was developed to have an instrumental fiber quality measurement system in place of hand classing that could be used in the U.S. cotton classification and cotton marketing. It took more than 25 years to complete the HVI systems and to use them in cotton classification. The development of HVI started in 1955 when Carl Cox asked Glenn Witts to invent an instrument (Fibronaire) for automated micronaire measurement. In 1960, Dan Davis (general manager of Plains Cotton Cooperatives Association (PCCA)) and Mr. Witts worked together and installed three fiber testing lines at PCCA. Each line had stations to measure micronaire, color and leaf/trash (Sasser and Moore, 1992; Personal communication with Emerson Tucker).

In 1966, USDA and the cotton industry representatives agreed that cotton classing should include length, length uniformity, strength, micronaire, color and trash. Therefore, the measurement principles for fiber length (fibrograph) and strength (Stelometer) were incorporated into the design of the testing lines. A system that includes all these measurements was first installed at the Textile Research Center (now Fiber and Biopolymer Research Institute) at Texas Tech University Lubbock, Texas in 1969. In 1991, for the first time, all the cotton bales produced in the U.S. were classified with the HVI testing system (Sasser and Moore, 1992).

Much of the cotton industry now depends on HVI for fiber quality measurements. Along with the cotton classification and cotton marketing, HVI fiber properties are also used in research (Moore, 1996, Kelly and Hequet, 2013).

HVI is a composite instrument that takes measurements using a series of discrete steps designed to quickly evaluate different fiber quality parameters. HVI measures UHML, UI, strength, elongation, color, trash, reflectance, and yellowness. Compared to the other fiber testing instruments, HVI is faster and costs less per measurement and is beneficial to yarn manufacturers especially when combined with a bale selection software (Chewing, 1994). Figure 1. 8 shows a Uster HVI 1000 with all the stages labeled. Fiber quality characterization with HVI can be done with two operator modes:

1. **System Testing**: This operating mode provides regular fiber properties including UHML, UI, strength, micronaire, elongation color and trash. Instead of raw data, this system provides fiber quality data after calibration using two USDA standard samples.
2. **Module Testing**: This operator mode allows users to measure fiber qualities with three independent modules such as 1) Micronaire module testing, 2) Color and Trash module testing, and 3) Length and strength module testing. This system can provide calibrated fiber qualities as well as raw data. For example, length and strength mode can provide the raw fibrogram, which is used to calculate UHML and UI.

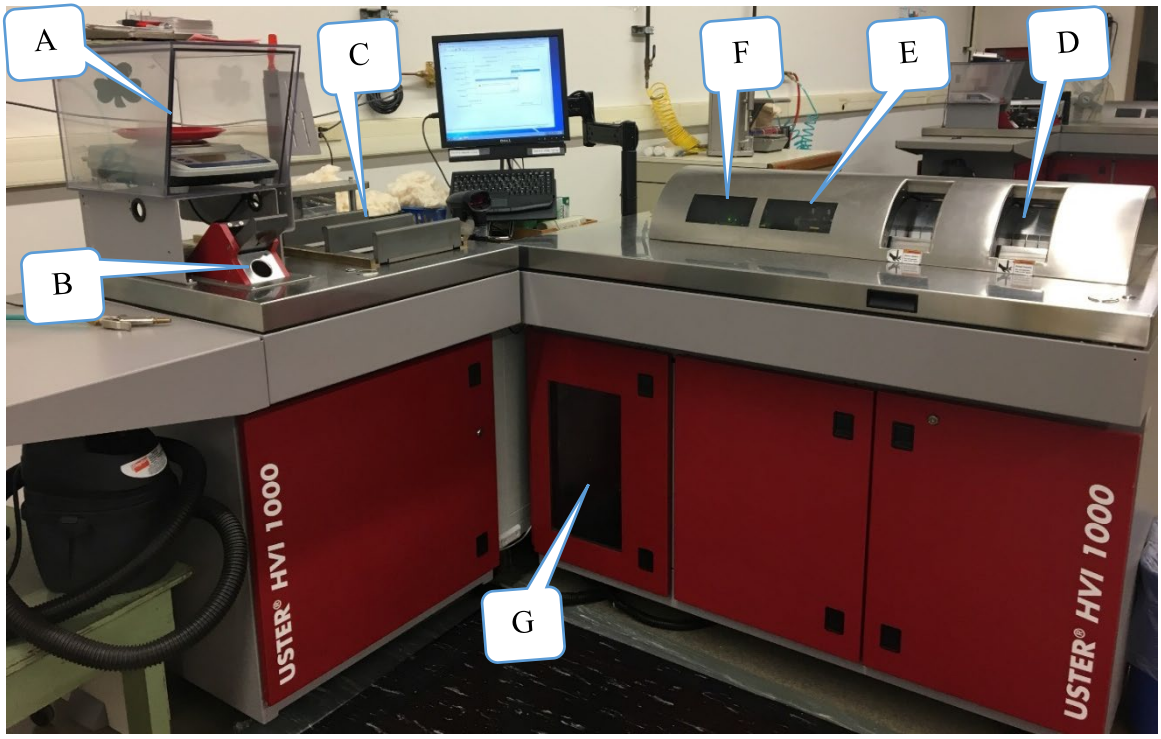

Figure 1. 8: High Volume Instrument (Uster HVI 1000) at Fiber and Biopolymer Research Institute, Texas Tech University. A. Micronaire weight scale B. Micronaire measurement chamber C. Color and Trash measurement trays D. Fibrosamplers E. HVI brush F. HVI scanning window G. Waste bin.

1.8.1.1. Micronaire

The overall fiber quality measurement with HVI could be separated into three workstations. In the first station, micronaire measurement is conducted Figure 1. 8, A&B). A cotton sample with a weight of 10±0.5 gm is taken and placed into the micronaire chamber. An airflow passes through the cotton fiber plug. The HVI measures the surface area of the fibers and reports the micronaire value (ASTM, 2011).

1.8.1.2. Color and Trash

HVI measures the color as Reflectance (Rd) and Yellowness (+b) using a filter and a pair of photodetectors (ASTM D5867, 2013). Cotton lint is placed on two trays to

completely cover the glass windows (Figure 1. 8 C). Samples are pressed from the top to eliminate any shadow. Black and white pictures are taken by a camera to analyze the foreign materials and a colorimeter measures the Rd and +b of the samples. HVI colorimeter measures the color of the sample (lint + trash), not the color of the lint (ASTM, 2013)

1.8.1.3. Fiber length

HVI fiber length measurement is based on the fibrograph principle originally proposed by Hertel (1940). A bundle of fibers is subsampled from the sample and placed in the fibrosampler (Figure 1. 9 A). The HVI comb is used to collect an unbiased sample of fibers to produce a fiber beard (Chu and Riley 1997) (Figure 1. 9 A&B). After the removal of extraneous material and fibers not caught by the comb, a beam of light is scanned over the fiber beards starting 3.81 mm away from the base of the comb to the end of the fiber sample (Figure 1. 9 C, D&E). A receiver is used to measure the amount of light attenuated by the fibers in the fiber beard by measuring the transmitted light between and through fibers. The maximum attenuation of light by the beard is represented by 100% which occurs at the starting of the scanning while 0% attenuation occurs when the scan extends beyond the fibers (ASTM 2013). The output of this optical system plotted as the function of distance is referred to as the fibrogram (Figure 1. 10) (Hertel 1940, Chu and Riley, 1997). Based on this fibrogram curve, the HVI provides two length parameters, UHML and UI. UI is the ratio of ML to the UHML expressed as percentage.

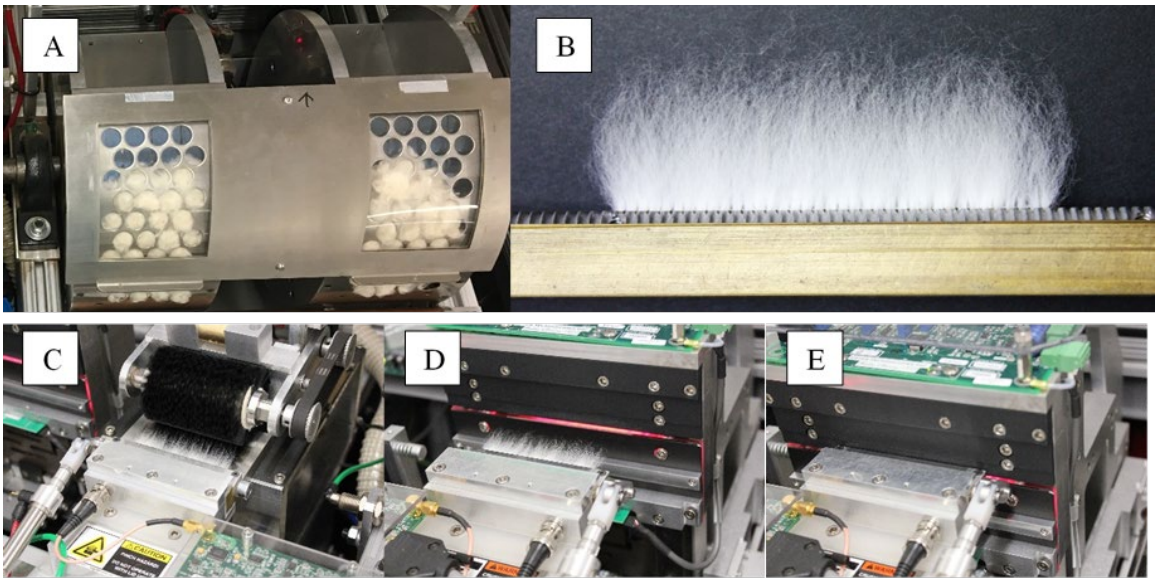

Figure 1. 9: HVI fiber length measurement principle. A. Fiber sample placed into the fibrosamplers to be caught by the combs B. fiber beard produced by the fibrosampler comb similar to the HVI beard C. Fiber beard is brushed to remove loose fibers and extraneous matter D&E. Fiber beard scanned over a red light beam.

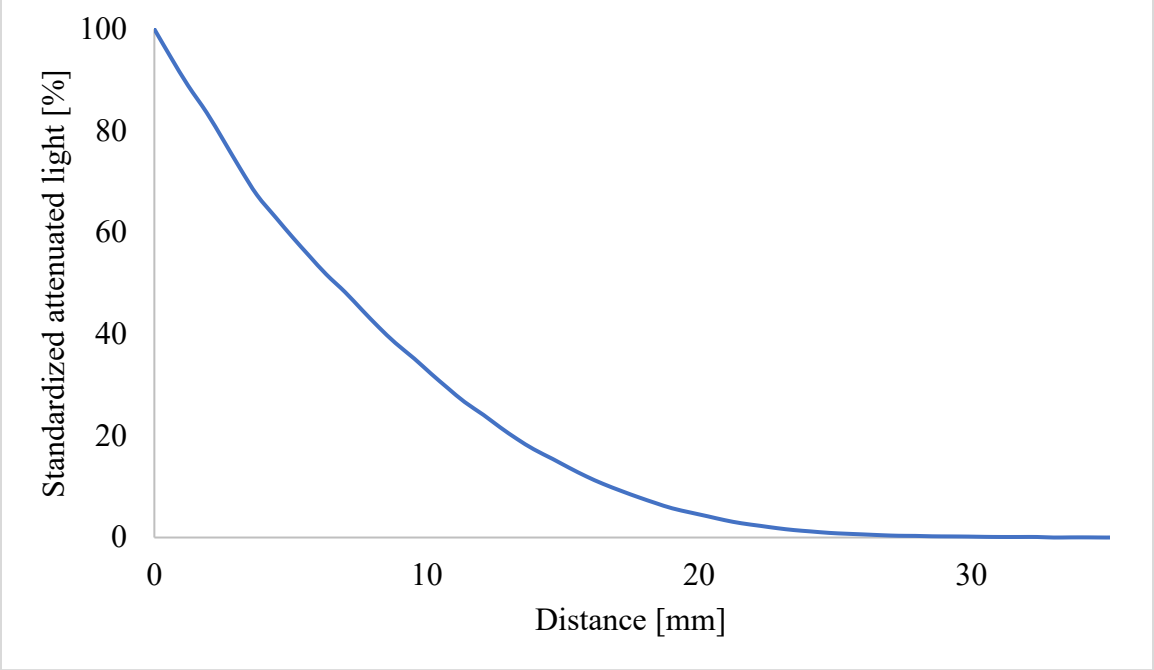

Figure 1. 10: A typical fibrogram and the HVI length (UHML and ML) measurement principle.

1.8.1.4. Strength and Elongation

After finishing the scanning of the fiber beard for fiber length measurement, HVI uses the same fiber beard to measure the tensile properties (Strength and Elongation). A pair of jaws, with 1/8 inch gauge length, clamps the fiber beard and a constant load is applied to pull and break the fiber beard to generate a stress-strain curve (Figure 1. 11). The clamping position varies from beard to beard based on the attenuated optical amount. The optical amount and the micronaire measurement are used to estimate the weight of the fiber, which is required for the measurement of fiber tenacity (Taylor, 1982, 1982; Naylor et al., 2013, 2014).

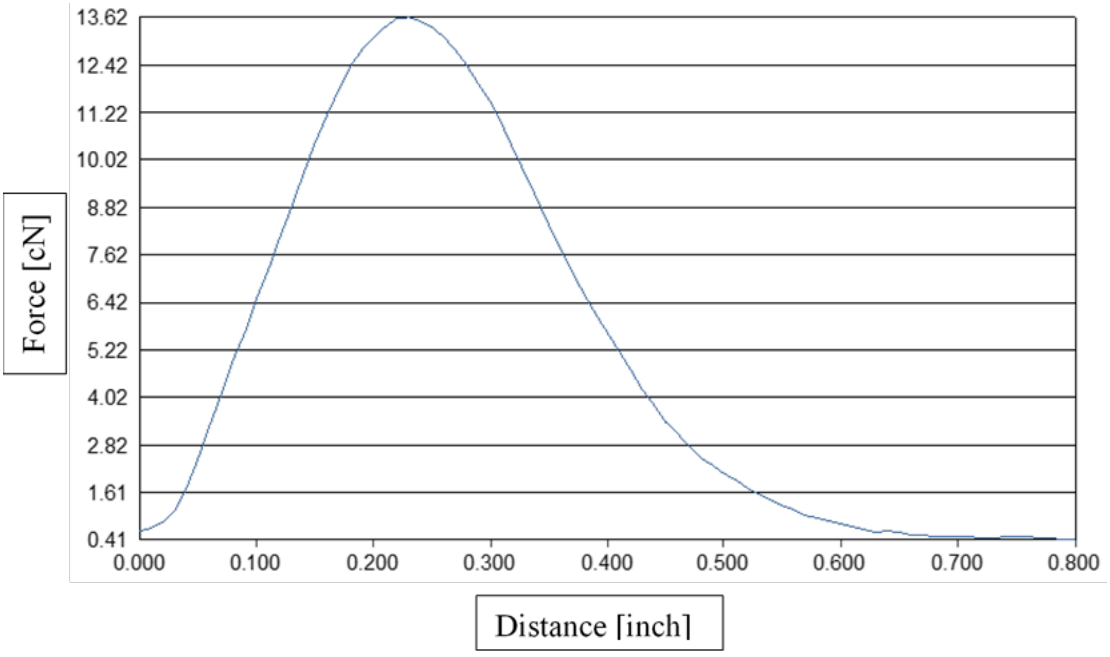

Figure 1. 11: HVI stress strain curve for fiber strength and elongation measurement.

Each HVI test is faster and less expensive than sample tests provided by many other instruments. In a laboratory setup, HVI can measure around 600 samples per day (8 working hours) which varies based on the number of replications. The cost per sample's measurement with HVI is also cheaper than many other fiber quality measurement

systems. In a research laboratory environment, HVI testing costs between $2.50 and $7 per sample based on the measurement protocol. However, HVI reports two fiber length parameters; UHML and UI; which is not enough to explain the total within-sample variation in fiber length (Wakeham, 1955; Kelly and Hequet, 2018). The fiber length variation characterized by current HVI length parameters is less than half of the length variation captured by AFIS length distribution by number (Kelly and Hequet, 2018). Therefore, HVI length parameters may not be enough for detecting differences in spinning performance (Kelly et al, 2013).

1.8.2. Advanced Fiber Information System (AFIS)

The Advanced Fiber Information System (AFIS) was primarily developed to provide a tool to spinners for the measurement of nep content in the sample (Figure 1. 12) (Shofner 1985, Shofner et al., 1995). Later, the instrument was improved for the measurement of within-sample variation in many other fiber quality attributes (Shofner and Shofner, 1999). Along with the neps (neps content, neps size and neps type) and trash (trash content, trash size) measurements, AFIS provides the complete distribution of cotton fiber length, maturity and fineness (Bragg and Shofner, 1993; Shofner and Shofner, 1999).

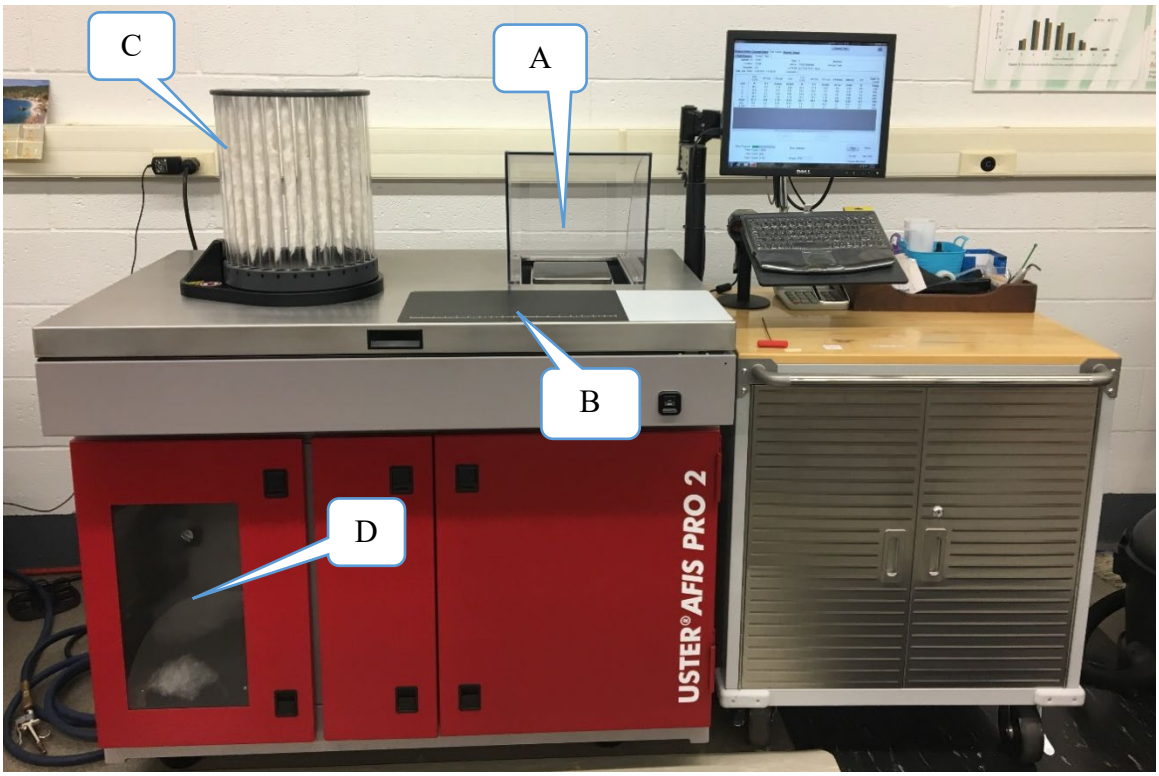

Figure 1. 12: Advanced Fiber Information System (Uster AFIS Pro 2). A. Scale for weight 0.5 gm of sample B. Mat with length scale to prepare 30 cm long sliver C. Canister to load the slivers into the AFIS system D. AFIS waste bin.

1.8.2.1. Measurement Principles

A 0.5 gm loose bundle of fibers shaped by hand, like a sliver (30 cm long), is prepared (Figure 1. 13) and placed into a canister. After feeding the instrument, a perforated individualizer covered with metal teeth separates the fibers, trash and neps (Bragg and Shofner, 1993; Shofner, 1999). The AFIS fiber individualization is an aggressive process resulting in fiber breakage.

Fibers, neps, and light seed coat fragments are separated from trash and heavy seed coat fragments.

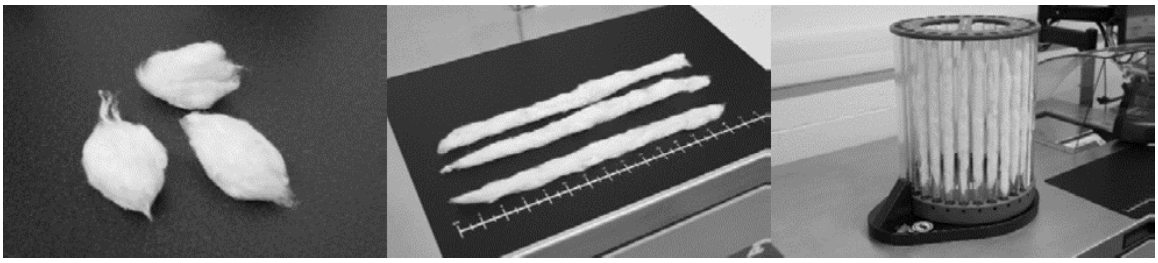

Figure 1. 13: Preparation of sliver for AFIS fiber quality measurement. A. 0.5 gm of cotton fibers were taken B. Loose bundle sliver were prepared C. Canister to load the sliver into the AFIS system (Kelly, 2014).

The individualized fibers are then aerodynamically presented to an electro-optical sensor for the measurement of different fiber properties (Bragg and Shofner, 1993). When the individual fibers pass the electro-optical beam, it records two signals. The primary signal records the light attenuated by the fiber and the time it takes to pass the sensor (Figure 1. 14). AFIS uses this signal to calculate the fiber length and provides a fiber length distribution as a histogram (Figure 1. 15). Neps are measured with the same signal. Neps are identified by the slope of the waveform which forms a peak rather than a plateau (Figure 1. 14).

The second signal records the light scattered by the same fiber from a 40o angle and provides, in combination with the 0-degree angle, the measurement of fiber fineness and maturity (Gordon et al., 2004). The electrical pulses of each signal are analyzed with a computer program to generate the reports of mean and distributional fiber maturity and fineness measurements.

Heavier particles such as trash and Seed Coat Fragments (SCF) are sent to a different electro-optical light sensor to measure the size and types of particles (Jones and Baldwin, 1995).

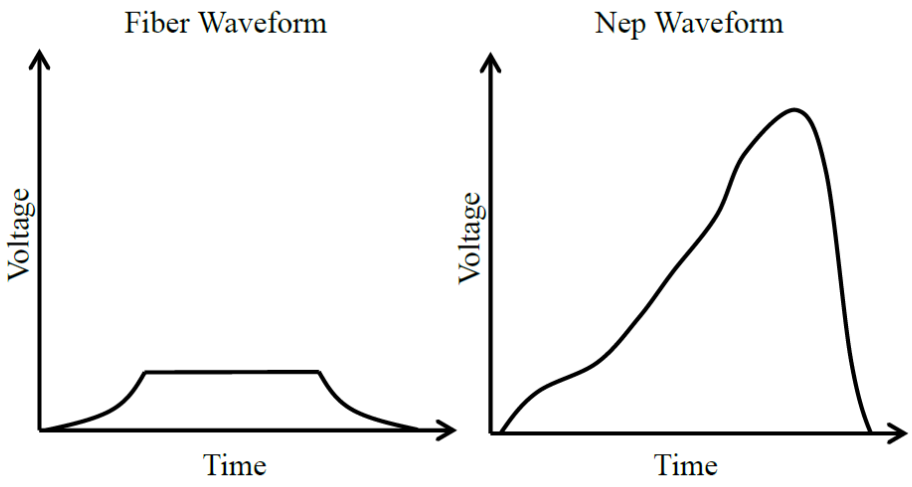

Figure 1. 14: Example of waveforms return by the AFIS electro-optical sensor. The figure illustrates the difference between waveforms for fiber and waveforms for neps (Kelly, 2014).

AFIS measures the length of 3,000 individual fibers and provides a complete fiber length distribution by number and by weight (Figure 1. 15). While the number-based length distribution provides the frequency of fibers in each 40 AFIS length bins, the weight-based length distribution provides the weight contribution of fibers in each 40 AFIS bins. In the length distribution by weight, the contribution of shorter fibers is hidden because they weigh less. In addition, the AFIS fiber length measurement assumes that the linear density of all length categories is uniform which is not true (Duckett et al., 1993). In general, short fibers are less mature than long fibers (Hequet et al., 2006).

Several length parameters are estimated from these length distributions including mean length by number (L(n)[in]), length by weight (L(w) [in], upper quartile length by weight (UQLw) [in], length CV (%) by weight and by number, short fiber content by

number (SFC (n) [%]) and by weight (SFC (w) [%]), and the length upper percentiles by number (L2.5% (n) [in] and L5% (n) [in]).

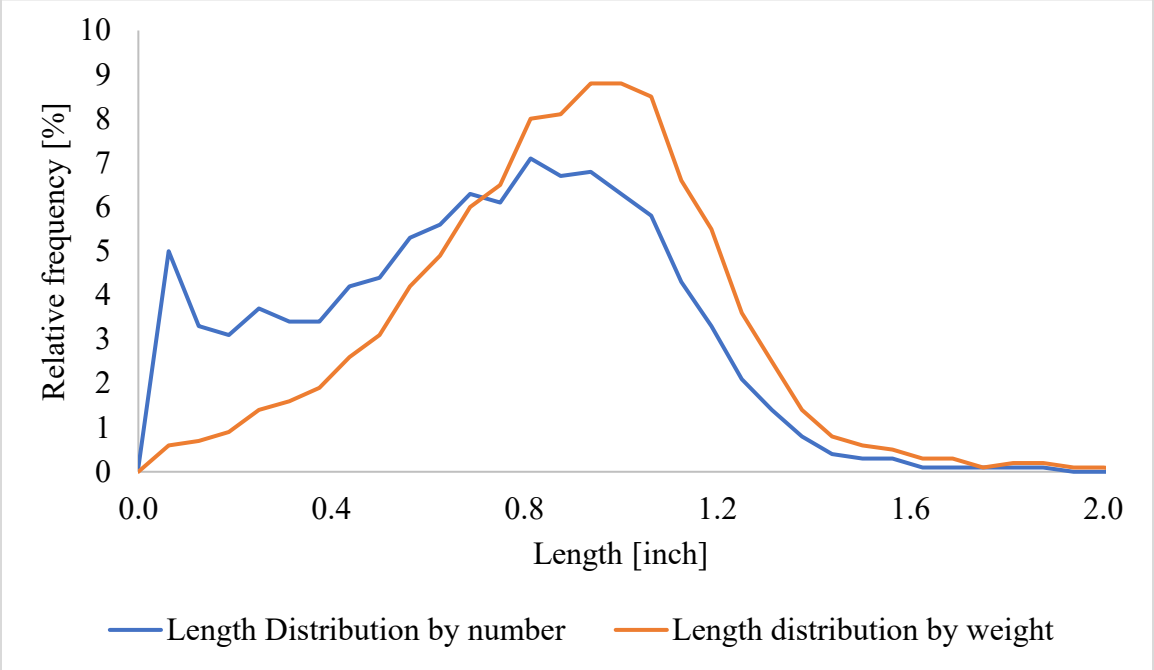

Figure 1. 15: AFIS length distribution by number and weight for the same sample. The figure illustrates that the length distribution by weight hides the impacts of short fibers in the distribution.

The complete fiber length distribution is useful in commercial manufacturing operations as well as in selecting superior cotton cultivars (Wakeham, 1955; Kelly and Hequet, 2018). The amount of sample required for AFIS measurement is small which allows cotton breeders to measure fiber length distribution for small size samples.

The measurement of cotton fiber quality with AFIS is time-consuming. Several weeks of training are required for an operator to be able to prepare the samples for AFIS measurement. An operator should be careful while making a 30 cm long sliver from

0.5gm of cotton fiber. This sliver making process takes time. After making the slivers carefully, the slivers are loaded into a canister which can hold 30 slivers. AFIS can measure fiber properties for 6 canisters in eight working hours including 1 canister for the daily check. In general, samples are measured with 3 to 5 replications for AFIS properties. Therefore, AFIS could measure a maximum of 50 samples per day (Uster manual AFIS Pro, 2006; Kelly and Hequet, 2018).

1.9. Yarn quality

1.9.1. Yarn tensile properties

Yarn tensile properties are important to determine the yarn quality and further processing efficiency. The winding and knitting efficiency are directly affected by the yarn tensile properties (Joy et al., 2010). Stronger and finer yarn production requires high-quality cotton fibers such as fiber that are longer, stronger, and with a better length uniformity (Faulkner et al., 2012; Ramey et al., 1977).

Yarn tenacity is mainly influenced by fiber length, fiber strength and fineness (Ramey et al., 1977; Hequet et al., 2007; Faulkner et al., 2012; Kelly and Hequet, 2013). Longer fibers provide better friction among fibers resulting in stronger yarns. Fineness also contributes to yarn strength. For a given yarn count and fiber maturity, finer fibers will increase the friction forces among fibers and ultimately yarn strength.

The amount of stretch in the yarn before rupture is called yarn elongation. Yarn elongation is determined by fiber quality, yarn twist and yarn count. Fiber bundle elongation is directly correlated to yarn elongation (Hertel and Craven, 1956; Louis et al., 1961; Backe, 1996; Hequet et al., 2007).

1.9.2. Yarn imperfection

The appearance of the fabric is highly dependent on yarn imperfections (Simpson and Fiori, 1975; Padmanabhan and Balasubramian, 1990). A high level of within-sample variation in fiber quality creates thin places, thick places and neps in the yarn structure (Hequet and Ethridge, 2000). Poor drafting is also the cause of yarn imperfections. Thick and thin places create weak points in the yarn that causes yarn breakage during further processing, especially in weaving.

Yarn hairiness and coefficient of variation (CVm%) are also important yarn imperfection parameters. Hairiness is an undesirable property and is determined by fiber properties, and spinning conditions (Zhu & Ethridge, 1997; Altas & Kadoğlu, 2006). Yarn twist, short fiber content and fiber strength are the main properties that influence the yarn hairiness and CVm%. According to Hequet and Ethridge (2000), the shortest and the longest fibers have a high correlation with the hairiness for all kinds of yarn. If cotton fiber properties such as strength, length and elongation increase then hairiness decreases for both ring and rotor spinning (Zhu and Ethridge, 1997).

1.10. Scope of the research

Breeders develop cotton germplasm with improved fiber properties to fit modern spinning technology raw material demands. During the development of new germplasm, breeders highly depend on HVI for fiber quality measurement. HVI was developed for cotton classification and marketing. It is not able to provide all the required fiber quality information needed to predict yarn quality. For example, HVI provides two fiber length measurements which are not enough for characterizing the fiber length information. Sometimes, breeders use AFIS on a small scale for fiber length distributional

measurements. The speed and cost of AFIS prohibit them from using it systematically for a large breeding program.

Spinners use HVI fiber properties to select the right cotton bales for certain types of yarn quality. Most of the large-scale spinners perform in-house AFIS measurements for distributional fiber quality measurements, for example, fiber length distribution. The complete fiber length distribution helps spinners to decide the types of yarn they can produce with certain types of fiber and what types of machine setting they should go for.

Spinners usually have a target yarn quality from their customers when they purchase cotton bales. After in-house AFIS measurements, they can find that the cotton they purchased is not suitable for their target yarn. When possible, spinners compensate for this by modifying machine settings which can slow production and result in profit loss. Therefore, spinners need a fiber length measurement providing information about total within-sample variation while they select their cotton bales to purchase.

The fiber length measurement with HVI that is used in cotton classing and marketing was developed in the 1970s. Lack of computing power prohibited the use of the whole fibrogram curve generated by the HVI. With the high computing power available today, it should be possible to analyze the whole fibrogram curve and to characterize the total within-sample fiber length variation. The goal of this dissertation is to develop a fiber length measurement with HVI providing better information about within-sample variation than current HVI output. This could be used as an improved selection parameter by the breeders and a better tool for the spinners to select cotton bales for purchasing.

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CHAPTER 2

INVESTIGATION OF HVI FIBER LENGTH MEASUREMENT: EXTRACTION AND STABILITY OF THE FIBROGRAM WITHIN HVI AND ACROSS HVIs.

2.1. Introduction

Cotton fiber length distributions are powerful predictors of yarn quality. Variation in fiber length within a sample impacts yarn strength and can result in irregularities (Cai et al., 2013; Wakeham, 1955). However, the most common fiber length parameters, Upper Half Mean Length (UHML) and Uniformity Index (UI), used in the cotton industry, are measured with the High Volume Instrument (HVI) and do not characterize the total within-sample variation in fiber length. Nevertheless, cotton breeders use these length measurements for selection in their breeding programs as well as spinners to select cotton bales during cotton purchasing to meet their customer's demand (B. R. Kelly & Hequet, 2018; C. M. Kelly, Hequet, & Dever, 2013). The reason behind the widespread use of these length parameters, despite not providing a complete measurement of length variation, is that there is no instrument on the market that can provide the measurement of fiber length distribution of all the cotton produced in the U.S in a reasonable amount of time. Moreover, HVI provides some other important fiber quality parameters such as strength, micronaire, color and trash that are also important to the cotton breeders and spinners.

Distributional fiber length measurements can be assessed with the Advanced Fiber Information System (AFIS). The AFIS measures the length of individual fibers in a sample. In general, three to five slivers of 0.5 g are prepared by hand and fed to the

instrument that measures about 3,000 fibers per sliver. From this, the histograms of fiber length distribution by number and by weight are derived. However, this instrument is not suitable for use by the cotton industry for cotton classification or by breeders in large breeding programs due to its speed (50 samples/machine/ 8-hours day). In addition, AFIS does not provide the measurement of some other important fiber quality parameters such as micronaire, strength, and color of the samples. The HVI is the only instrument that can measure samples from all of the cotton bales produced every year in the U.S. and is used across all segments of the cotton industry.

HVI fiber length measurements are based on the fibrogram principle that requires the HVI to generate a fibrogram curve (Chu & Riley, 1997; Hertel, 1940). According to the fibrogram theory, a fiber beard prepared with an HVI comb is scanned over light from 3.81 mm away of the base of the comb towards the tip of the fiber beard, while a sensor above measures the optical amount attenuated by the beard (Krowicki & Thibodeaux, 1990). The scanning starting point is considered as the 100% attenuated light, i.e., it is an amount-standardized distribution. Fewer and fewer fibers are available to be scanned when the scanning moves towards the tip of the fiber beard. When there is no fiber available for attenuating the light, the HVI system is finished scanning the beard. This point is considered as 0% attenuated light. The function of the distance traveled by the fiber beard against the attenuated optical amount generates the fibrogram curve.

According to Hertel's theory, HVI reports UHML and UI by drawing tangents from 100% and 50% span lengths to the fibrogram curve measuring Mean Length (ML) and UHML respectively (Figure 2. 1) (Hertel, 1940). However, this does not depict the current measurement of UHML and UI by the HVI system (Personal communication with

USDA AMS, Memphis). Instead of drawing tangents, HVI measures span lengths to report UHML and UI. While ML is not reported by the system, it is used to calculate the UI which is the ratio of ML to the UHML. These two length parameters are widely used across the cotton industry including the US cotton classification and cotton marketing.

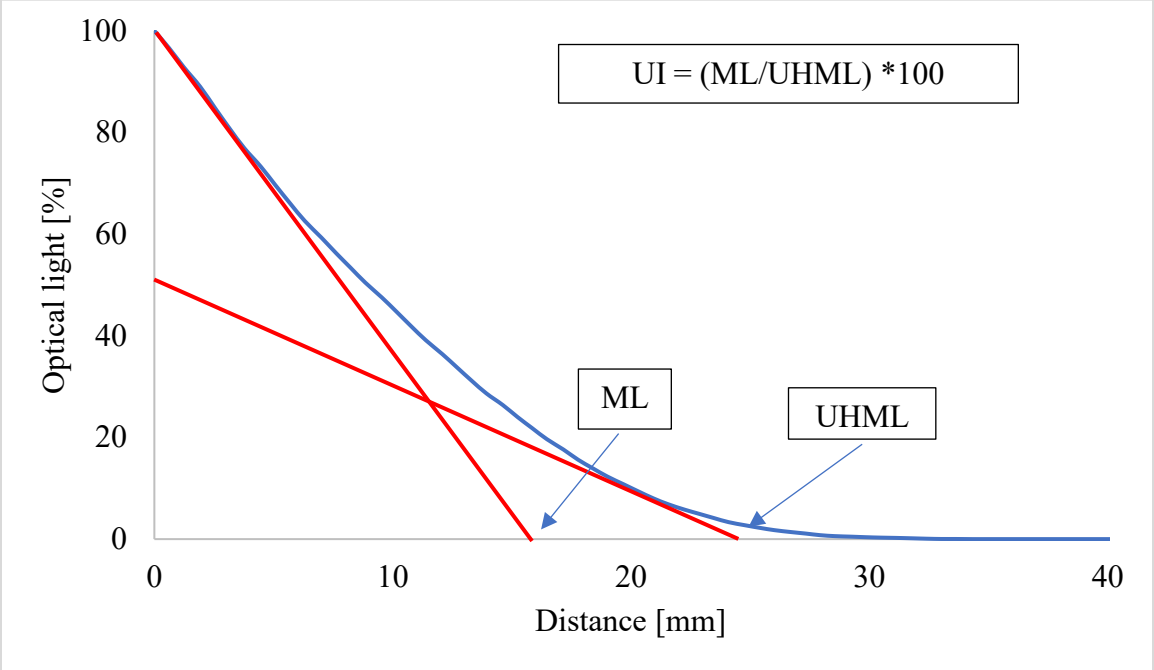

Figure 2. 1: A typical fibrogram generated by HVI and the principles of current fiber length measurement.

The distributional fiber length measurement could be calculated using the whole fibrogram (Louis & Fiori, 1967). Graphically they showed that the fibrogram could provide the fiber length distribution similar to the Suter-webb array method, assuming that the optical amount corresponds to a weight. The fiber length distribution obtained using the fibrosampler is almost identical to the distribution of the original sample (Chu & Riley, 1997). Preysch, 1979 developed an equation using 2.5% span length and 50% span length from the fibrogram to estimate the short fiber content (SFC).

The HVI system operates in two different modes, i.e., system testing and module testing. The system testing mode uses all HVI measurement modules and provides the standard reports to the central database at the Fiber and Biopolymer Research Institute (FBRI) at Texas Tech University. This standard-report includes micronaire, strength, UHML, UI, color and trash. For fiber length measurement, this testing mode does not report the fibrogram curve. Instead, it discards the curve after storing the UHML and UI data. The second mode, module testing, allows the user to pick the measurements they need. Three independent modules are available, micronaire, color/trash, and length/strength.

The length/strength module testing mode can provide a fibrogram curve. However, it is not reported to the central database of the FBRI, i.e., there is no report in the database that makes fibrogram readily available for analysis. Therefore, the fibrogram should be extracted from the native HVI software.

2.2. Objectives

The objectives of this chapter are:

1. To develop a method to extract the fibrogram from the native HVI software.
2. To determine whether the fibrogram measurements are stable over time.
3. To determine whether the fibrogram measurements are stable across multiple HVIs.

2.3. Materials and Method

A subset of 50 commercial samples were selected for the first experiment, developing the fibrogram extraction method and for the third experiment, stability of the fibrogram

measurement across multiple HVIs. For investigating the stability of the fibrogram measurement over time, two card web samples were used.

All these samples were conditioned for at least 48 hours at 21±10 C and 65±2% RH prior to testing. Samples were measured using HVI length and strength module testing mode for fibrogram.

2.3.1. Extracting the fibrogram data

The goal of this experiment is to develop a protocol to extract the raw data used to generate the fibrogram curve. To develop this method multiple replications or multiple fibrograms from various samples are enough. However, to determine the ease of the proposed method, a large number of fibrograms are required. Therefore, a set of 50 commercial samples were selected and measured them with 10 replications of the fibrogram to provide 500 fibrograms in total.

The native HVI software reports the fibrograms in several graphical formats such as .xls and .pdf. However, these formats are not open source. Therefore, it does not allow direct access to the raw data. Among the available formats, xls and pdf provide vectored graphics of the fibrograms. It means that the information used to generate the fibrogram curve is embedded in the image. Thus, the vectored images were converted into an open-source format to access the data.

2.3.1.1. Extracting fibrogram data using xls file

The fibrogram reports from the native HVI software were exported in .xls format. The .xls is the default format for Microsoft excel and the information stored in this format is in a binary format. A new version of Microsoft excel, .xlsx, is based on XLM

(Extensible Markup Language). In this format the information is stored into a text file. The excel file in one format could be opened and saved into another format. Thus, the fibrograms in the .xls files were converted to .xlsx file format.

The .xlsx also allows compression of the data into a zip file that separates all the graphical figures into the Enhanced Metafile (emf) image format. Then, a batch conversion file was created using the program location of Inkscape (Inkscape 0.91) installed on the computer. This batch file allowed converting all the emf files into scalable vector graphics (SVG) files. The fibrogram curves from these SVG files could be extracted manually but it would be time-consuming. A MATLAB (Math Works Inc., MATLAB R2018a) script was developed that allowed retrieving the raw data of thousands of fibrograms rapidly.

2.3.2. Stability of the fibrogram measurement

Cotton fiber length could be highly variable within a sample or within a bale, it could result in variation among fibrograms within a sample. This within-sample variation in fiber length needs to be minimized in order to investigate the true deviation of the measurement by the instrument. Therefore, two well-blended card web samples with distinct fibrograms were used for this experiment.

The stability of the fibrogram over time was conducted at two different levels: short-term stability and long-term stability.

2.3.2.1. Short-term and Long-term stability

After proper conditioning, samples from these two cottons were measured with 210 replications within a day for the short-term stability study.

For the long-term stability study, samples were measured about the same time every day for over 30 working days with 60 replications each day. The laboratory conditions were carefully monitored to make sure that there was no issue with air conditioning. It was also confirmed that no mechanical work was done on the HVI used within this period. After completing the measurements, the slopes (reading vs. time) of the selected span lengths were calculated.

Several span lengths were selected such as 2.5%, 5%, 10%, 20%, 30%, 50%, 60%, 70%, 80% and 90% to have representative data points for the fibrogram to determine whether it is stable or not.

2.3.3. Stability of the fibrogram across HVIs

The investigation of the stability of the fibrogram among HVIs requires an adequate number of samples representing a wide range of fiber length variation. The same set containing 50 commercial samples were also used in this experiment. After proper conditioning, these samples were measured with 10 replications with three HVIs. Fibrograms data were extracted using a MATLAB (Math Works Inc., MATLAB R2018a) script (described in 2.2.1.1).

To determine whether the fibrograms are reproducible across HVIs, several span lengths such as 2.5%, 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% and 90% were selected and compared among HVIs.

2.4. Result

2.4.1. Extracting the fibrogram data

The extraction of the fibrogram using the .xls format allows extracting thousands of fibrograms very quickly. Figure 2. 2 shows the average of 10 replications of the fibrogram per sample for 50 commercial samples. The current fiber length parameters provided by the HVI are the measurement of longest fibers in the sample (Delhom, Kelly and Martin, 2018; Kelly and Hequet; 2018). However, the extracted fibrograms using 50 commercial samples show that the middle region of the fibrogram holds comparatively higher fiber length variation among samples. A quick method of fibrogram extraction could allow researchers to look into the total variation captured by the whole fibrogram.

The fibrogram data structure limits the use of many statistical techniques. First, the standard attenuated optical amount for one fibrogram bin is highly collinear to the neighboring bin. Second, the fibrogram provides the optical amount as a response variable bounded between 0% to 100%. It could create nonlinearity of the measurement, especially when working with the values nearest to the extreme. While the interest by the cotton industry is to get the measurement of fiber length, the response value of raw fibrogram is standardized optical light.

Therefore, the fibrograms are flipped to obtain a length-response curve rather than an amount-response curve (Figure 2. 3). The interpolated data of the length-response curve were calculated using a MATLAB script. Interpolated data points were calculated for every 1% increment in standardized optical amount providing 101 bins in order to provide good coverage of the curvature in the raw fibrogram.

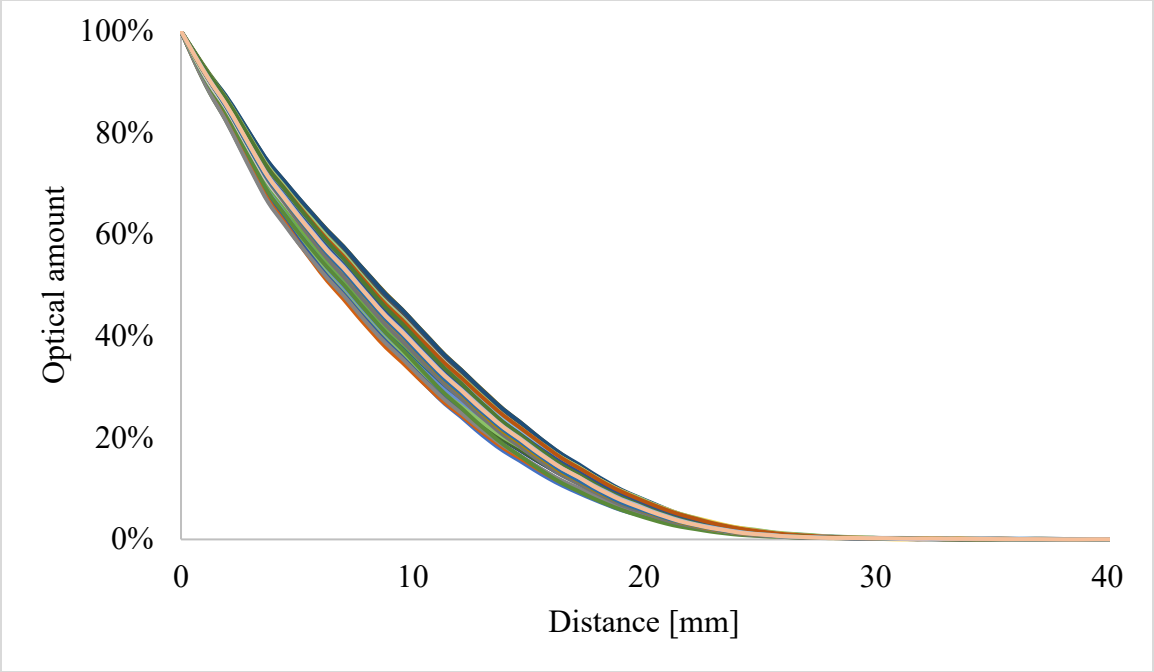

Figure 2. 2: Fibrograms of 50 samples exported using the xls file from the HVI software.

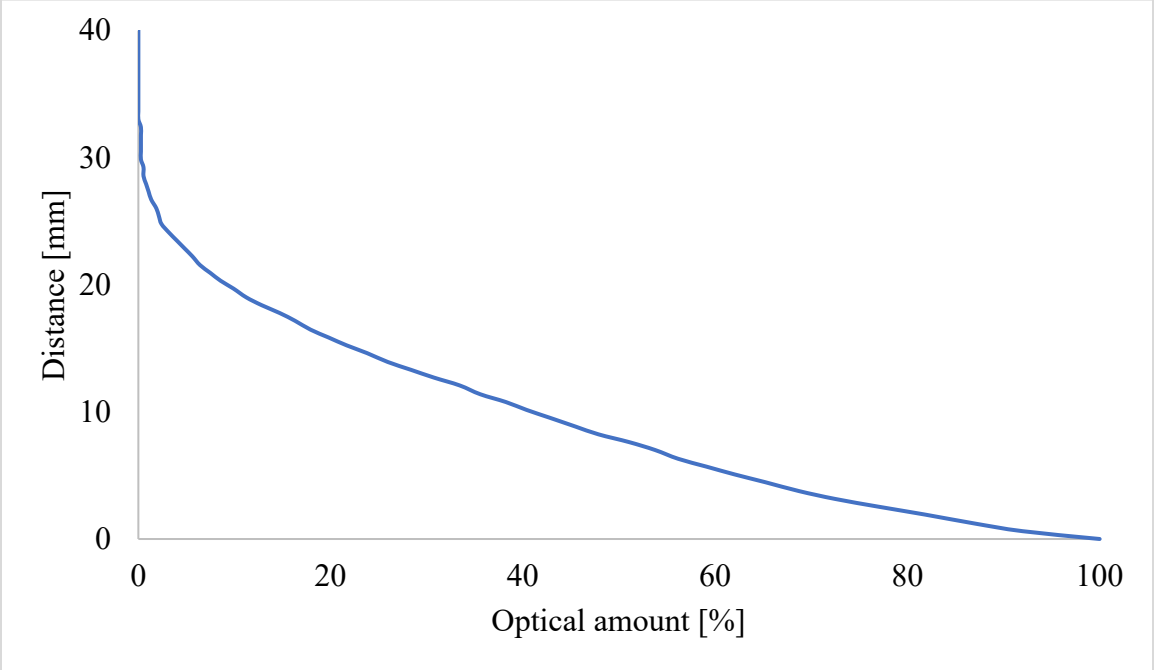

Figure 2. 3: Flipped curve representing the fibrogram as a length-response curve.

2.4.2. Stability of the fibrogram

Investigating the stability of the fibrogram measurement is important to determine whether the whole fibrogram curve can be used to retrieve the fiber length distribution. If the fibrogram measurement is not stable or drifts over time, it would limit its interest. Several parameters together or individually could explain excess variability among fibrograms. First, the HVI comb may not grab the fiber sample properly from the fibrosampler or some teeth of the comb could be damaged/broken. Second, the HVI brush may not remove all the loose fibers and extraneous materials properly.

2.4.2.1. Short term stability

The short-term stability of the fibrogram measurement was investigated using two well-blended card web samples. These two samples were measured with 210 replications within a day.

Figure 2. 4 shows that the standard errors of all the span lengths for sample 1 range from 0.000686 to 0.036551 mm which are very low. The maximum standard error 0.036551 mm is found at the 50% span length.

Similar results are found for sample 2 (Figure 2. 5). The standard errors for this sample range from 0.00061 to 0.035306 mm and the maximum is obtained for the span length 51%. This means the HVI provides a stable fibrogram measurement within a day. The higher standard errors at 50% span length for sample 1 and 51% span length for sample 2 supports the previous assumption that the fiber length variation captured by the fibrogram are higher in the middle region of the curve.

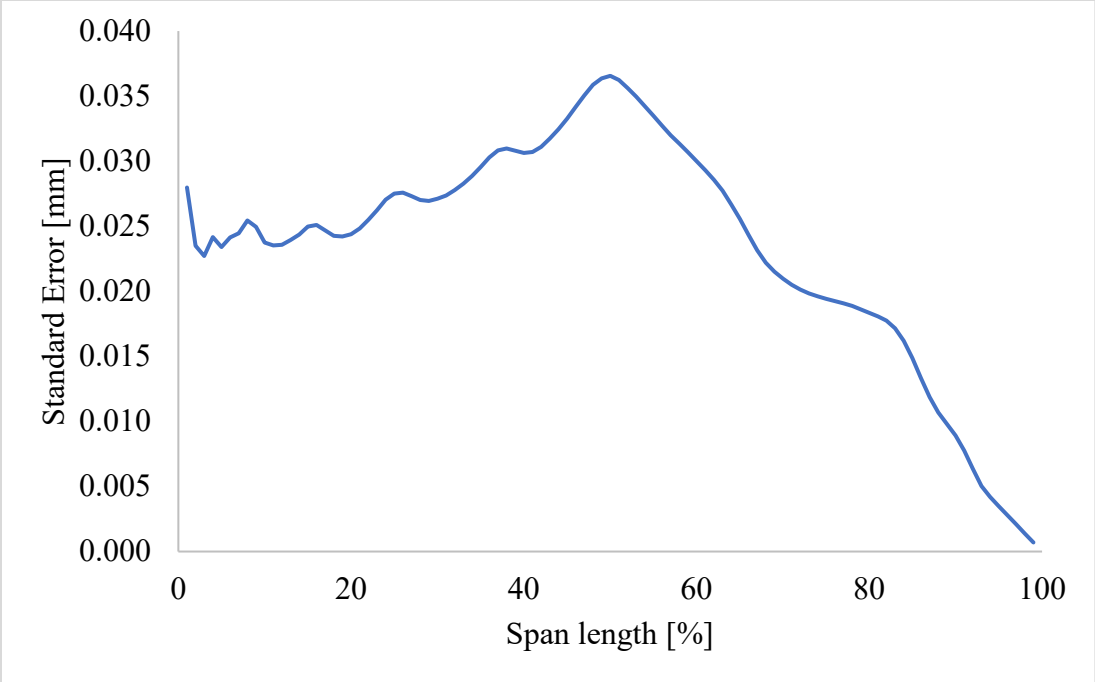

Figure 2. 4: Standard errors of fibrogram across all the span lengths within a day for sample 1.

Figure 2. 5: Standard errors of fibrogram across all the span lengths within a day for sample 2.

2.4.2.2. Long-term stability

Short term stability shows that the fibrogram measurements are stable within a day, but it is not enough to determine the instrumental drift for the long term. Therefore, after investigating the short-term stability, it is necessary to investigate the long-term stability of the fibrogram measurement.

Figure 2. 6 shows that the slopes for the span lengths 2.5%, 5%, and 10% are -0.00004, 0.00004 and 0.0000008 respectively for sample 1 which are very low, almost zero. Figure 2. 7 shows the slopes of 2.5%, 5% and 10% are 0.0001, 0.0001 and 0.0001 respectively for sample 2 that are also almost zero, similar to sample 1. Slopes of the other selected span lengths for both samples are also close to zero (Table 2. 1). A statistical significance test at alpha level 0.05 shows that the slope of the selected span lengths over time for both samples are not significantly different from zero (Table 2. 2). That means for both samples, HVI provides stable fibrograms over time.

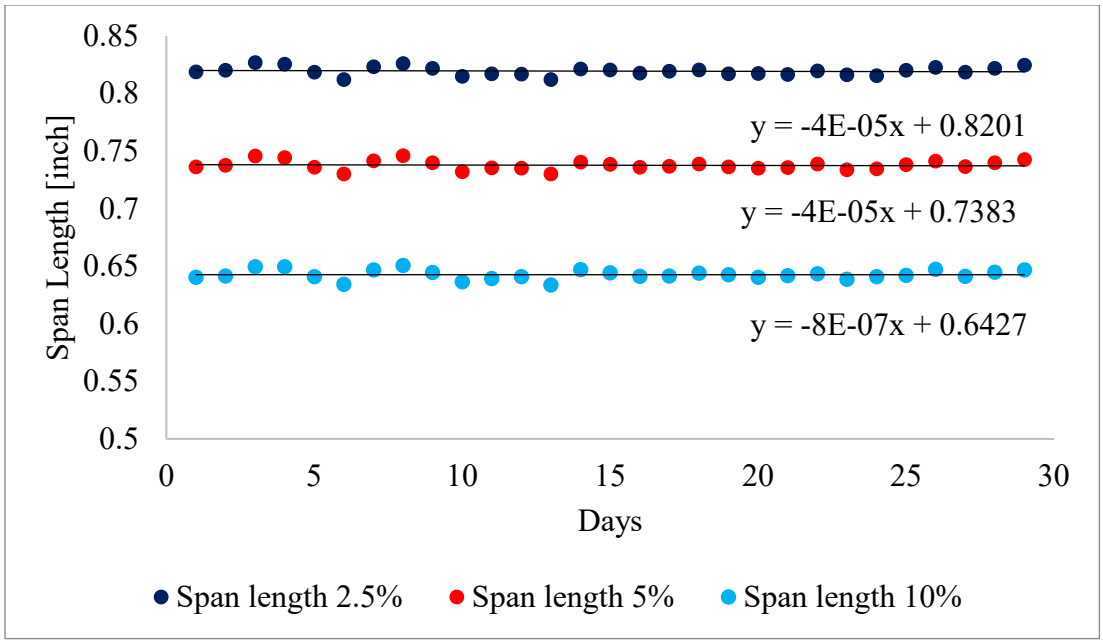

Figure 2. 6: Changes in slopes for span lengths 2.5%, 5% and 10% over 30 working days for sample 1.

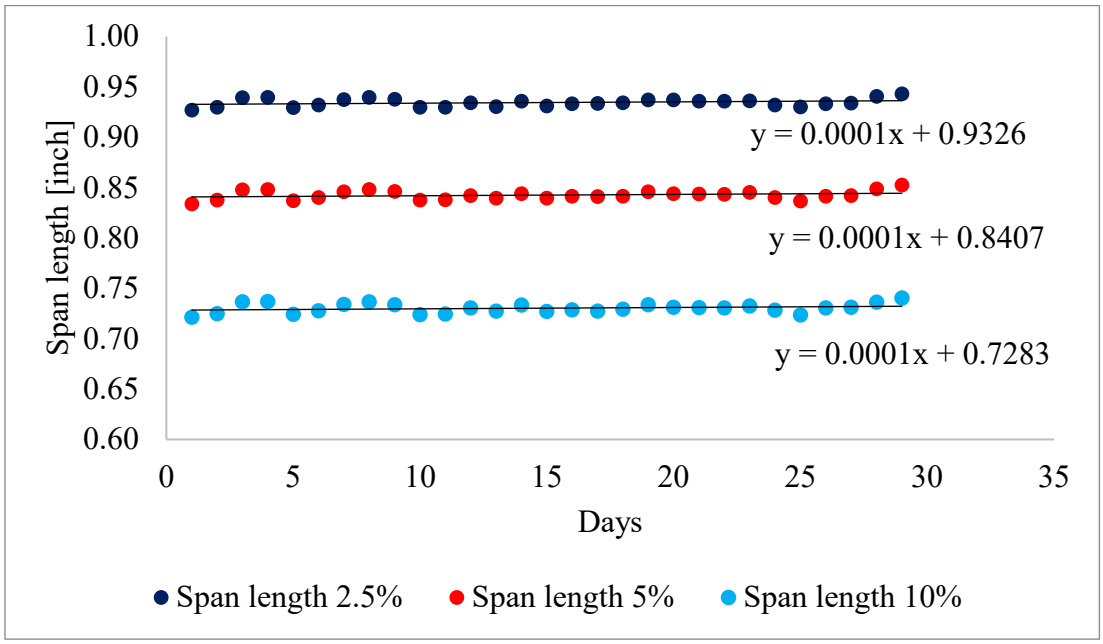

Figure 2. 7: Changes in slopes for span lengths 2.5%, 5% and 10% over 30 working days for sample 2.

Table 2. 1: Slopes of the selected span lengths for Sample 1 and Sample 2 measured for 30 working days.

Span length	Slope (Sample 1)	Slope (Sample 2)
20%	0.0000200	0.00010
30%	0.0000200	0.00010
40%	0.0000200	0.00008
50%	0.0000005	0.00001
60%	0.0000100	-0.00006
70%	0.0000060	-0.00006
80%	0.0000030	-0.00005
90%	-0.0000030	-0.00002

Table 2. 2: Statistical significance test for the slopes over time for both samples shows that they are not significantly different from zero.

Sample	Mean	CI
1	-0.000000391	0.0000143352 ns
2	0.0000363636	0.0000484702 ns

ns: non-significant, alpha: 0.05.

2.4.3. Stability of the fibrogram across HVIs

Stability of the fibrogram measurements across HVIs is another important step to determine whether the fibrogram measurement could be used across the cotton industry.

The result obtained by regression analysis between HVI 1 and HVI 2 for all the selected span lengths shows that they are significantly related. The slopes and offsets of some of the span lengths are not significantly different from 1 and 0 respectively while some are significantly different (Table 2. 3).

For example, the regression analysis of the 2.5% span length shows a good agreement between HVI 1 and HVI 2 (Figure 2. 8). The slope of the span lengths 2.5%, 5%, 10%, 20%, 30%, 40%, 70% and 90% are not significant different than 1 while the slope of span length 50%, 60% and 80% are significantly different than 1 (Table 2. 3). The offset of the

span lengths 2.5%, 5%, 10%, 20%, 30%, and 40% are not significantly different than 0 while the offset of span lengths 50%, 60%, 70%, 80% and 90% are significantly different than 0 (Table 2. 3). Similar results were observed between HVI 1 and HVI3 as well as HVI 2 and HVI 3 (Figure 2. 9, Figure 2. 10, Table 2. 4 and Table 2. 5).

An interesting observation here is that the span lengths that show significant differences represent comparatively shorter fibers in the sample. One reason behind this difference could be the current HVI fiber length measurement principle. HVI measures UHML and ML (reports UHML and UI) that represent the longer fibers in the sample and over time HVIs were calibrated and maintained only for these two parameters.

The significant differences for some slopes and offsets mean that a correction procedure is required to bring the fibrogram measurements at the similar level across HVIs.

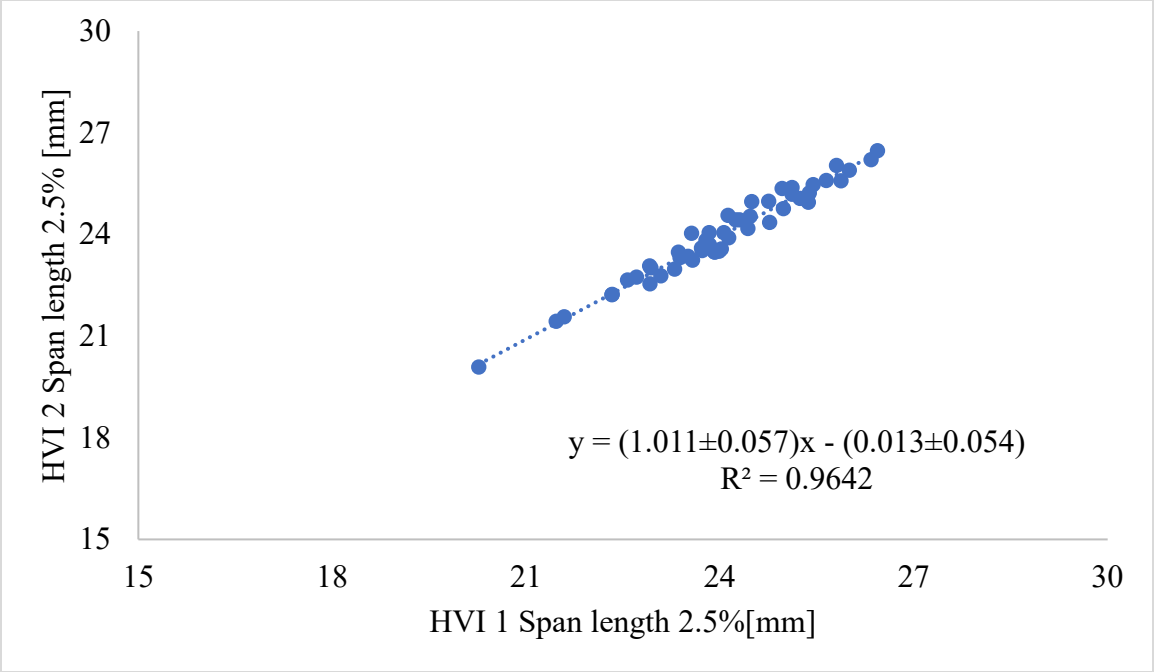

Figure 2. 8: The simple linear regression of span length of 2.5% between HVI 1 and HVI 2 does not show any significant difference.

Table 2. 3: The R2s, slopes and offsets of the simple linear regression between HVI 1 and HVI 2 for selected span lengths.

Span length	R^2	Slope	Offset
2.5%	**0.96**	1.011±0.057	-0.33±1.37
5%	**0.94**	1.008±0.068	-0.23±1.47
10%	**0.92**	1.012±0.086	-0.41±1.63
20%	**0.94**	0.998±0.102	0.03±1.57
30%	**0.84**	0.945±0.117	0.71±1.47
40%	**0.80**	0.918±0.132	0.97±1.35
50%	**0.75**	**0.860±0.142**	**1.35±1.14**
60%	**0.68**	**0.817±0.162**	**1.5±0.94**
70%	**0.63**	0.859±0.190	**1.07±0.74**
80%	**0.58**	**0.783±0.192**	**0.99±0.46**
90%	**0.53**	1.120±0.306	**0.33±0.29**

Bold R^2 shows a statistically significant relationship between HVIs.

Bold slope and offset shows relationships that are significantly different from 1 and 0 respectively.

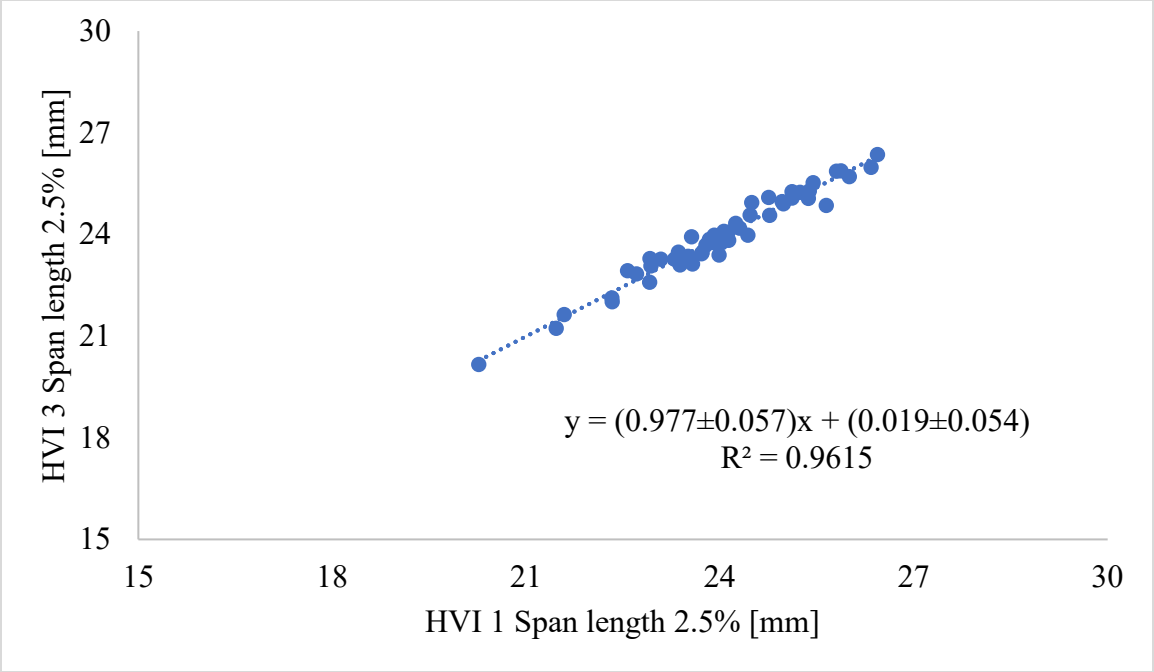

Figure 2. 9: The simple linear regression of span length of 2.5% between HVI 1 and HVI 3 does not show any significant difference.

Table 2. 4: The R2s, slopes and offsets of the simple linear regression between HVI 1 and HVI 3 for selected span lengths.

Span length	R2	Slope	Offset
2.5%	**0.96**	0.977±0.057	0.48±1.37
5%	**0.95**	0.979±0.064	0.41±1.37
10%	**0.93**	0.982±0.076	0.28±1.45
20%	**0.90**	0.962±0.092	0.58±1.42
30%	**0.86**	0.919±0.109	1.07±1.37
40%	**0.81**	0.871±0.142	1.42±1.24
50%	**0.75**	**0.807±0.134**	**1.75±1.07**
60%	**0.67**	**0.720±0.148**	**2.08±0.86**
70%	**0.57**	**0.759±0.190**	**1.65±0.74**
80%	**0.57**	0.805±0.203	**1.14±0.48**
90%	**0.53**	1.247±0.344	**0.38±0.3**

Bold R^2 shows a statistically significant relationship between HVIs.

Bold slope and offset shows relationships that are significantly different from 1 and 0 respectively.

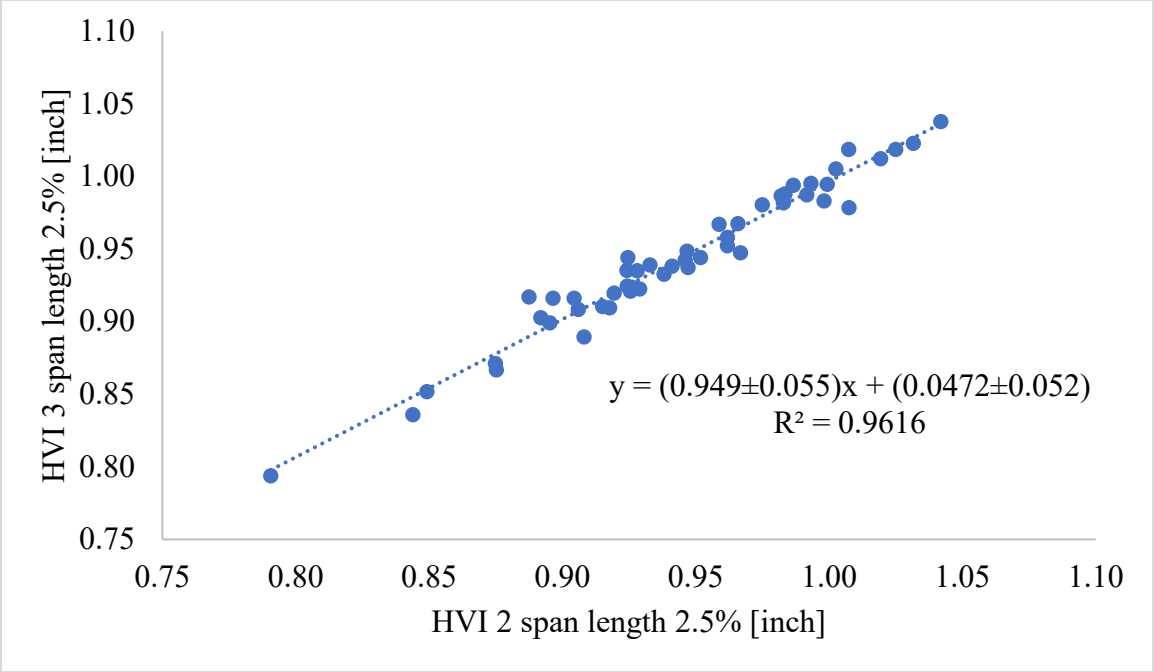

Figure 2. 10: The simple linear regression of span length of 2.5% between HVI 2 and HVI 3 does not show any significant difference.

Table 2. 5: The R2s, slopes and offsets of the simple linear regression between HVI 2 and HVI 3 for selected span lengths.

Span length	R^2	Slope	Offset
2.5%	**0.96**	0.949±0.055	1.19±1.32
5%	**0.95**	0.945±0.063	1.19±1.37
10%	**0.93**	0.923±0.074	1.47±1.4
20%	**0.90**	0.906±0.090	1.47±1.37
30%	**0.86**	0.894±0.106	1.35±1.35
40%	**0.83**	**0..859±0.114**	**1.45±1.19**
50%	**0.79**	**0.832±0.126**	**1.35±1.04**
60%	**0.73**	**0.760±0.135**	**1.52±0.84**
70%	**0.64**	**0.742±0.162**	**1.35±0.71**
80%	**0.61**	0.813±0.188	**0.71±0.53**
90%	**0.56**	0.834±0.216	**0.41±0.3**

Bold R^2 shows a statistically significant relationship between HVIs.

Bold slope and offset shows relationships that are significantly different from 1 and 0 respectively.

2.5. Conclusion

It is possible to extract the raw data from the fibrograms reported in vectored graphic files from the HVI software. The process of extracting the raw data using a MATLAB script is efficient compared to manual extraction. Therefore, it would be possible to perform statistical analysis on the whole fibrogram curve to determine whether it holds any potential fiber length information.

For a given HVI, the selected span lengths observed show that the fibrograms is stable both on the short-term and long-term. Therefore, fibrogram curve could be used as a potential fiber length measurement if it holds important fiber length information that are not used currently.

The results obtained for the stability of the fibrogram across HVIs show that all the HVIs at FBRI provide consistent results for the portion of the fibrogram curve which represents the longer fibers in the sample while the portion of the fibrogram that represents the shorter fibers in the samples shows more variation among HVIs. It means that a correction procedure is needed to bring all machines at the same level.

2.6. References

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CHAPTER 3

CHARACTERIZING THE TOTAL WITHIN-SAMPLE VARIATION IN COTTON FIBER LENGTH USING THE HVI FIBROGRAM

3.1. Introduction

Cotton fiber is a naturally produced industrial raw material that exhibits within-sample variation in length and other fiber quality attributes. Within-sample variation in cotton fiber length is important in every sector of the cotton industry (Kelly and Hequet, 2018; Kelly et al., 2013; Wakeham, 1955). While, everything else being equal, it is possible to produce finer and stronger yarns with samples that possess a longer mean length (El Mogahzy et al., 1990; Krifa and Ethridge, 2006; Thibodeaux et al., 2008a), all of the fibers in the samples can affect processing and yarn quality (Cai et al., 2013). Samples with high length variation among fibers result in an increased number of imperfections in the yarn, slower processing speeds, and increased waste (Backe, 1986; Behery, 1993; Faulkner et al., 2012; Tallant et al., 1959; Thibodeaux et al., 2008a).

High Volume Instrument (HVI) testing is widely used for cotton classification and research. Breeders often use HVI cotton fiber length measurements along with other fiber properties to select their breeding lines and ultimately release cultivars that fulfill the demand of the textile industry (Kelly and Hequet, 2013; Kelly et al., 2012). HVI length parameters, Upper Half Mean Length (UHML) and Uniformity Index (UI), are often the only fiber length measurements available to spinners purchasing U.S. cotton bales. These length measurements are readily available and are used by spinning mills to

select bales with the potential to meet their production goals (El Mogahzy and Gowayed, 1995).

Processes from harvesting to ginning and cleaning break fibers and alter the within-sample distribution of fiber length (Armijo et al., 2019; Hardin et al., 2018; Hughs et al., 2013). Even spinning processes can degrade fiber quality by breaking fibers, and as a result, the quality of fiber in the yarn is not the same as the quality of the raw fiber (Krifa, 2008, 2006). However, it is often not possible to track these changes through processing using the most common fiber length parameters provided by the HVI.

HVI fiber length measurements are based on the fibrogram principle originally proposed by Hertel (Hertel, 1940). In order to measure fiber length using this principle, a comb collects a sample of fibers to produce a fiber beard (Figure 3. 1) (Chu and Riley, 1997). Before measurement, the beard is brushed to remove loose fibers and trash particles. The beard is then scanned over a light source starting 3.81 mm away from the base of the comb to the end of the fiber sample (Krowicki and Ramey, 1984; Krowicki and Thibodeaux, 1990), and a receiver on the opposing side of the beard is used to measure the amount of light attenuated by the beard. The starting point of the scanning of the beard is the maximum point of light attenuation and is used to standardize the measurement to 100%. As the beard is scanned over the light toward its tips, where fewer fibers are present to block the light, the scan eventually reaches a point where no fibers are long enough to attenuate the light. This results in a 0% point on the curve. The change in attenuation from 100% to 0% builds a curve called the fibrogram (Figure 3. 2) (Chu and Riley, 1997; Hertel, 1940).

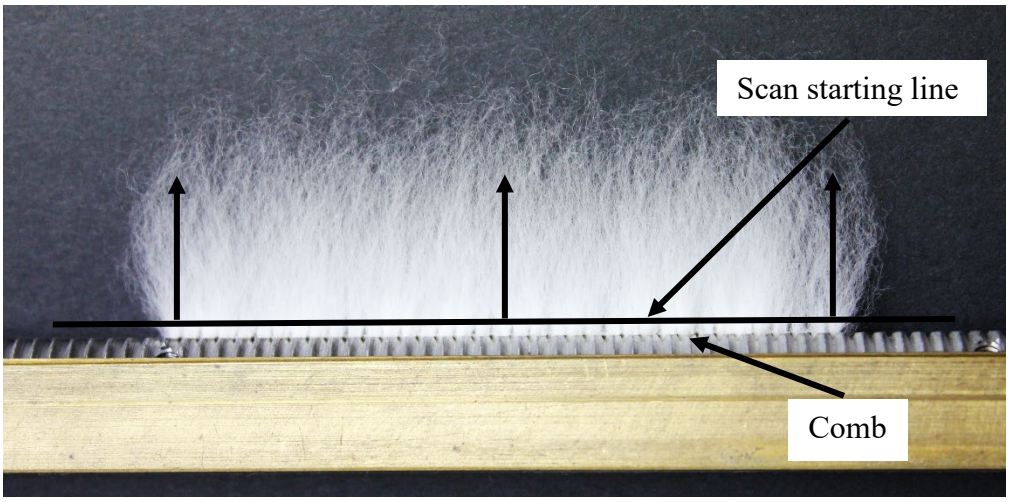

Figure 3. 1: A fiber beard prepared with a fibrosampler shows how fibers are scanned for the fiber length measurements with HVI.

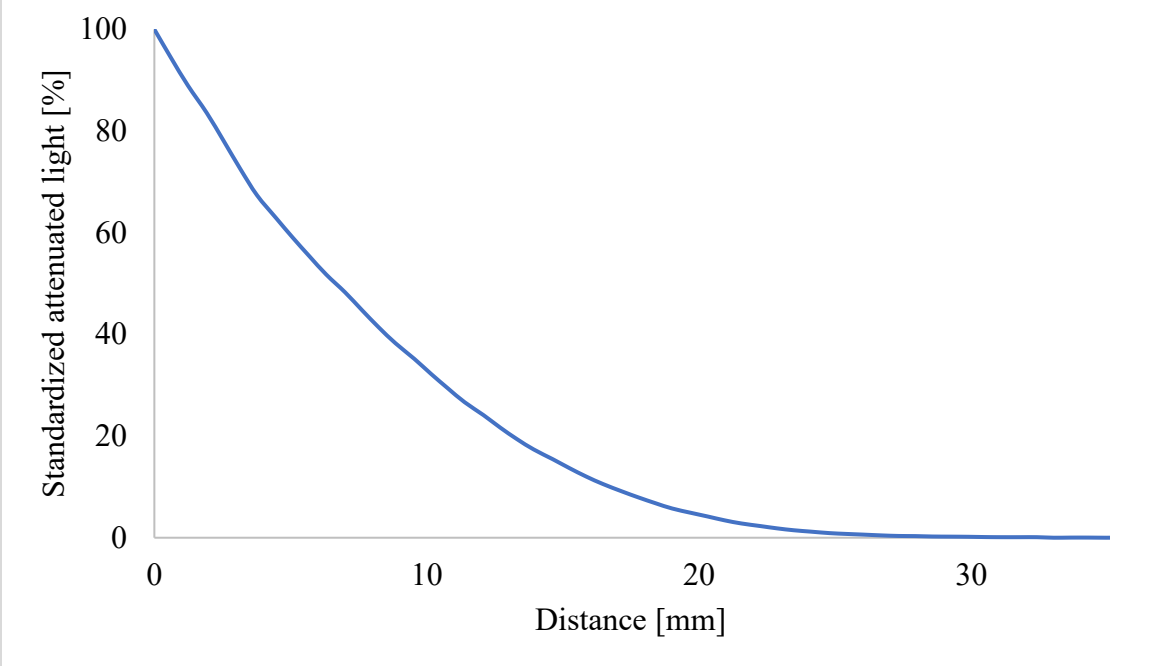

Figure 3. 2: A typical fibrogram generated by High Volume Instrument (HVI).

Two length measurements, Upper Half Mean Length (UHML) and Mean Length (ML), are extracted from the HVI fibrogram. Uniformity Index (UI) is then obtained by calculating the ratio of ML to the UHML expressed as a percentage. Because many fibers are not measured by the HVI length module, i.e., they are either trapped in the comb needles or they do not extend into the portion of the beard used to measure length, these two length parameters represent only the longer fibers in the sample (Hertel and Lawson, 1964; Krowicki and Ramey, 1984; Krowicki and Thibodeaux, 1990). After extracting these two length measurements, the fibrogram data are discarded by the instrument.

The limitation of relying on current HVI fiber length parameters is that they do not characterize the total within-sample variation in fiber length needed to explain variation in yarn quality (Cai et al., 2013; Kelly and Hequet, 2018; Wakeham, 1955). The current HVI system does not measure fiber length variation related to shorter fibers in the sample (Zeidman et al., 1991; Zeidman and Batra, 1991). A higher short fiber content (SFC) in the raw cotton increases the rate of yarn breakage during manufacturing with in high-speed modern spinning systems and also increases the hairiness level of the yarn (Thibodeaux et al., 2008a; Zeidman and Batra, 1991). SFC negatively affects the manufacturing process and ultimately the end product quality (Tallant et al., 1959; Thibodeaux et al., 2008a). The negative impact of short fibers on yarn quality creates a need for the cotton industry to have a better measurement of SFC in raw cotton (Cai et al., 2011; Thibodeaux et al., 2008b; Zeidman et al., 1991; Zeidman and Batra, 1991).

Within sample variation in cotton fiber length can be measured with an Advanced Fiber Information System (AFIS) (Kelly and Hequet, 2018). The AFIS measures the

length by number based on individual fibers and provides the complete fiber length distribution as a histogram (Figure 3. 3) (Bragg and Shofner, 1993). Because they are based on the full within-sample variation in fiber quality, AFIS fiber length measurements hold important information needed for the development of germplasm with improved spinning performance (Kelly and Hequet, 2013, 2018; Kelly et al., 2013). While the AFIS fiber length measurement is faster than many other methods, it is too slow to be practical to meet the demands of the commercial cotton classification.

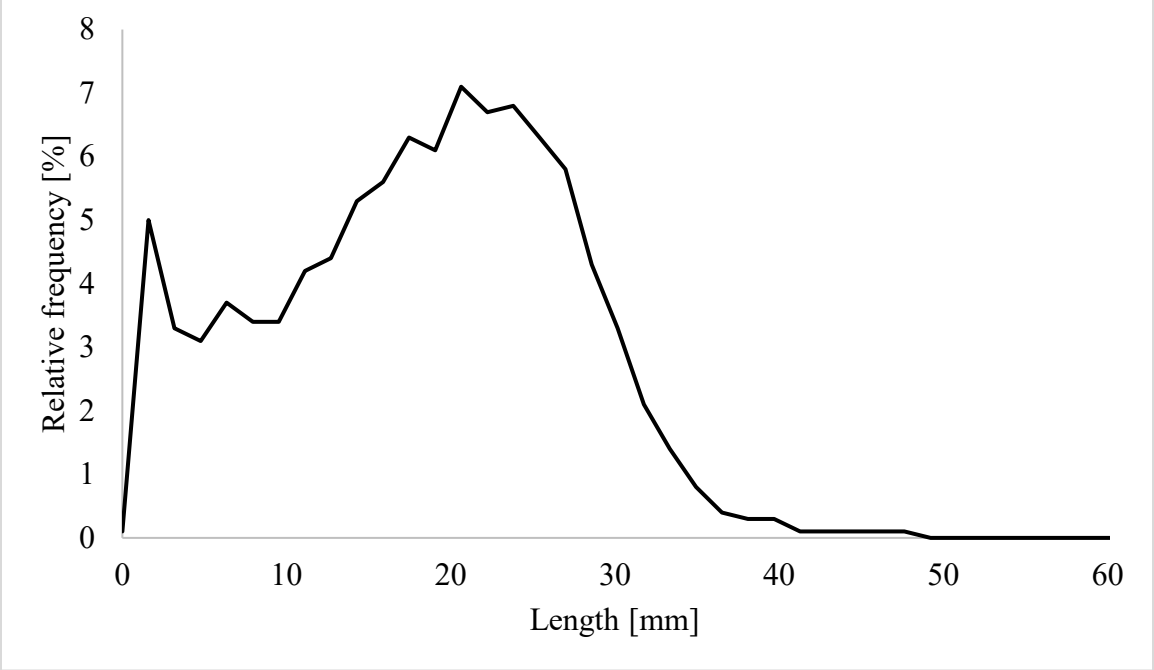

Figure 3. 3: Complete fiber length distribution by number measured with Advanced Fiber Information System (AFIS).

HVI length parameters based on current laboratory protocols measure only the longest fibers in the fiber beard, but the parameters are extracted from a curve that characterizes variation in the lengths of all fibers included in the measured beard. The first objective of this research is to characterize the relationship between the most

common HVI length parameters, UHML and UI, and the fibrogram. The second objective is to develop a method for defining new length parameters that characterize variation in the fibrogram that is not captured by UHML and UI. Finally, we evaluate whether the information captured by these new length parameters is useful for explaining yarn quality.

3.2. Materials and Methods

The first analysis, relating UHML and UI to the variation in the fibrogram, is based on samples taken from a large subset of the commercial production in the United States. These samples are used to identify the portion of the fibrogram captured by current HVI length measurement protocols. A small subset of the commercial samples is then used to identify additional variation not currently captured by UHML and UI, effectively defining new length parameters derived from the complete fibrogram curve. The investigation into the usefulness of the new length parameters requires samples large enough to produce yarn. Thus, the usefulness of the new length parameters is evaluated on two sample types, with one set representing a range of fiber quality that might be present in a breeding program and the other set representing a range of fiber quality expected in commercial bales. . These two sets of samples are different than the sample set used to characterize the fibrogram fiber length variation.

Each of these experiments depends on evaluating the within-sample variation of fiber length using the fibrogram. Two operation modes of the HVI were needed to assess this variation in quality:

System Testing –The typical HVI fiber quality report is provided by the system testing operating mode. The report includes several important fiber quality parameters

such as UHML, UI, Strength, Micronaire, Yellowness, and Reflectance. This mode does not provide a fibrogram curve. The fiber length measurements (UHML and UI) for this mode are calibrated with two USDA standard samples.

Module Testing – HVI has three independent testing modules, i.e., length and strength, micronaire, and color and trash. The Length and Strength module allows the operator to test using only the length and strength portion of the instrument. For the strength measurement, micronaire needs to be entered manually as it is one of the variables used to determine the mass of the sample being broken. This module provides a non-calibrated fibrogram curve. The portion of the fiber beard going from the edge of the comb to the scanning starting point is 3.81 mm (0.15 inch) long and is the same for all Uster HVIs (Hertel and Lawson, 1964; Krowicki and Ramey, 1984; Krowicki and Thibodeaux, 1990). Values are expressed as distances and not lengths because the starting offset distance is not included for analysis in this research. However, this is a constant offset and including it should not change the presented results.

The fibrogram curve is reported as a vectored image file and not a raw data file. Thus, a specialized procedure is required for extracting the fibrogram data and using the information present in the curve.

3.2.1. Extracting the Fibrogram

The data points of the fibrogram represent the standardized attenuated light amount as a function of the distance traveled by the fiber beard through the light sensing apparatus inside the HVI. The HVI records the level of attenuated optical light with a 0.635 mm (0.025 inch) step from 0 mm to 50.8 mm, resulting in 81 data points when including the zero point. The HVI reports these data points when run in module testing as vectored

plots embedded in an excel file. A MATLAB (Math Works Inc., MATLAB R2018a) script was developed to automate the extraction of the 81 data points that characterize the fibrogram generated by the HVI for each sample.

The fibrogram is used to measure lengths, such as UHML and UI, but the raw response values for the fibrograms are reported as standardized attenuated light in percentage for a given displacement (Figure 3. 2). We transposed the fibrogram curves to a set of fixed light attenuation levels in order to have a curve measurement where distance is the response (Figure 3. 4). All fibrogram analyses in this paper have been conducted on transposed fibrograms where distances are the response values. This conversion ensures the data extracted from the fibrogram curves during further statistical analysis is proportional to fiber length and not attenuated light.

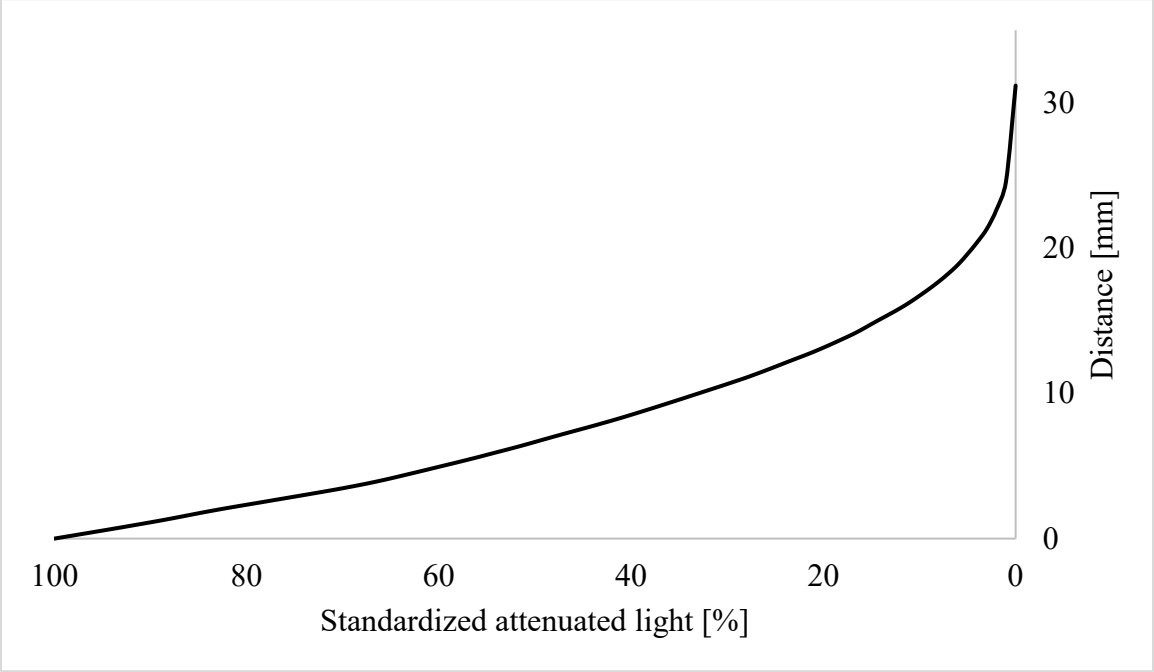

Figure 3. 4: An illustration of the transposed fibrogram where distance is the response values.

The transposition into a distance-response curve was conducted with the MATLAB script to export the data from the HVI report. The optimal number and location of the interpolation points depend on the sample set and type. Because this was an initial investigation into the fibrogram and three types of samples were used in the analysis, the script was setup to identify fixed 1% intervals between 0% to 100% standardized attenuated light. This resulted in a distance-response curve of span lengths for 101 light attenuation levels. The span length 100 is an origin point and is always zero, and the span length at 0% does not characterize fiber length data. Therefore, these two span lengths were excluded from the analysis. This set of 99 span lengths was used in the analysis of all datasets included in this paper.

3.2.2. Current fiber length parameters

An evaluation of standard HVI length parameters, UHML and UI, is needed before defining new length parameters. A set of 19,628 USDA AMS samples covering a wide range of fiber length characteristics seen in commercial production were selected to meet this objective. A 4-4-10 (4 color and trash measurements; 4 micronaire measurements; 10 length and strength measurements) testing research protocol was used to obtain the typical HVI fiber quality parameters of 19,628 USDA AMS samples. These samples were measured with HVI (Uster HVI ™ 1000) at the Fiber and Biopolymer Research Institute (FBRI) from 2011 to 2016. While the HVI reports UHML and UI, it measures UHML and ML. The UI parameter is not measured directly but is calculated as the ratio of ML to UHML expressed as a percentage. In this part of the study, the raw values measured by the HVI were evaluated by calculating ML from UHML and UI. The linear correspondence of UHML and ML was determined using simple linear regression.

3.2.3. Investigation of the fibrograms

The fibrogram is reported by the HVI when using the Length and Strength Module Testing mode. In order to obtain the full suite of typical HVI fiber quality characteristics along with the fibrogram data, the samples were first run in the system test mode followed by a length and strength module test.

A sub-set of 538 USDA AMS samples out of the 19,628 original samples was measured with HVI Length and Strength Module Testing with 10 replications to evaluate the fibrogram curves. The distance-response fibrogram curve were generated and each sample was represented as the average of the 10 length and strength module replications.

The 99 points in the distance-response curves are multicollinear and do not characterize unique types of length variation. A principal component analysis (PCA) of the averaged fibrograms was used to summarize the total variation in fiber length captured by the fibrogram (Math Works Inc., MATLAB R2018a). The PCA characterizes each type of variation in the fibrogram curve, such as magnitude and shape, as independent variables called scores.

While these scores are commonly used to plot the original data in a PCA biplot, they can also be used as independent variables in a statistical analysis (Jolliffe, 1982). In this research, these scores were used to define independent variables that characterize the maximum amount of length variation captured by the fibrogram as linear combinations of the original 99 span lengths. The formula used to calculate the scores was saved and applied in other types of analysis described in this paper.

3.2.4. Explaining variation in yarn quality

3.2.4.1. Sample selection

Fiber length characteristics depend on genetics, environment, and fiber processing (Armijo et al., 2019; Hardin et al., 2018; Kothari et al., 2015; Porter et al., 2017; Richmond and Fulton, 1936; Wanjura et al., 2019). Processes such as lint cleaning can break fibers and alter the within-sample distribution of fiber length. Breeder samples can have a wider range of genetic variation and are subjected to different processes than commercial samples. All of these factors have the potential to affect the within-sample distribution of fiber length and, as a result, the fibrogram curve. Therefore, it is important to determine whether the fiber length variation captured by the whole fibrogram can be useful to predict yarn quality for different types of samples. Two sets of samples with a sufficient amount of fiber for spinning trials, and which represent different sample types, were selected for this experiment (Table 3. 1 and Table 3. 2).

Set A: A set of 60 commercial-like samples representing a wide range of fiber length were selected for this experiment. This set consists of twelve commercial varieties grown in five different locations across the Texas High Plains in 2016: locations in Cochran, Terry, Mitchell, Bailey and Gaines County. The twelve varieties grown in each location included FM 1830 GLT, FM 1911 GLT, CP 3475 B2XF, DP 1522 B2XF, DP 1612 B2XF, NG 3517 B2XF, NG 4545 B2XF, NG 3406 B2XF, NG 3405 B2XF, PHY 333 WRF, PHY 243 WRF, and PHY 308 WRF. A John Deere 7460 stripper harvester was used to harvest all locations except Mitchell. The Mitchell county location was harvested using a producer JD 7460 stripper harvester. The samples were ginned at the USDA ARS Cotton Production and Processing Research Unit in Lubbock, TX with a

Continental 93-saw gin –Double Eagle (1575 mm wide). This commercial type gin has saw-type lint cleaner (one), condenser, and bale press. The processing speed of the seed cotton cleaner was two bales per foot per hour while the ginning speed was conducted at a constant speed of 1.5 bales per foot per hour. The averaged moisture content across all the samples was 6.8% prior to ginning.

Set B: A set of 127 diverse samples were selected to have a wide range of fiber quality. Some of these samples are obsolete varieties developed without HVI screening, some are breeder germplasm, and some are commercially grown modern varieties. These samples were grown in an irrigated field at Weslaco Research and Extension Center with one field rep. The samples were harvested with a single-row mechanical spindle type cotton picker (1957 IH) modified for the research plot harvest. The samples were then ginned with a laboratory 10 saw gin without lint cleaner.

3.2.4.2. Fiber quality measurements

The typical HVI fiber quality parameters were measured with a system testing protocol (4 Color and Trash, 4 Micronaire, 10 Length and Strength). The fibrograms were measured with the length and strength module testing mode with 10 replications. The fibrograms were converted to distance-response curves and a PCA was performed on each set to summarize the total within-sample variation in fiber length captured by the fibrogram in the presence of multicollinearity. PC scores were used to represent the variation in fiber length captured by the fibrogram curve.

Fiber length was also evaluated with AFIS (USTER® AFIS Pro 2) for 5 replications of 3,000 fibers. The first cumulative distribution of AFIS length distribution by number was calculated in order to summarize the total within-sample variation. The

PCA was not performed on raw AFIS length distributions by number because it is a frequency distribution. Therefore, the PCA was performed on the first cumulative distribution of fiber length of each set to summarize the total within-sample variation in fiber length captured by the AFIS length distribution by number. PC scores were used to represent the within-sample variation in fiber length captured by AFIS length distribution by number.

Table 3. 1: Summary of HVI fiber quality parameters for two sets of samples.

Fiber quality	Set A				Set B			
	Min	Ave	Max	CV%	Min	Ave	Max	CV%
Micronaire	3.2	4.3	5.2	12.3	3.3	4.6	5.6	9.9
Strength [g/tex]	25.4	28.7	31.9	5.0	24.4	31.2	38.9	9.0
Elongation (%)	6.1	8.6	10.9	13.0	3.10	5.09	7.30	17.9
UHML (mm)	26.7	29.0	31.8	3.5	25.7	29.7	35.1	7.7
UI (%)	77.6	81.3	84.1	1.5	77.9	82.2	85.8	1.8
Rd (%)	70.1	76.2	81.6	3.5	68.6	72.6	75.7	1.8
+b	6.7	8.4	9.6	7.4	6.5	7.7	9.2	6.2

Table 3. 2: Summary of AFIS fiber quality parameters for two sets of samples.

Fiber quality	Set A				Set B			
	Min	Ave	Max	CV%	Min	Ave	Max	CV%
Neps [count/g]	226.0	390.1	608.0	23.3	182.0	357.6	823.0	31.8
UQLw [mm]	27.4	29.7	33.0	3.8	26.2	31.2	37.9	8.5
Ln [mm]	16.8	18.8	22.4	5.8	17.3	20.6	24.9	7.7
SFCn [%]	20.3	30.0	39.0	11.6	14.8	24.7	37.0	16.3
Fineness [mtex]	142.0	163.1	184.0	5.3	136.0	166.1	201.0	7.5
Maturity Ratio	0.77	0.85	0.93	3.9	0.80	0.92	1.01	3.6

3.2.4.3. Yarn production

At least 10 lbs of cotton fibers from each sample were used to produce carded ring spun yarn. A yarn count of 30Ne was identified as a target count for this project. The goal was to produce yarn with a count as close to 30Ne as possible without excluding samples from the spinning trial. A coarser yarn count was used for Set B because some samples did not exhibit a fiber quality profile well-suited for the production of 30Ne yarn. Samples from Set B were spun into 24Ne carded ring spun yarn.

Set A: Cottons from the sample set A was carded (Truetzschler, DK 903) with a production rate of 54.40 kg/hr to produce card sliver. The carded sliver was then drawn

twice with the speed of 548.64 meters/minute and 365.76 meters/minutes respectively, to minimize within sliver variation in mass. After the reduction of the linear density of these slivers by roving (SACO-LOWELL maremont, FC-1B), samples were processed to 30 Ne yarns on a ring spinning frame (Suessen, Fiomax1000) with a speed of 14,588rpm and a twist of 19.93 TPI. Ten bobbins per sample were produced.

Set B: Cottons from sample set B were carded (Rieter, C4) with a production rate of 9.07 kg/hr to produce card slivers. The carded sliver was then drawn twice with a speed of 274.32 meters/minute to minimize within sliver variation in mass. After the reduction of the linear density of these slivers by roving (SACO-LOWELL Maremont, FC-1B), samples were processed to 24 Ne on a ring spinning frame (Suessen, Fiomax1000) with a speed of 13,588rpm and a twist of 18.37 TPI. Ten bobbins of yarn per sample were produced. Samples were processed for a coarser yarn count than set A with a lower production rate.

The yarns were then evaluated for tensile properties and imperfections on 10 bobbins. For each bobbin, the yarn count was determined on 220 meters, and yarn tensile properties were measured on 20 single end breaks performed with the STATIMAT DS (Textechno STATIMAT, Textile testing technology, Germany). In addition to tensile property testing, 400 meters of yarn per bobbin was tested with the Uster Tester 5 (Uster® Technologies AG) for yarn evenness and imperfections.

3.2.4.4. Yarn quality

Genetic and agronomic effects, harvesting and ginning effects, and even the fiber quality measurement methodology can impart collinearity among fiber quality measurements. It is important to control for this multicollinearity when evaluating

whether the full fibrogram curve relates to variation in yarn quality (Mogahzy, 1989). A partial least squares regression was used to relate variation in fiber and yarn quality while controlling for multicollinearity.

Four different Partial Least Square Regression (PLSR) models were set up to investigate whether the full fibrogram contains variation in fiber quality needed to explain some of the variations in yarn quality.

Model 1: Micronaire, Strength, Elongation, Reflectance (Rd) and Yellowness (+b).

Model 2: Model 1 + UHML and UI

Model 3: Model 1 + Length parameters based on the major principal components of variation in the fibrogram

Model 4: Model 1 + Major Principal Components of variation in the AFIS length distribution by number.

Model 1 characterizes variation in yarn quality without length parameters. The importance of fiber length in characterizing variation in yarn quality is well established in the literature (Thibodeaux et al., 2008a; Wakeham, 1955). The model without length parameters is included in this analysis as a point of comparison for the non-nested models and is not expected to be a suitable model.

Model 2 shows a more typical scenario, where UHML and UI are added to Model 1. Model 3 then replaces the typical HVI length parameters, UHML and UI, with the full variation in fiber length captured by the fibrogram. Finally, Model 4 replaces the HVI length parameters with components of variation extracted from the AFIS length distributions by number. Thus, Model 4 provides a model based on individual fiber measurement of the complete within sample distribution of fiber length.

Each model was first evaluated by determining how much variation in yarn quality is explained by each set of fiber quality parameters based on the R2 statistic. While PLSR was selected to prevent overfitting, there is always a risk of overfitting resulting in a reduction in the predictive power of a model. A second statistic was used to evaluate the predictive power of each model.

Leave one out cross validation (LOOCV) is a method used to estimate the mean squared error of prediction (MSE) of PLSR models and is preferred to simple cross-validation when evaluating model fit (Mevik and Cederkvist, 2004). In this procedure, one sample was withheld, and the model was refit to the remaining set of samples. The model was then used to predict the value of the sample withheld from the model and the error in this prediction was recorded. This procedure was repeated until each sample was withheld one time and the error of each prediction was recorded. The average error generated during this prediction provides an estimate of the mean squared error of prediction.

3.3. Results and Discussion

The HVI testing of commercial samples reveals a strong relationship between UHML and ML (Figure 3. 5). The r-squared value between UHML and ML is 0.95, indicating that 95% of the variation in fiber length characterized by UHML is also characterized by ML. While the HVI reports another length parameter, UI, it is calculated from these two variables, UHML and ML (UI = (ML/UHML) * 100).

The ASTM definition of UHML is “the mean length by number, of the longer one half of the fiber by weight” and ML is “the average length of all fibers in the test specimen based on mass-length”(ASTM D123, 2019). However, HVI does not measure

the fiber length by number or by weight; it measures the attenuated optical light along with the distance traveled by the fiber beard during scanning. According to Hertel's fibrogram theory, ML and UHML should be calculated from a tangent to the curve from the 100% and 50% span lengths, respectively. The fibrogram measurements of 538 USDA AMS samples were used to determine how closely the current length parameters follow this theory.

The pairwise correlation between UHML, and each of the span lengths was plotted and used to determine the span lengths used to determine the measurement. This was repeated for HVI UI. Variation in the region of the fibrogram corresponding to the tips of the longest fibers highly correlates with variation in UHML and ML (Figure 3. 6). The highest level of correlation with UHML is with the span length of 1.8%, where the r-squared value is 0.999 (Figure 3. 6). The highest level of correlation with ML is with the span length of 7.8%, where the r-squared value is 0.999 (Figure 3. 7). This suggests UHML is calculated from the 1.8% span length and ML is calculated from the 7.8% span length.

Given that the HVI length parameters are calculated from the highly collinear variation at the 1.8% and 7.8% span lengths, they are unlikely to characterize the total length variation captured by the complete fibrogram curve. Much of the region of the fibrogram representing the shorter fibers is not captured by UHML and UI (Figure 3. 7). This region of the curve may be important, as fibrogram curves exhibit variation across the whole curve rather than only at the longest portion of the curve (Figure 3. 8).

In order to extract additional independent types of length variation from the fibrogram curve, a PCA was performed to identify the largest sources of variation in fiber

length characterized by the full fibrogram, revealing more than one independent type of length variation characterized by the fibrogram curve (Figure 3. 9). The first three variables explain approximately 99% of the variation available in the fiber length.

The relationship between loadings of the first three components with the span lengths shows the types of fiber length variation captured by each component (Figure 3. 10). These three components are independent and characterize different types of fiber length variation. The loadings of the first principal component show a positive relationship with all of the span lengths, while the loadings for the second component show a negative relationship with the span length representing shorter fibers in the sample and positive relationship with the span length representing longer fibers in the sample. Finally, the loadings of the third principal component show a positive relationship with the span lengths representing the shorter and longest region of the fibrogram, and negative relationship with the medium to longer region of the fibrogram. The two span lengths used for the current HVI length measurements (1.8% and 7.8% span length) do not capture the variation in fiber length that can be characterized by the second and third component.

The nature of length variation characterized by each of these principal component axes can be elucidated by comparing them back to the original fibrogram curves. Doing so reveals that the first principal component explains length variation due to differences in the average length of the fibers in the beard, or length magnitude (Figure 3. 10 and Figure 3. 11). This type of length difference is common between samples and accounts for 91% of the total variation in this set. A larger value along this axis represents a sample that has longer fibers overall. While selecting cotton bales based on this variable

could provide more desirable raw material for spinning than the current HVI length parameters, it cannot be used alone as it does not characterize differences in within-sample variation in fiber length.

The second variable explains variation due to the shape differences in the fibrograms and it explains approximately 7% of the total fiber length variation among these samples (Figure 3. 10 and Figure 3. 12). This type of variation is not captured by the standard HVI length parameters. Because this variable captures differences in within-sample variation, some span lengths have a positive correlation with this axis while others have a negative correlation. Thus, a larger value along this axis indicates distributional differences in fiber length that result in a crossover along the fibrogram curve. Excessive within-sample variation in fiber length increases the occurrence of mass imperfections in the yarn (Backe, 1986; Behery, 1993; Tallant et al., 1959; Thibodeaux et al., 2008a). Selecting cotton bales based on this component should help reduce imperfection in the yarn structure.

The third variable captures another type of within-sample variation in fiber length that causes the fibrogram curves to crossover twice Figure 3. 10 and Figure 3. 13). This type of variation among these samples is less common and accounts for 1% of the total variation in fiber length among the samples. While this does not account for a large portion of the total variation, variation in yarn mass is sensitive to within-sample variation in fiber length, and this parameter may hold important information about variation in yarn quality.

HVI length parameters, UHML and UI, do not adequately characterize the total length variation captured by the fibrogram. The total variation in fiber length captured by

the fibrogram can be summarized as linear combinations of span lengths using PCA. The scores from this analysis represent independent sources of variation that parameterize differences in within-sample variation in fiber length. The importance of this additional length information is investigated in the next section by manufacturing yarn and comparing them to more typical HVI and AFIS length parameters in their ability to explain variation in yarn quality.

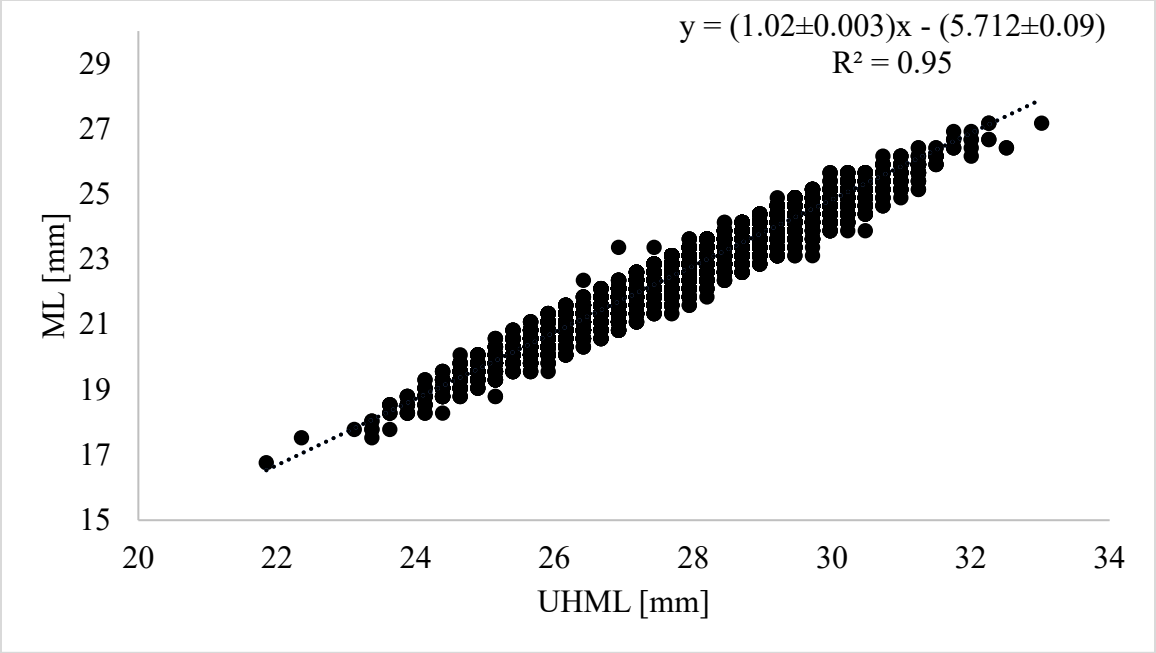

Figure 3. 5: Simple linear regression between UHML and ML of 19,628 USDA AMS samples shows high correlation between current HVI length parameters.

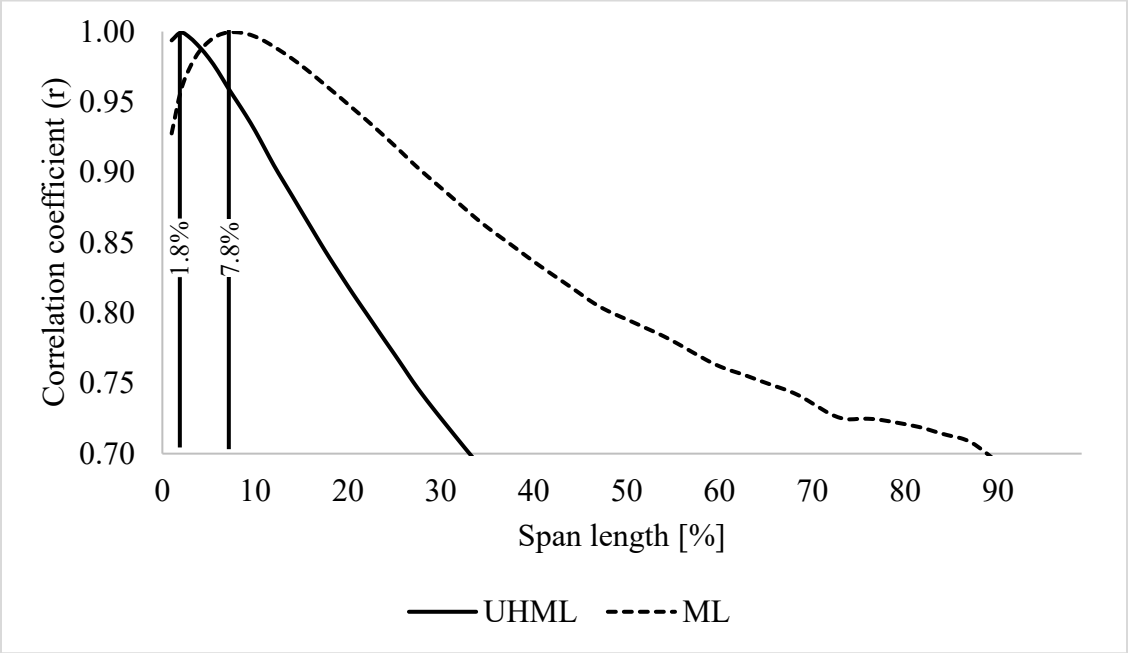

Figure 3. 6: Linear regression of 538 USDA AMS sample's UHML and ML with all the span lengths along with the fibrogram curve shows that the highest correlation of UHML and ML are with 1.8% span length and 7.8% span length respectively.

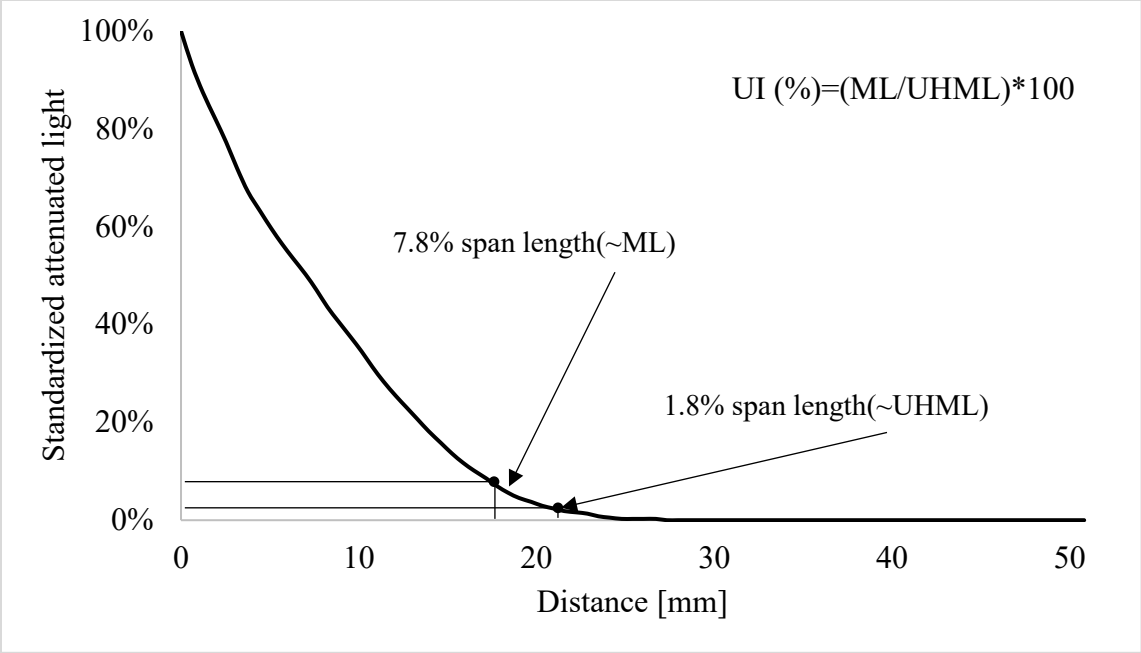

Figure 3. 7: An illustration of the current fiber length measurement principles of HVI which shows the two points from the curve are used for the measurement of UHML and ML.

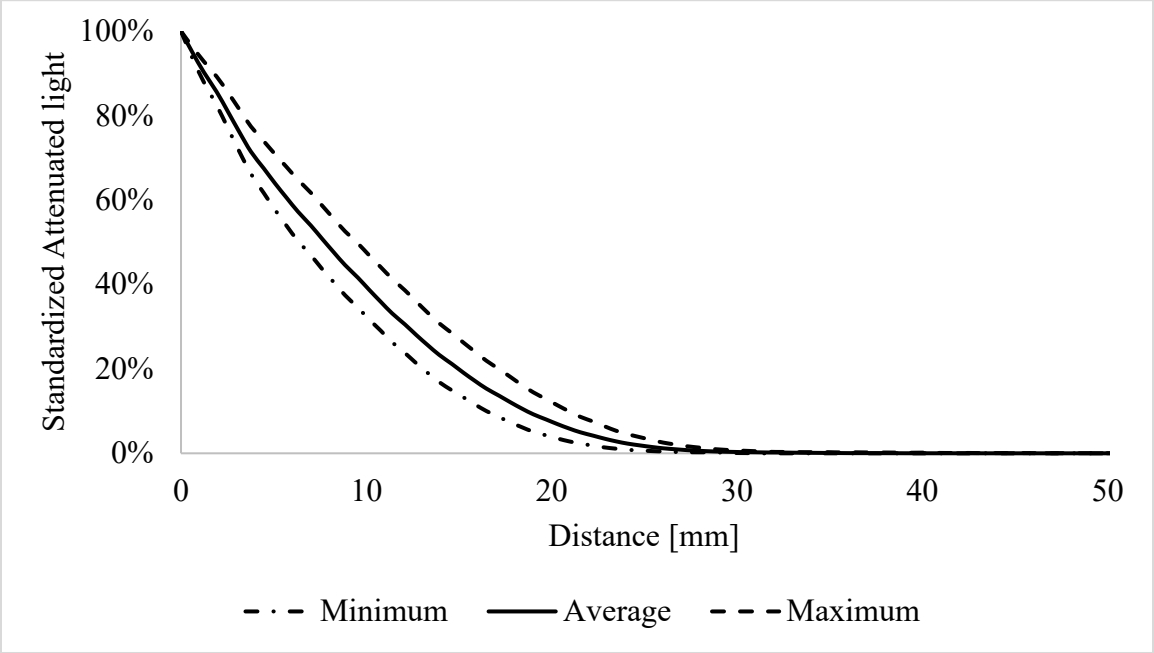

Figure 3. 8: Range of within sample variation in fiber length captured by the fibrograms of 538 USDA AMS samples. The solid line shows the averaged fibrogram while the dashed lines show minimum and maximum values for each length group.

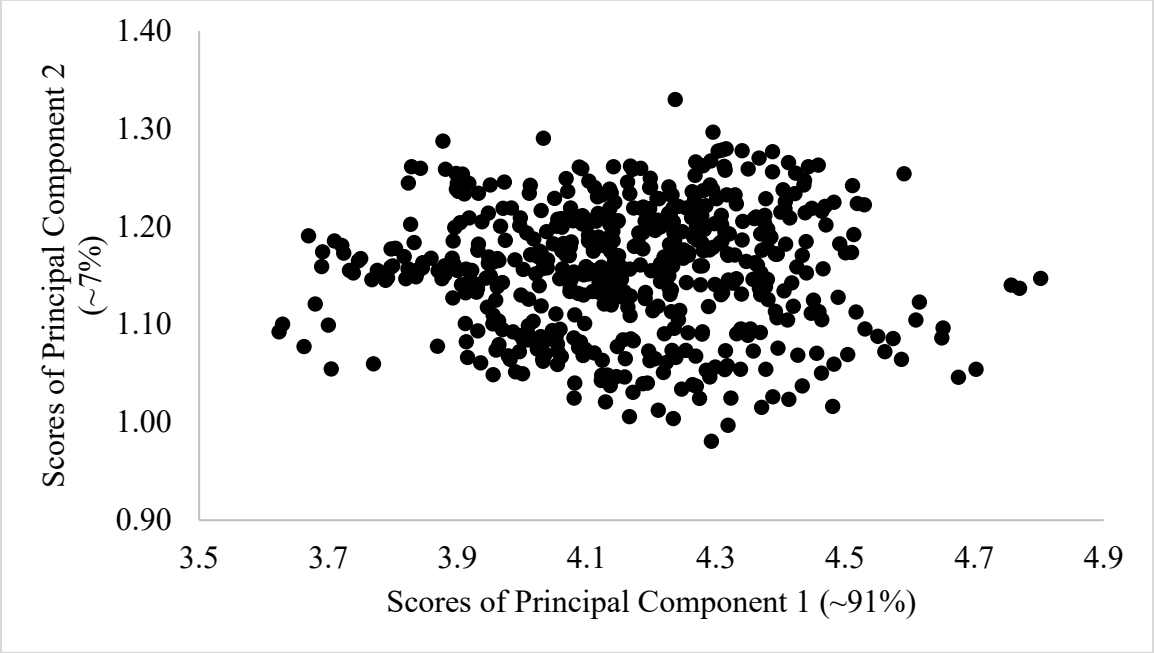

Figure 3. 9: Relationship between scores of first and second principal components shows that they are independent and characterize approximately 98% of the total within sample variation.

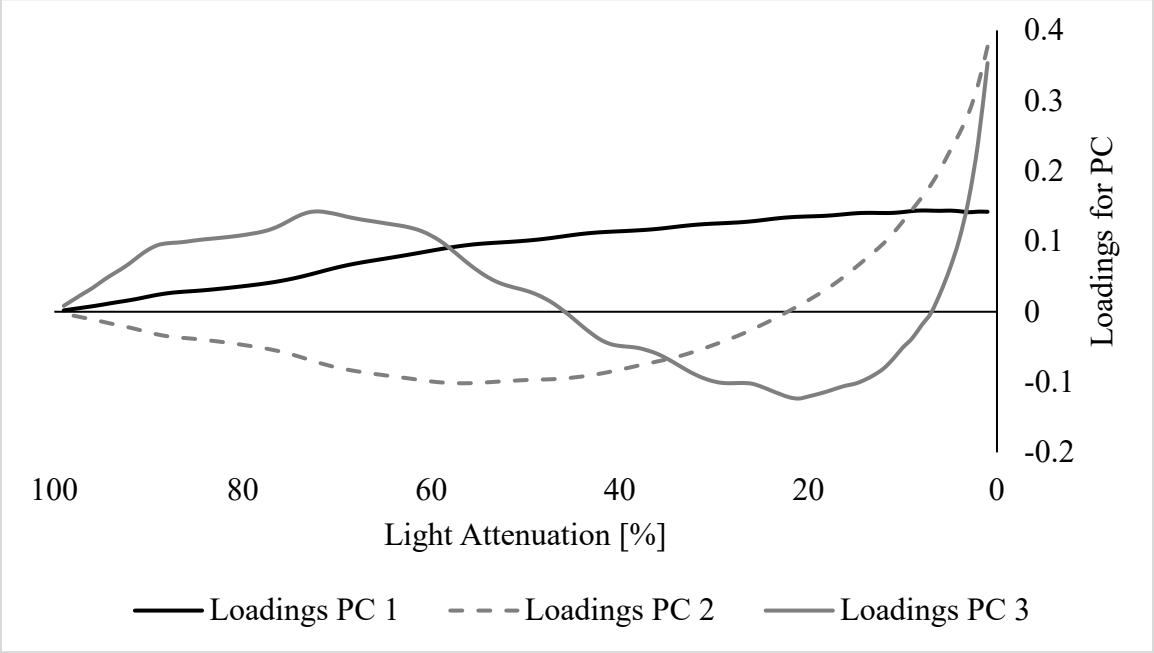

Figure 3. 10: The relationship between loadings of each principal components with the span lengths.

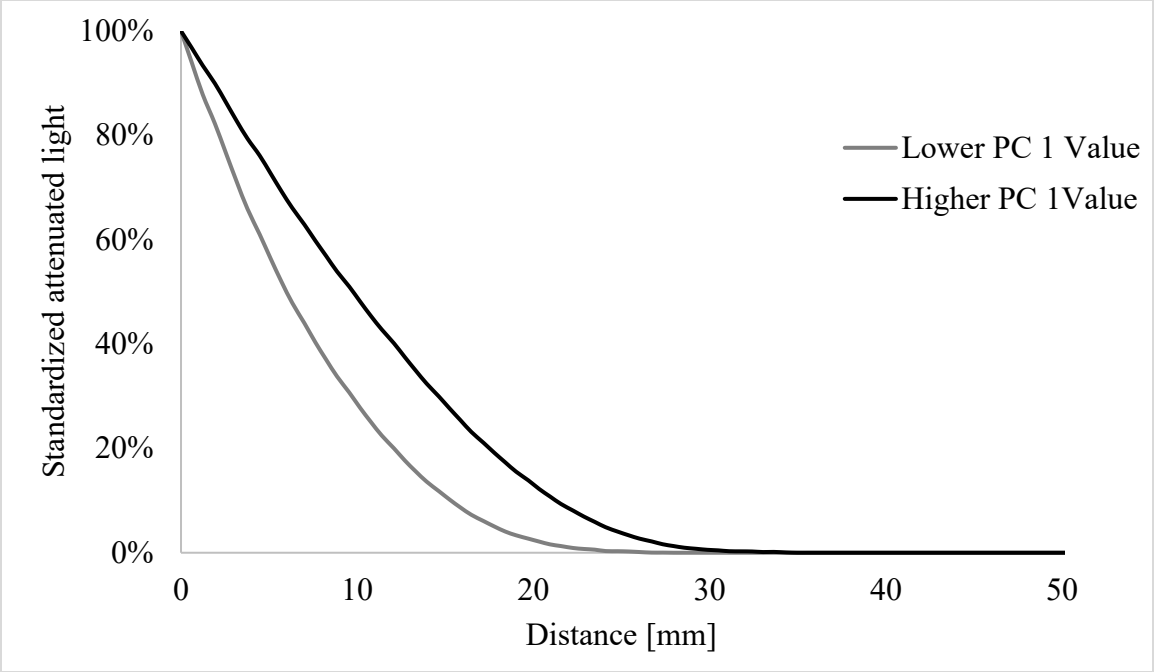

Figure 3. 11: Fibrograms selected based on the difference in newly identified variable 1 show the magnitude difference.

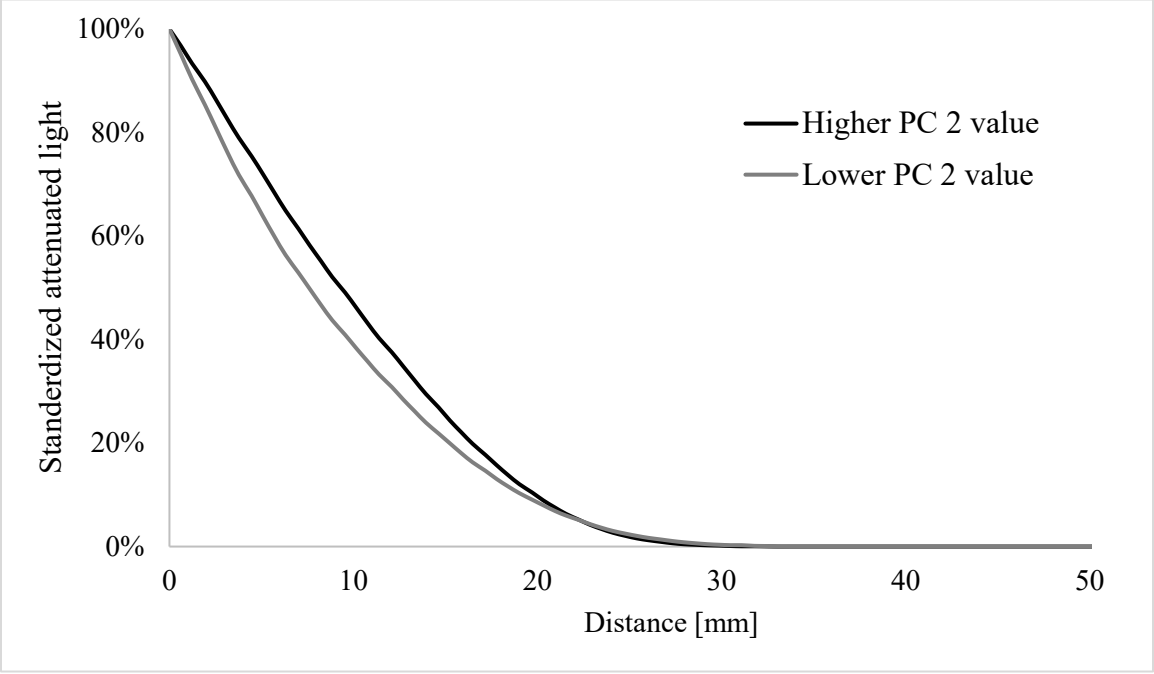

Figure 3. 12: Fibrograms selected based on the difference in newly identified variable 2 show the shape difference.

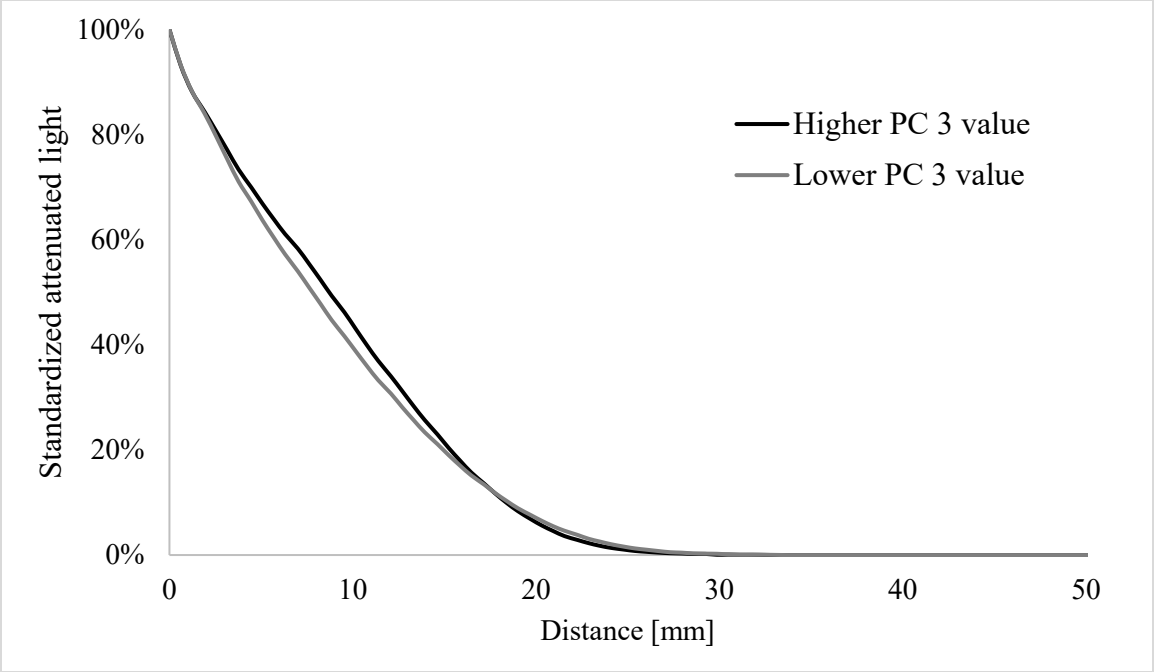

Figure 3. 13: Fibrograms selected based on the newly identified variable 3 show the shape difference caused by double cross over.

3.3.1. Development of prediction models

The yarn spun from the samples chosen for this objective represents a range of yarn quality characteristics for tensile properties and yarn imperfections needed for characterizing the relationships between the model parameters (Table 3. 3 and Table 3. 4). Yarn Tenacity ranges from 9.52 [g/tex] to 15.08 [g/tex] while the coefficient of variation in yarn mass (CVm%), and important yarn quality metric, ranges from 15.08% to 18.88% among the commercial samples. The range in yarn tenacity for the breeder samples is 9.48 [g/tex] to 22.91 [g/tex], while the CVm% ranges from 12.52% to 18.57%. While a direct comparison cannot be made between these two sample sets due to samples

preparation and yarn types, both sets exhibit a range in yarn quality characteristics needed for investigating the impact of variation in fiber quality on yarn quality.

PLSR yarn quality prediction models were chosen for minimizing the multicollinearity caused by the intercorrelation between fiber quality parameters. Regression between observed and predicted yarn quality for both sample sets show a significant linear component in the relationship characterized by the models at the alpha level 0.05 (Table 3. 5).

Table 3. 3: Range of variation in yarn quality parameters for sample set A.

Yarn Quality	Minimum	Average	Maximum	CV%
Tenacity [g/tex]	9.52	11.89	15.08	10.08
CVm%	15.08	16.70	18.88	5.30
Thin places [count/km]	5.00	31.20	99.25	65.96
Thick Places [count/km]	181.25	353.24	606.50	31.73
Neps 200% [count/km]	181.50	371.82	646.25	32.12
Hairiness [no unit]	5.58	6.63	9.00	10.26

Table 3. 4: Range of variation in yarn quality parameters for sample set B.

Yarn Quality	Minimum	Average	Maximum	CV%
Tenacity [g/tex]	9.48	15.01	22.91	19.10
CVm%	12.52	15.17	18.57	7.40
Thin places [count/km]	0.00	9.40	72.50	107.96
Thick Places [count/km]	387.75	1027.48	2076.30	27.77
Neps 200% [count/km]	73.25	246.20	529.75	42.59
Hairiness [no unit]	4.77	5.99	7.08	8.61

Table 3. 5: Pairwise comparison between observed and predicted yarn quality shows significant linear relationship.

Yarn quality	Set A				Set B			
	R^2	F	Slope	Offset	R^2	F	Slope	Offset
CVm%	0.86*	<0.001	0.86±0.09	0.00±0.09	0.77*	<0.001	0.77±0.07	0.00±0.07
Tenacity	0.89*	<0.001	0.89±0.08	0.00±0.08	0.93*	<0.001	0.93±0.04	0.00±0.04

3.3.2. Explaining variation in yarn quality

Fiber length is an important fiber quality characteristic to consider when explaining variation in yarn quality (Table 3. 6 and Table 3. 7). Models of yarn quality

that do not include fiber length information explain the lowest amount of variation in yarn quality.

The greatest amount of variation in an imperfection parameter explained by the model without a length parameter (Model 1) is hairiness, explaining 51% (Table 3. 6) for the commercial-like samples and 75% (Table 3. 7) for the diversity set. This stands in contrast with the amount of variation explained in yarn tenacity. When not using a length parameter, the standard HVI parameters explained 66% (Table 3. 6) of the variation in yarn tenacity among the commercial-like samples and 86% (Table 3. 7) of the variation in yarn tenacity among the diversity set.

The length parameters that hold the most important information for explaining yarn quality are those provided by the full fibrogram. Models including the full information extracted from the fibrogram (Model 3) have the greatest explanatory power of the models considered. The models including full fibrogram-based length parameters explained 89% of the variation in yarn tenacity for the commercial-like samples (Table 3. 6) and 93% of the variation in yarn tenacity for the diversity set (Table 3. 7), this is more than either the standard HVI length parameters or the AFIS length distribution-based length parameters (Model 4).

Information about fiber length provided by the full fibrogram provides a greater improvement when explaining the occurrence of yarn imperfections. The standard HVI parameters, including UHML and UI, explained 74% of the CVm% among the commercial-like samples and 69% among the diversity set. Replacing UHML and UI with the length parameters based on the full fibrogram increased this to 86% and 78%,

respectively. Excessive within-sample variation in fiber length increases within-sample variation in yarn mass captured by the CVm% measurement.

Despite characterizing the complete within-sample variation in fiber length, the AFIS length distribution does not improve the explanatory power of the models over the variables extracted from the full fibrogram (Table 3. 6 and Table 3. 7). The AFIS length parameters improved explanatory power over the standard HVI length parameters, UHML and UI, but did not exceed the explanatory power of the length parameters based on the full fibrogram. Complete fibrogram explains yarn quality better than or at least as good as AFIS length distribution by number. One reason could be the number of fibers tested per sample. Samples were measured with AFIS with 5 replications of 3,000 fibers totaling 15,000 fibers per sample. On the other hand, a fiber beard contains more than 20,000 fibers. If we assume the weight of a fiber beard is 80 mg, the ML is 20 mm by number and the fineness is 170 mtex, then the number of fibers in that beard would be 23,530. For ten replications the total number of fibers tested would be approximately 235,300 which is 26 times larger than AFIS fiber length measurements. Therefore, fibrograms may represent the original samples more accurately than the AFIS length distribution by number.

3.3.3. Evaluating goodness of fit

The fibrogram improves the estimated goodness of fit of the models captured by MSE, as models including length parameters derived from the full fibrogram provide the lowest mean squared error of prediction.

Models constructed with the base HVI parameters without including any length parameters have a poorer goodness of fit based on MSE. The MSE for the models

characterizing variation in yarn produced from the commercial-like bales ranges from 0.18 to 0.49 (Table 3. 6), while the MSE for models based on the diversity set ranges from 0.15 to 0.83 (Table 3. 7).

The estimated model MSE indicates an improved fit with the addition of the standard HVI length parameters, UHML and UI. The model of Thick places for the commercial-like bales based on HVI fiber quality parameters with UHML and UI has an MSE of 0.27, compared to 0.49 with no length parameter (Table 3. 6). Similarly, the model of Thick Places for the diversity set based on HVI fiber quality parameters with UHML and UI has an MSE of 0.78, compared to 0.83 with no length parameter (Table 3. 7).

Length parameters based on the complete fibrogram provide another improvement in the estimated model MSE. For the commercial-like bales, the model of Thick places based on HVI fiber quality parameters including the length parameters based on the full fibrogram in place of UHML and UI has an MSE of 0.17, compared to 0.49 with no length measurement and 0.27 with UHML and UI (Table 3. 6). Similarly, the model of Thick Places for the diversity set when using the length parameters based on the full fibrogram in place of UHML and UI has an MSE of 0.62, compared to 0.83 with no length measurement and 0.78 with UHML and UI (Table 3. 7).

Improvements in the AFIS length distribution have been shown to result in an improved yarn quality (Kelly et al., 2013). The results presented here are consistent with this literature, as the length distribution by number from AFIS provides an improvement in MSE over the standard HVI length parameters, UHML and UI. However, the models including the total variation captured by the AFIS length distribution do not have a better

MSE than the model including the length variation captured from the complete fibrogram. MSE for the yarn quality models with AFIS length distribution by number is not lower than the yarn quality model constructed with the complete fibrogram (Table 3. 6 and Table 3. 7).

Table 3. 6: Sample set A. The R2s show the amount of variation in yarn quality explained by different models. The MSEs, analyzed by the Leave-one-out cross-validation process, show the performance of each model while predicting yarn quality.

Model	Tenacity [g/tex]		CVm%		Thin places [count/km]		Thick Places [count/km]		Neps [count/km]		Hairiness [no unit]	
	R^2	MSE	R^2	MSE	R^2	MSE	R^2	MSE	R^2	MSE	R^2	MSE
1	0.66	0.41	0.46	0.49	0.40	0.49	0.45	0.49	0.42	0.45	0.51	0.18
2	0.82	0.23	0.74	0.26	0.63	0.34	0.73	0.27	0.69	0.27	0.84	0.07
3	0.89	0.16	0.86	0.14	0.77	0.22	0.83	0.17	0.78	0.19	0.87	0.05
4	0.86	0.19	0.70	0.29	0.56	0.38	0.68	0.31	0.62	0.33	0.77	0.09

Table 3. 7: Sample set B. The R2s show the amount of variation in yarn quality explained by different models. The MSEs, analyzed by the Leave-one-out cross-validation process, show the performance of each model while predicting yarn quality.

Model	Tenacity [g/tex]		CVm%		Thin places [count/km]		Thick Places [count/km]		Neps [count/km]		Hairiness [no unit]	
	R^2	MSE	R^2	MSE	R^2	MSE	R^2	MSE	R^2	MSE	R^2	MSE
1	0.86	0.15	0.66	0.38	0.43	0.63	0.24	0.83	0.35	0.72	0.75	0.27
2	0.89	0.13	0.69	0.36	0.47	0.60	0.32	0.78	0.43	0.65	0.83	0.19
3	0.93	0.09	0.78	0.26	0.49	0.61	0.48	0.62	0.46	0.64	0.89	0.13
4	0.89	0.13	0.73	0.31	0.47	0.61	0.43	0.66	0.46	0.65	0.81	0.23

3.4. Conclusion

Fiber length parameters measured using current HVI protocols do not adequately characterize within-sample variation in fiber length. The two fiber length parameters

(UHML and UI) reported by HVI are based on the measurements of 1.8% span length and 7.8% span length, which are highly correlated and only characterize variation in the length of the longest fibers in the sample. The results presented in this paper demonstrate that more information is available in the fibrogram curve than is currently used.

When considering variation along the whole fibrogram curve, and not just two highly collinear points on the curve, it is possible to characterize more than one type of fiber length variation among samples. These can be used to define new length parameters that better capture within-sample variation in fiber length. Because these parameters are based on the HVI fibrogram, they can provide cotton breeders valuable information from an instrument they are already using, the HVI.

Variations in fiber length based on the full fibrogram are also important for explaining variation in yarn quality. Using an independent statistic, our results showed that the new fiber length variables also improve the prediction of yarn quality over standard HVI length parameters, and they may be as good as the variation in fiber length captured by the AFIS length distribution by number. These new length parameters could provide spinning mills important information needed to identify raw materials needed to meet their production goals.

While these results are encouraging, more work needs to be done. Currently, HVI UHML and UI measurements are calibrated based on a two-point calibration protocol. This calibration is performed after the 1.8% and 7.8% span lengths are extracted from the fibrogram curve, leaving the remaining curve uncalibrated and unused. If it is to be used, the calibration of the HVIs with the whole fibrogram needs to be investigated.

While the approach presented here is an attempt to characterize the whole fibrogram curve, other strategies may exist. It may also be possible to identify a set of span lengths that adequately capture variation characterized by the fibrogram curve. Either approach would need to be automated and reported in a format familiar to the cotton research community. Once these new measurements are shown to be stable, and a calibration method is developed, these parameters will provide the cotton industry with a new method for assessing the within-sample distribution of fiber length without the need for additional testing.

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CHAPTER 4

DEVELOPMENT OF A MULTIVARIATE CORRECTION METHOD FOR HVI FIBROGRAM MEASUREMENTS

4.1. Introduction

Cotton fiber quality measurements are used across the cotton industry for different purposes, such as identifying bales for purchase, determining the proper settings on spinning equipment, and evaluating germplasm in research. Mathematical correction techniques are used across various laboratories to enable a consistent interpretation of fiber quality measurements across the industry. For example, many laboratories participate in the CSITC (Commercial Standardization of Instrument Testing of Cotton) round test to make sure cotton fiber quality measurements are comparable across the industry. Thus, any new measurement technique requires the development of a correction procedure.

Cotton fiber length is among the essential fiber quality parameters used by the cotton industry for predicting yarn quality. Breeders focused on improving fiber quality are using fiber length along with other fiber quality parameters to select superior breeding lines (B. Kelly & Hequet, 2013; C. M. Kelly et al., 2013). Screening their nursery based on these parameters allows them to release germplasm with the potential for improved spinning performance (Joy et al., 2012; Kelly et al., 2013). Textile mills use fiber length along with other fiber quality parameters to select cotton bales that enable them to spin their targeted yarn quality (Yang and Gordon, 2017).

The focus on length extends beyond the longest fibers in the sample. Genetic variations, agronomic practices, and environmental effects contribute to the fiber length variation within a bale (Stewart, 1975; Faulkner 2010; Feng et al., 2011; Ayele et al., 2017; Mauget et al., 2019). This within-bale variation in fiber length impacts yarn quality (Wakeham, 1955). High within-sample variation causes problems during processing, which results in a higher number of imperfections in the yarn (Behery, 1993; Everett E. Backe, 1986; Tallant et al., 1959; Thibodeaux et al., 2008). Therefore, measuring the within-sample variation in fiber length is essential for selecting elite breeding lines as well as for mills managing throughput and yarn quality (Kelly et al., 2013).

The High Volume Instrument (HVI) fiber length measurements, Upper Half Mean Length (UHML) and Uniformity Index (UI), are based on the fibrograph principle (Hertel, 1940). An HVI comb prepares a fiber beard by catching fibers bulging out of a fiber sampling mechanism. After removing the extraneous matters and loose fibers through brushing, the resulting beard is scanned over a red-light beam, and a sensor above the beard measures the amount of light attenuated by the beard (Hertel, 1940; Chu and Riley, 1997; Delhom et al., 2018; Kelly et al., 2015). The starting point of the scanning, which is 3.81 mm (0.15 inch) from the edge of the comb (Hertel & Lawson, 1964; Krowicki & Thibodeaux, 1990), represents the total population of fibers to be scanned. The fibers do not attenuate 100% of the light at this point. The maximum amount of light is attenuated at the starting point, so the measurement at the start of the scan is standardized to 100%. While the fiber beard is scanned over the light towards the tip of the beard, fewer and fewer fibers are available to be examined. Eventually, the scan reaches a point where no fiber remains to be scanned, and no light is blocked, creating a

0% attenuated light (Kelly et al., 2015; Delhom et al., 2018). The changes in the percentage of light attenuated by the fiber beard from 100% to 0% are recorded by the HVI and used to generate a light attenuation vs. displacement curve called the fibrogram (Figure 4. 1). The HVI reports two fiber length parameters, UHML and UI calculated from this curve (Hertel, 1940; Chu and Riley, 1997). The fibrogram itself is not reported as a regular output of the instrument.

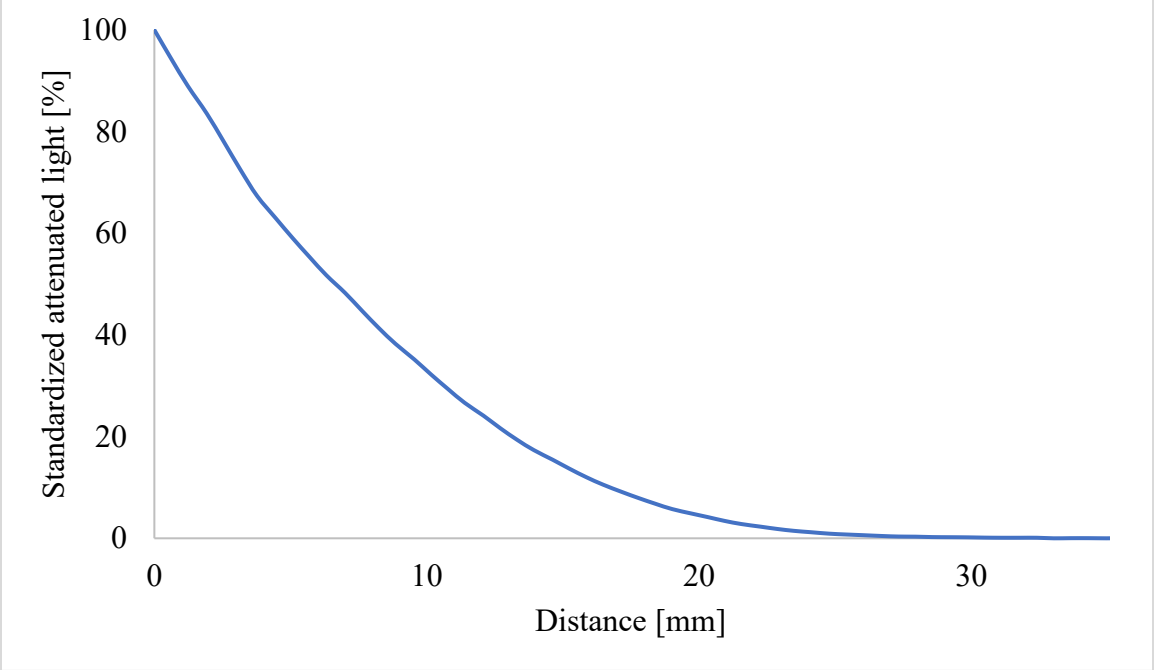

Figure 4. 1: A fibrogram generated by the High Volume Instrument (HVI).

The fibrogram may hold valuable information about the within-sample variation in fiber length that is not currently reported but is needed by the industry (Louis and Fiori, 1967; Vertel et al., 1968; Krowicki and Duckett, 1987). In addition, the two length parameters currently reported by the HVI do not characterize the total within-sample

variation in fiber length captured by other measurement techniques, such as the Advanced Fiber Information System (AFIS) (Kelly et al., 2018a).

While the fibrogram measurement may hold more information than the widely used HVI length parameters, UHML and UI, it is not a corrected measurement. It is possible to access the complete fibrogram curve when the samples are measured with HVI length/strength module testing mode (Kelly et al., 2018b). The lack of a correction protocol for the fibrogram limits the utility of the measurement. In order to use the total within-sample variation captured by the whole fibrogram curve, a correction procedure is needed that brings the fibrogram curve measurements made by different HVIs to the same level. In this research, we propose a method for correcting the complete fibrogram so that the measurement is consistent and comparable across multiple HVIs. This protocol is then validated on a larger set of independent samples.

4.2. Materials and Methods

4.2.1. Establishing the fibrogram correction method

A sub-set of 529 commercial samples covering a wide range of fiber quality characteristics were selected with the goal of identifying samples exhibiting a wide range in fibrogram shape characteristics. All the samples used in this experiment were conditioned for at least 48 hours at 21±1 0C and 65±2% RH prior to testing. The fibrogram measurement was obtained for these samples using a 10 replication HVI protocol.

The fibrogram curve is not a regular output of HVI report. However, the fibrogram curve could be exported from the native HVI software when samples are

measured with the HVI length and strength module testing mode. Fibrograms obtained through the module testing report are vector graphic images. Extracting data from the vector graphic fibrogram using a MATLAB script provides 81 data points.

4.2.1.1. Defining reference fibrogram measurements

There is not an established reference method for the fibrogram measurement. In lieu of a reference method, one of the three HVIs at the Fiber and Biopolymer Research Institute (FBRI) was chosen to provide the reference fibrogram measurements used in this research. The HVI selected to provide the reference measurement is henceforth referred to as the "Reference HVI."

4.2.1.2. Defining correction domain and reference loadings

The raw fibrogram curve characterizes within-sample length variation as the standardized light attenuation along with preset distances from the HVI comb. The fibrogram is the second cumulative distribution of fiber length histogram, which Hertel referred to as the R curve and can be expressed with Equation 1 (Hertel, 1940; Chu and Riley, 1997). The fibrogram curves used in this research were mathematically flipped following a technique established in literature so that the curve represents within-sample length variation as a length response curve (Kelly et al., 2018b). The length response fibrogram curve was established by interpolating the curve along with a preset number of levels. The resulting curve (Equation 2) characterizes the within-sample variation in fiber length as a set of lengths.

$$R(X) = \int_{x}^{Lm}(L - X)p(L)dL \quad \text{..... (1)}$$

$$g(X) = R^{-1}(X) \quad \text{..... (2)}$$

Where Lm is the longest fibers in the sample, X is the distance from the clamp, p(L) is the length-frequency distribution.

The fibrograms were flipped that made length as response value and optical light (%) as independent value of the measurement. Reducing the number of points, for example using less than the original 81, has the potential of losing relevant data before the curve is evaluated. While some additional points (>81) may help determining better the curvature of the fibrogram, an excessive number of points would not be helpful. The fibrogram data points are interpolated at fixed intervals (1%) between 0% to 100%, in correspondence with the standardized attenuated light. Two span lengths, 0% and 100%, are excluded from further analysis because there is no fiber length data for 0% span length and 100% span length is an original point corresponding to zero fiber length.

One way of correcting the fibrogram curve would be to use equations obtained by regression between the reference HVI and the test HVI for each of the 99 data points. While this would require 99 independent correction equations, it would ignore the collinear nature of the fibrogram curve. In order to facilitate the comparison of the fibrograms across different HVIs, a correction procedure is needed that respects the collinear nature of fiber length along a fibrogram.

The proposed correction procedure is based on Eigen decomposition of the reference samples set (Figure 4. 2). The method first transforms the fibrogram data into a linear space, where the fibrogram curvatures are represented as independent variables. A widely implemented method of Eigen decomposition is Principal Component Analysis (PCA). PCA characterizes the largest amount of variation with fewer components that allows to minimize the number of equations needed to correct the fibrogram as a curve.

In this experiment, PCA was not used as an analysis tool, it was used to identify the equations needed to transform the data into a linear space. The correction of the within-sample variation or the shape of the curve are conducted in this linear domain. The obtained coefficients or loadings for each of the major axis or principal components by the eigen decomposition of reference samples set are considered as reference loadings and used to transform any fibrogram into the same correction domain.

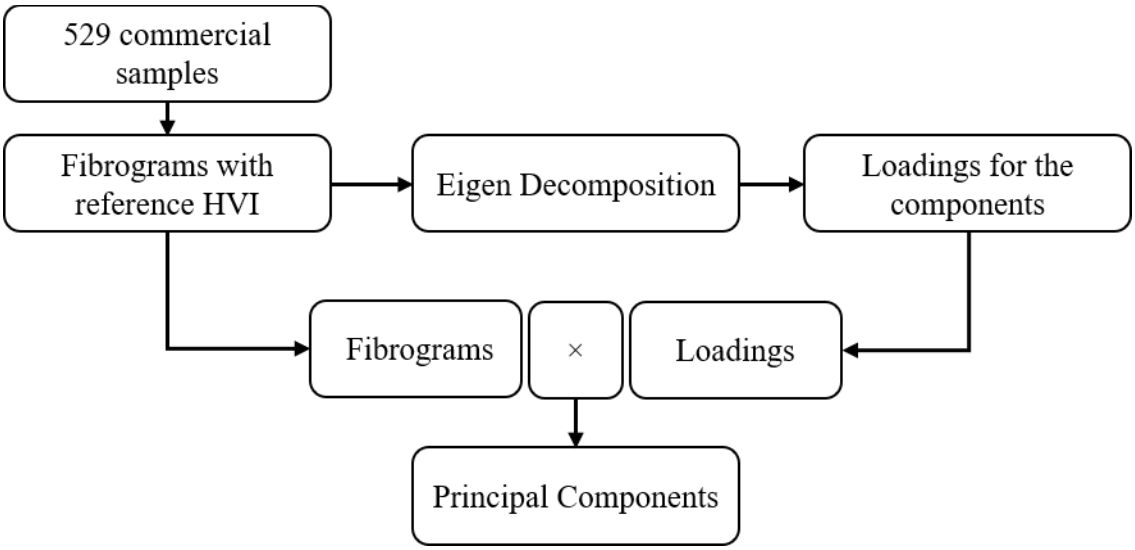

Figure 4. 2: Eigen decomposition to transform fibrograms into the correction domain.

4.2.1.3. Reference correction samples

Two major points were considered during the identification of the reference correction samples. First, how many independent components should be included in the correction procedure? Second, how many samples are required for correcting each of the components?

In the third chapter of this dissertation, it was demonstrated that at least three principal components are required to explain an adequate amount of fiber length variation

captured by the whole fibrogram curve. Therefore, the first three components were considered to correct the fibrogram across HVIs.

While one of the main concerns during the development of a correction method is to minimize the number of samples required to correct the measurement, it is also important to investigate whether the selected components between instruments show linear relationship or not. At least three data points are required to determine whether the relationship is linear or not.

In order to capture the maximum possible range of fiber length variation within the reference set, two extreme and one median samples for each of the first three components were selected to provide a total of nine reference correction samples.

4.2.1.4. Correction equations

The two other HVIs at the FBRI were chosen as Test HVI 1 and Test HVI 2 in order to establish the correction procedure. Figure 4. 3 shows the flow chart for establishing the correction equations. The nine samples selected as reference material were measured with the Test HVIs with 10 replications of the fibrogram. The reference loadings were used to transform the fibrogram into the correction domain, and the scores for the first three components for these nine samples were calculated.

Simple linear regressions between the Reference HVI and the Test HVIs for each of the components were conducted independently. The slopes and offsets of the regression equations were used to correct the measurement, and the regression equations were considered as the correction equations.

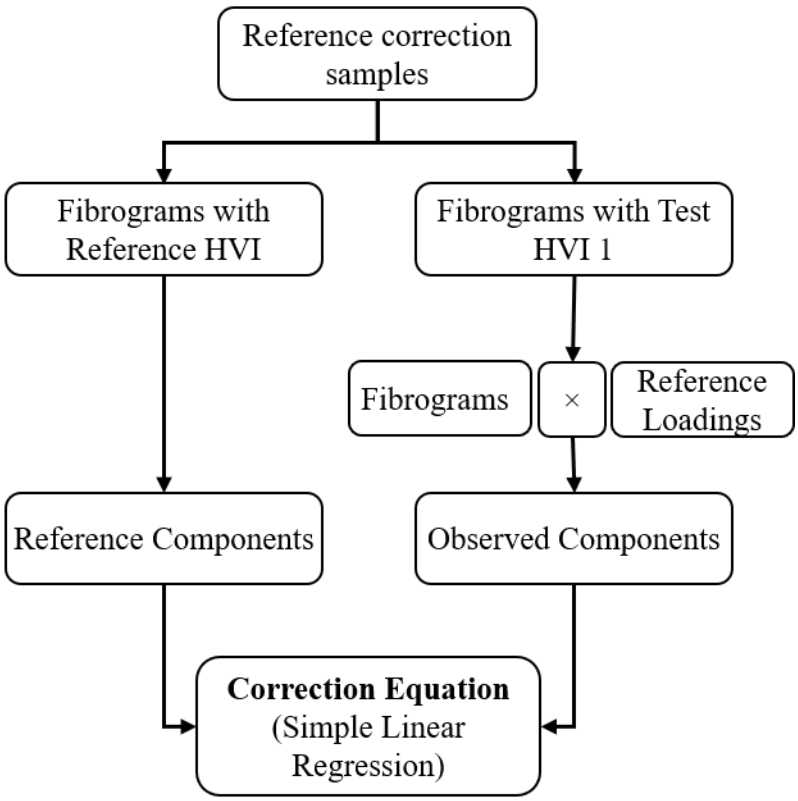

Figure 4. 3: Establishment of correction equation by simple linear regression.

4.2.2. Applying correction equations

A set of 10 replications of the fibrogram measurement were obtained using a sub-set of 452 commercial samples with both the Reference HVI and the Test HVIs. The Reference loadings were then used to transform all the fibrograms into the correction domain, and scores for the components were recorded (Figure 4. 4). The component scores from the Reference HVI are the reference values for these samples. The scores for each of the components for Test HVI 1 and Test HVI 2 are the observed values for the same samples (Figure 4. 4). The established correction equations were then applied to the observed components. The estimated components after using the correction equations are the corrected components. Corrected components were then retransformed into the original domain, fibrogram domain, using the reference loadings. (Figure 4. 4).

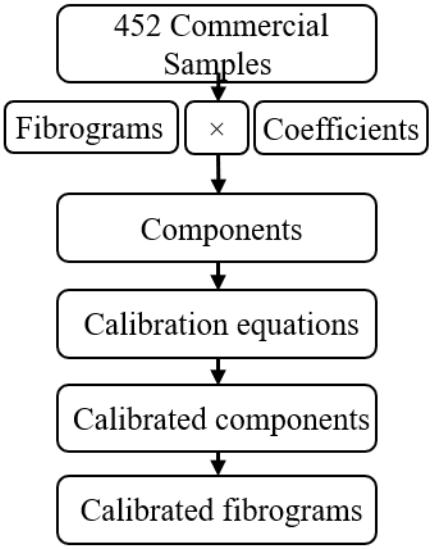

Figure 4. 4: Application of the correction equations to correct the fibrogram measurements.

Euclidean Distances (ED) (Equation 3) of fibrograms were calculated between the Reference HVI and Test HVIs before and after correction in order to determine whether the correction procedure brings the fibrograms measured with Test HVIs to the Reference HVI level.

$$ED = \sum_{i=0}^{100}[\sqrt{\{(Xi - Yi)^2\}}] \quad \text{..... 3}$$

Where, X= Reference Fibrogram and Y= Fibrogram before or after correction.

The histogram for these two distributions were then compared to determine whether the deviation between fibrograms reduced globally or not.

4.2.3. Validation of the correction procedure

Validation of the proposed correction procedure using an extra set of samples could determine the robustness and the full potential of the fibrogram measurements. A large independent set containing 932 commercial samples was selected to validate the proposed correction procedure.

After proper conditioning, samples were measured with 10 replications of the fibrogram with the Reference HVI and the Test HVIs. The fibrograms were transformed into the correction domain by using the reference loading, and the component scores were recorded.

The developed correction equations were applied to the components scores of the Test HVIs. To determine whether the correction procedure reduces the deviation between the fibrograms measured with the Reference HVI and Test HVIs, EDs were calculated before and after correction.

4.2.4. Reducing the number of samples required for fibrogram correction

The previous section outlined a theoretical method for correcting the fibrogram. While this approach works, the method requires too many samples to be practical when implemented in a laboratory setting. Three samples for each of the first three components (totaling 9) were selected independently during development of correction procedure to confirm that the samples cover the maximum possible range within the reference set and to determine the linearity of the fibrogram measurements in its correction domain.

This part of the experiment was conducted to determine whether it is possible to reduce the number of samples required to correct the fibrogram measurements. The

correction procedure was evaluated using sets of 9 (Previously used), 5, 4, 3, and 2 samples and compared among themselves. Each set of correction samples was selected to cover the maximum possible range of each component within the Reference samples set.

The correction equations were developed following the same procedure using each set of correction samples. Correction equations for each of the correction sample sets were applied on 932 commercial samples (validation set). The corrected components were retransformed into the original fibrogram domain. EDs (Equation 3) of fibrograms were calculated between the Reference HVI and Test HVIs before and after correction. EDs obtained using each of the correction samples sets were compared among themselves to identify the minimum number of samples required to correct the fibrogram measurements.

4.3. Results and Discussion

4.3.1. Establish the correction procedure

The correction samples were selected out of the reference samples set to make sure that they cover a wide range of fiber length variation within this set. Figure 4. 5 and Figure 4. 6 show the range of fiber length variation covered by the reference set and the amount of fiber length variation explained by first three components. The range of the fiber length variation covered by the 9 correction samples are shown in Table 4. 1, Table 4. 2 and Table 4. 3 respectively for the Reference HVI, Test HVI 1 and Test HVI 2.

Regressions of components between Reference HVI and Test HVI 1 show a significant linear component in the relationships (Figure 4. 7, Figure 4. 8 and Figure 4. 9). As the components between HVIs are linearly correlated, slopes and offsets from the regression equations could be utilized for correcting the fibrogram measurements to bring

them to a similar level. Table 4. 4 shows the obtained correction equations for the two test HVIs.

After applying the correction equations on a set of 452 commercial samples measured with Test HVI 1 and Test HVI 2, they were compared with the Reference HVI.

The global performance of the proposed correction equations was determined by calculating ED for 452 commercial samples before and after correction (Figure 4. 10). The results suggest that the correction reduces the deviation between fibrograms measured with the Reference HVI and Test HVI 1. The solid line in Figure 4. 10 is the distribution of ED before correction, and the dashed line is the ED after correction. The peak of the ED distribution before correction is at the bin 4-5 mm when the peak of the ED distribution after correction is at bin 2-3 mm.

The result obtained by utilizing the proposed correction procedure to correct the fibrograms measured with the Test HVI 2 indicates that this HVI is already in good agreement with the Reference HVI (Figure 4. 11). The peak of the ED between the Reference HVI and Test HVI 2 are at the bin 1-2 mm before and after correction.

The correction procedure could not eliminate the differences between Reference HVI and Test HVIs completely (Figure 4. 10 and Figure 4. 11). One possible reason behind this could be that the range of the components covered by the correction samples do not cover adequately the components range observed on the 452 commercial samples. Another reason could be excessive within-sample variation. Fibers from a sample measured with different HVIs are not identical. Therefore, higher within-sample variation could cause deviations that cannot be corrected by the proposed correction method.

However, the goal was to develop a correction method for the whole fibrogram curve that reduces the deviation between HVIs, and the results suggest that the proposed correction method brings the fibrograms in a better agreement between Reference HVI and Test HVI.

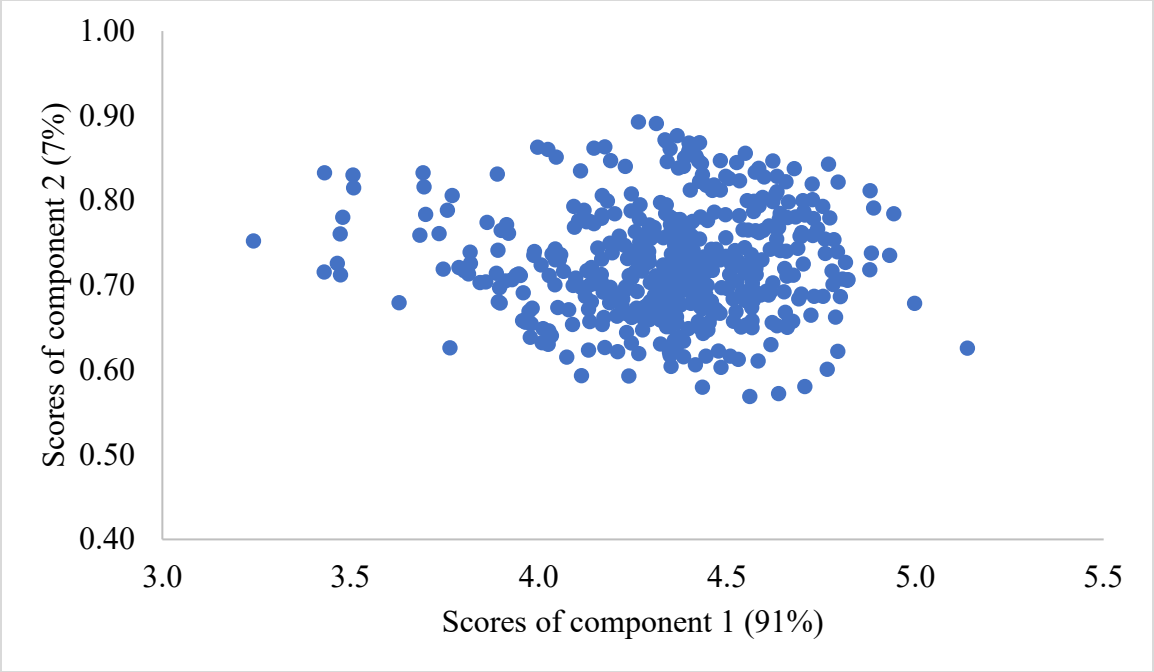

Figure 4. 5: Scores of the component 1 and 2 showing the range of fiber length variation captured by the fibrogram measured with the Reference HVI.

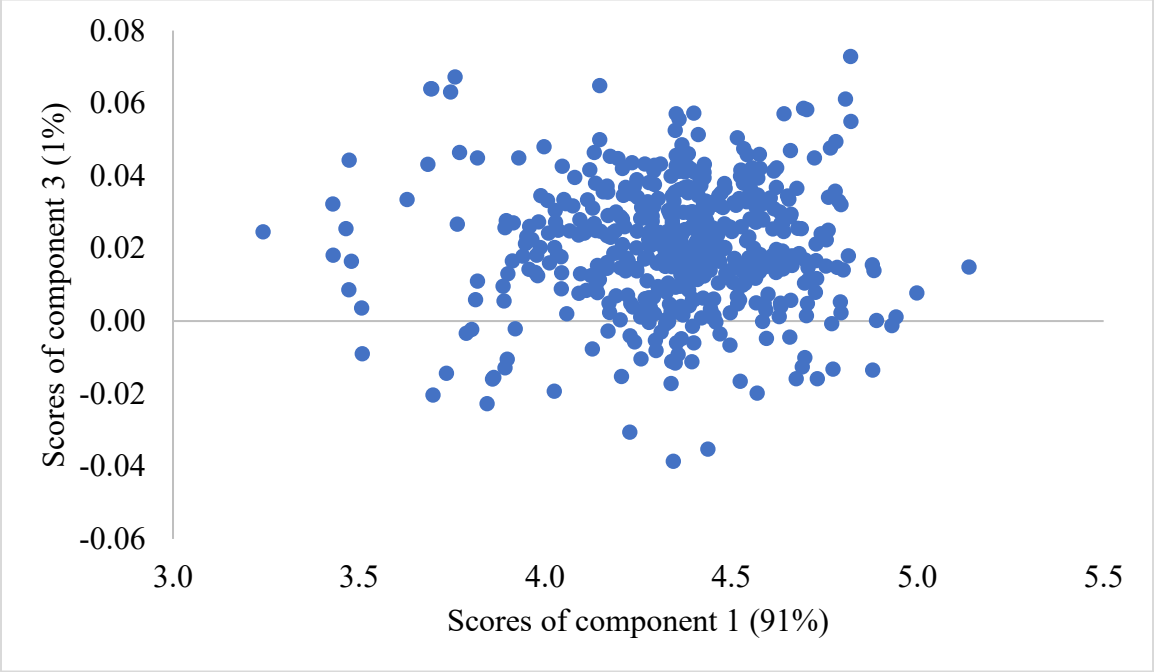

Figure 4. 6: Scores of the component 1 and 3 showing the range of fiber length variation captured by the fibrogram measured with the Reference HVI.

Table 4. 1: Correction samples measured with the reference HVI were selected covering the maximum possible range for each component. Sample 1.1, 1.2 and 1.3 selected based on principal component 1. Samples 2.1, 2.2 and 2.3 selected based on principal component.

Sample	PC 1	PC 2	PC 3
1.1	3.440	0.661	0.054
1.2	4.394	0.657	0.042
1.3	5.008	0.600	0.041
2.1	4.714	0.506	0.043
2.2	4.325	0.823	0.044
2.3	4.416	0.650	0.040
3.1	4.237	0.626	-0.003
3.2	4.469	0.672	0.051
3.3	4.830	0.630	0.105

Table 4. 2: Range of fiber length variation for selected correction samples measured with the Test HVI 1.

Sample	PC 1	PC 2	PC 3
1.1	3.487	0.706	-0.012
1.2	4.203	0.803	-0.047
1.3	4.878	0.706	-0.058
2.1	4.697	0.578	-0.039
2.2	4.391	0.875	-0.017
2.3	4.412	0.758	-0.071
3.1	4.049	0.790	-0.101
3.2	4.429	0.754	-0.058
3.3	4.672	0.796	-0.032

Table 4. 3: Range of fiber length variation for selected correction samples measured with the Test HVI 2.

Sample	PC 1	PC 2	PC 3
1.1	3.478	0.672	0.036
1.2	4.272	0.690	0.019
1.3	4.979	0.614	0.023
2.1	4.780	0.505	0.029
2.2	4.305	0.804	0.044
2.3	4.429	0.678	0.002
3.1	4.220	0.619	-0.006
3.2	4.509	0.685	0.016
3.3	4.657	0.707	0.050

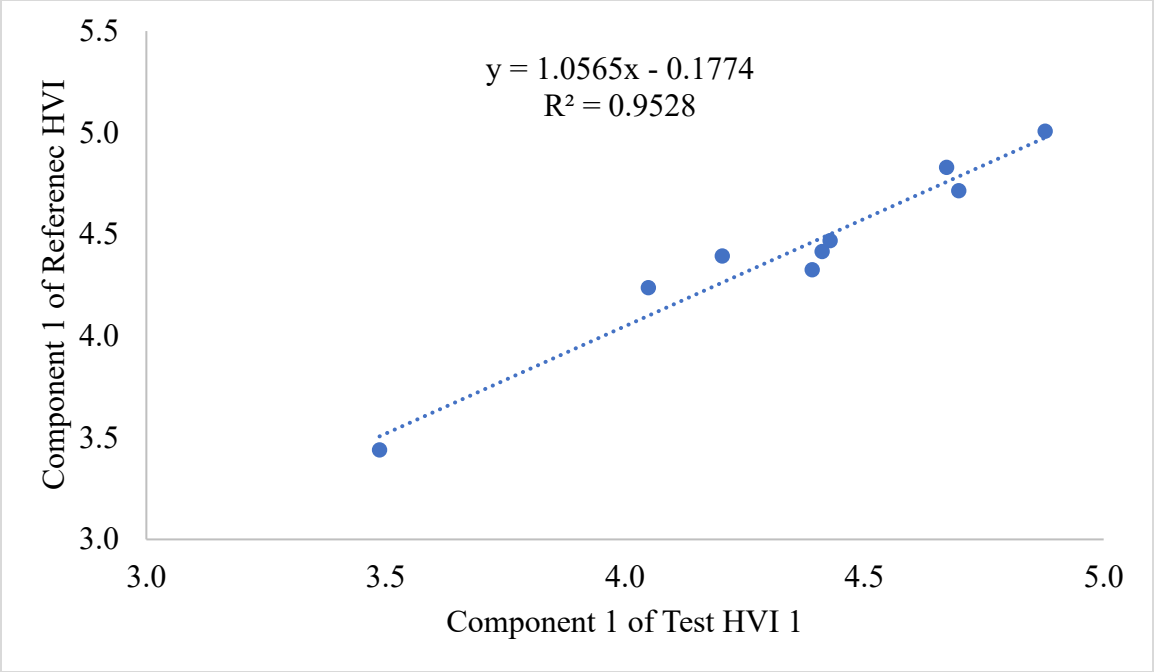

Figure 4. 7: Simple linear regression of component 1 between Test HVI 1 and The Reference HVI.

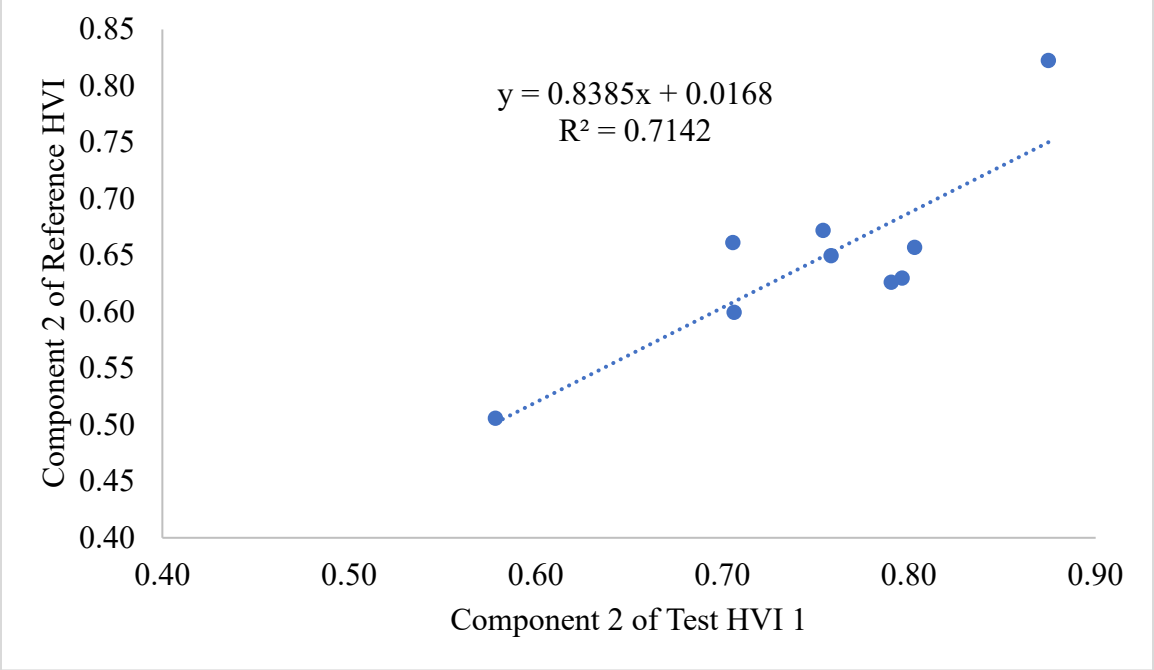

Figure 4. 8: Simple linear regression of component 2 between Test HVI 1 and the Reference HVI.

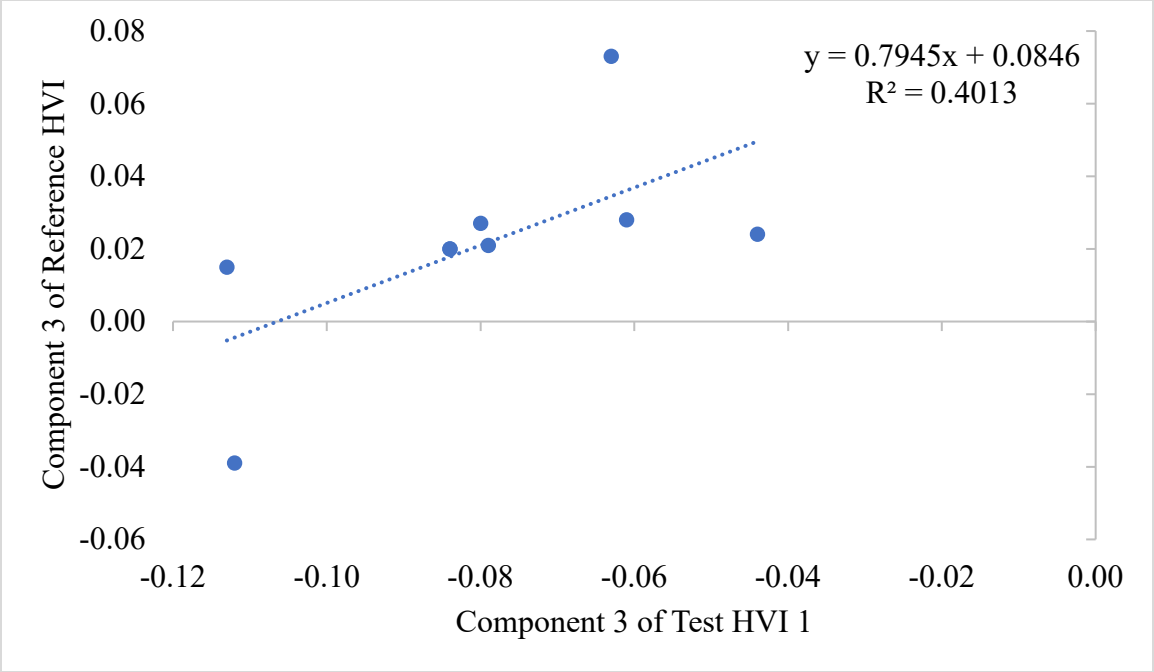

Figure 4. 9: Simple linear regression of component 3 between Test HVI 1 and the Reference HVI.

Table 4. 4: Developed correction equations for the Test HVI 1 and Test HVI 2 for the first three components.

Component	**Test HVI 1**	**Test HVI 2**
1	$Y_1 = 1.0565x - 0.1774$	$Y_1 = 1.0304x - 0.1109$
2	$Y_2 = 0.8385x + 0.0168$	$Y_2 = 0.96x + 0.0101$
3	$Y_3 = 0.7945x + 0.0846$	$Y_3 = 1.1578x + 0.0189$

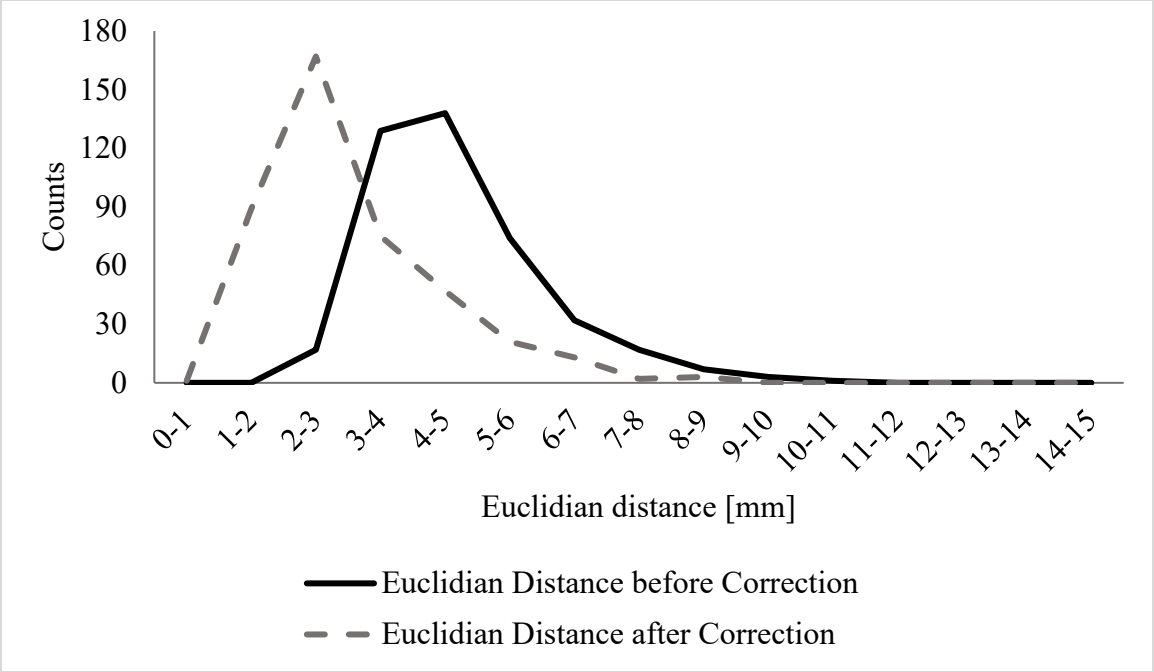

Figure 4. 10: Euclidian Distance (ED) for the Test HVI 1 before correction (solid line) and after correction (dashed line).

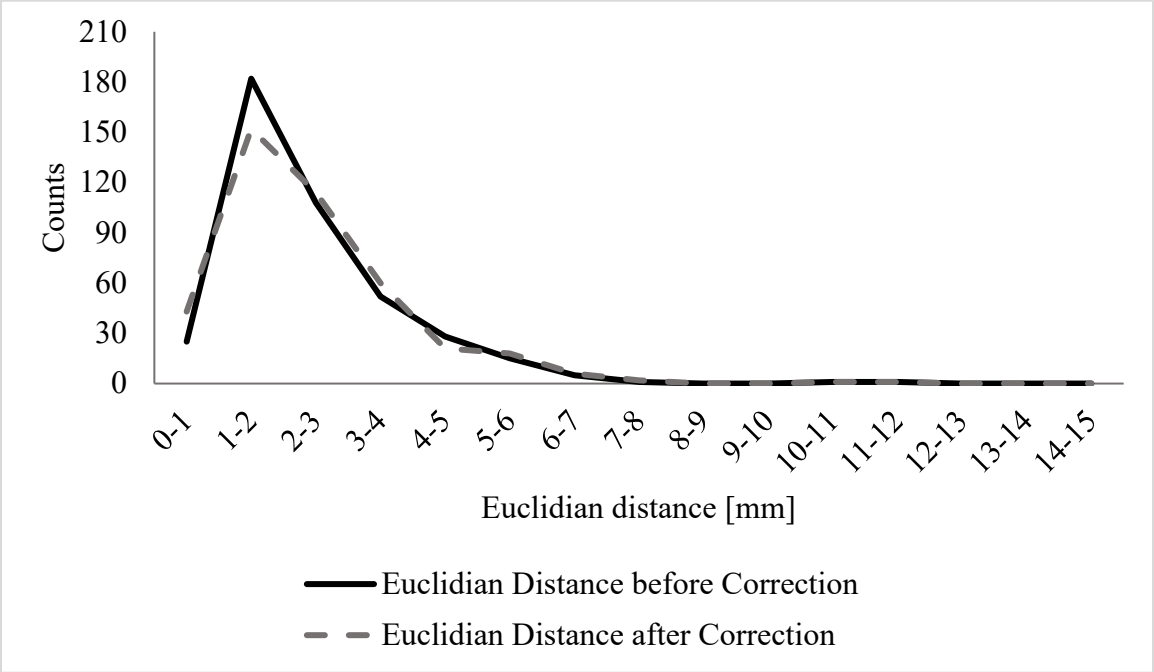

Figure 4. 11: Euclidian Distance (ED) for the Test HVI 2 before correction (solid line) and after correction (dashed line).

4.3.2. Validation of the correction procedure

Validation of the correction procedure on a larger set of samples across multiple HVIs would provide more confidence about how well the proposed method performs. Therefore, the proposed correction procedure was validated using 932 commercial samples.

The validation results demonstrated and validated that the fibrograms measured with the Test HVIs could potentially be corrected to bring them at the similar level than the Reference HVI. Figure 4. 12 shows the EDs before and after the correction for the Test HVI 1. The solid line represents the ED before correction, and the dashed line represents the ED after correction. The peak of the ED distribution before correction is at the bin 0.15-0.175 inch while the peak of the ED distribution after correction is at the bin 0.075-0.10 inch. Therefore, the correction procedure reduces the deviation of the fibrogram measurements between the Reference HVI and Test HVI 1.

The results obtained by the application of the proposed correction procedure on the fibrograms measured with Test HVI 2 demonstrated that the Test HVI 2 does not require any correction. Figure 4. 13 shows the EDs distribution before and after correction for Test HVI 2. The solid line represents the EDs before correction, and the dashed line shows the EDs after correction. The peak of the histogram for both the solid line and the dashed line is around 0.075-0.10 inches. This result is similar to the result obtained when the correction procedure was developed for the Test HVI 2, meaning that the Test HVI 2 is already in a good agreement with the Reference HVI.

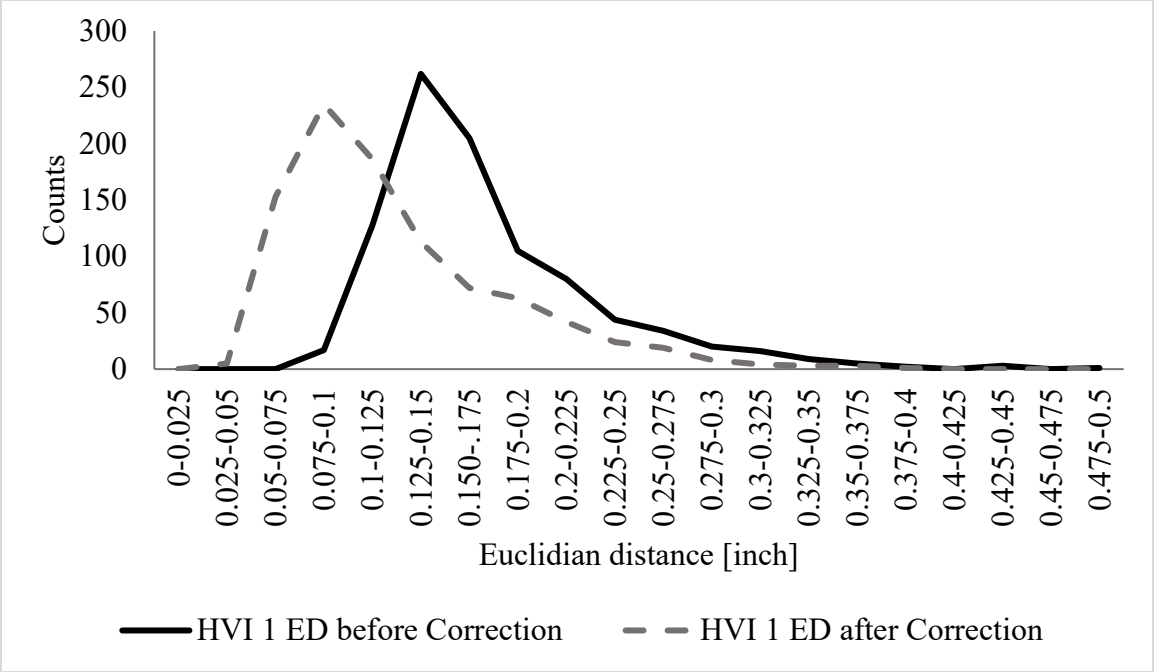

Figure 4. 12: Euclidian Distance (ED) for the Test HVI 1 before correction (solid line) and after correction (dashed line).

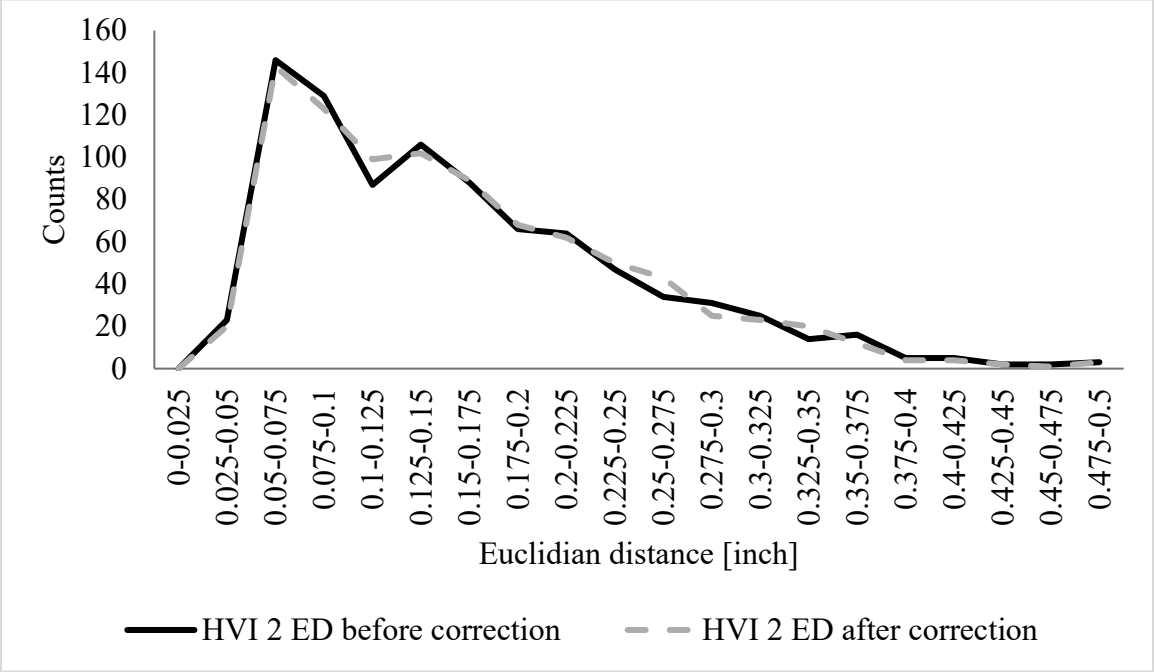

Figure 4. 13: Euclidian Distance (ED) for the Test HVI 2 before correction (solid line) and after correction (dashed line).

4.3.3. Reducing the number of samples required for fibrogram correction

One of the main questions while developing correction method for the fibrogram is: "what could be the absolute minimum number of samples required to correct the fibrogram measurements"? Therefore, following the same principle, correction equations were developed using fewer samples than 9.

It is already demonstrated that the relationship of components between Reference HVI and Test HVIs are linear. Therefore, reduction of the number of samples would not limit the analysis. The earlier results demonstrated that the Test HVI 2 does not require a correction method. Therefore, Test HVI 2 was excluded from this part of the experiment.

The result obtained by using sets with fewer than 9 samples demonstrated that the required number of samples for establishing the correction procedure could be reduced to as low as 3 samples. Figure 4. 14 shows the sum of EDs of fibrograms between Reference HVI and Test HVI 1 before correction and after corrections. The sum of EDs of fibrograms between Reference HVI and Test HVI 1 before correction is 2294 mm. When 9, 5, 4 and 3 samples are used to establish the correction method, the sum of EDs of fibrograms between Reference HVI and Test HVI 1 are almost same (1492 mm, 1459 mm, 1457 mm, and 1487 mm).

The correction procedure developed using 2 samples did not reduce the deviation between Reference HVI and Test HVI 1 at all (Figure 4. 14). The sum of EDs is 2293 mm which is same as the EDs between the Reference HVI and Test HVI 1 before correction, 2294 mm.

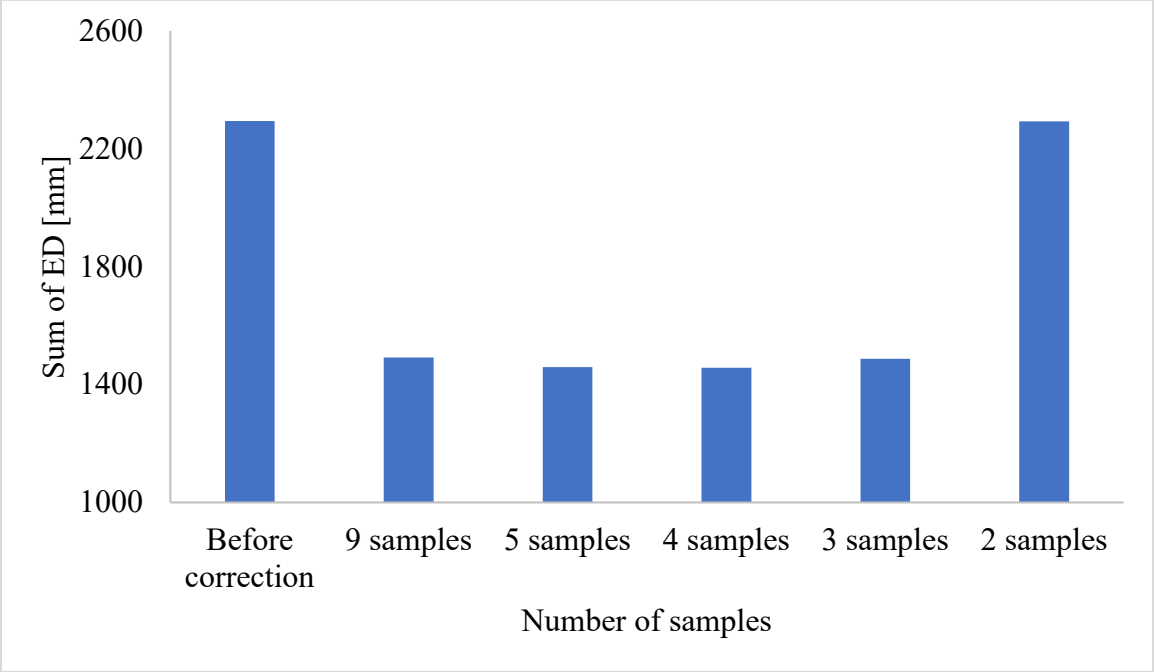

Figure 4. 14: Sum of the EDs of 932 commercial samples before and after correction using the different numbers of samples.

4.4. Conclusion

The cotton industry requires a fast and reliable method to measure the within-sample variation in fiber length. The total fiber length variation captured by the HVI fibrogram could be a potential solution. To utilize the fiber length variation captured by the whole fibrogram curve across the cotton industry, a method for correcting the whole fibrogram curve was developed in this research.

The fibrogram correction results obtained by utilizing the proposed correction procedure demonstrated and validated that the fibrograms measured with different HVIs could be corrected to bring them at a similar level. This means that the total within-sample variation in fiber length captured by the entire fibrogram could potentially be used across the cotton industry for various purposes, such as selecting elite germplasm or better mill management throughput.

The correction procedure performs at the same level no matter whether they are developed using 9 samples or 3 samples. This means that the range of fiber length variation covered by the 9 samples required for establishing the correction procedure could also be covered by using as few as 3 samples.

This research was done in order to determine whether it is possible to correct the entire fibrogram curve and bring the fibrogram measurements at a similar level across HVIs. The next step is to produce reference cottons that could be used across the industry (worldwide). This would require an organization such as the USDA-AMS to produce and distribute such reference material. It would also require working with the HVI manufacturers to modify the current HVI software. Finally, it would require a major

research undertaking to determine how this additional information can be used by the different segments of the industry.

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CHAPTER 5

SUMMARY AND CONCLUSION

The United States is the third leading cotton-producing country behind India and China, as well as the leading cotton exporting country. The U.S. exports most of its cotton to Asia, where ring spinning is dominant. The target for U.S. cotton is the 30s Ne ring-spun yarn market. Textile mills require high-quality cotton to produce premium yarns. Cotton breeders are working on releasing germplasm with improved fiber quality that could process more efficiently. They make their decision based on fiber quality parameters while selecting elite germplasm. To purchase cotton bales that meet the quality demand, spinning mills depend on specific fiber quality parameters.

Within-sample variation in cotton fiber length is among the essential fiber quality parameters needed to predict yarn quality. Within-sample variation in fiber length can affect almost all yarn quality parameters. Therefore, a fast and reliable system for evaluating within-sample variation in fiber length is needed.

Current fiber length measurements, UHML and ML, are extracted from the same region of the fibrogram curve measured with HVI. These two length measurements also represent the longest fibers in the sample. Investigation of the current measurements, UHML, and ML, compared with the whole fibrogram curve, shows that these two measurements are inadequate for characterizing the total within-sample variation in fiber length captured by the fibrogram and are highly collinear. The linear relationship between UHML and ML, using 19,827 commercial samples, is high (R2= 0.95). Though ML is not a reported HVI length parameter, it is used to calculate the UI (UI =

100*ML/UHML). Therefore, UHML and UI do not provide unique types of fiber length measurements.

The development of a system for extracting the whole fibrogram from the HVI software allows performing statistical analyses to determine whether the entire curve holds any additional useful fiber length variation information. The extracted raw fibrograms from HVI contain 81 collinear data points. A principal component analysis can summarize and explain this variation with fewer independent variables. The results obtained using several sample sets, such as commercial samples and breeders samples, show that at least three independent variables are required to capture fiber length variation from the fibrogram.

The variation of fiber length captured by the whole fibrogram curve is essential to predict yarn quality. Partial Least Square Regression (PLSR) prediction models, using fiber properties as predictor variables and yarn properties as response variables, were designed in order to determine the importance of fibrogram fiber length variation compared to current HVI length parameters and the Advanced Fiber Information system (AFIS) fiber length distribution by number. The results obtained using commercial-like samples and breeders samples show that the fiber length variation captured by the entire fibrogram curve is better than the current HVI length parameters and at least as good as AFIS length distribution by number to predict yarn quality.

The fiber length variation captured by the fibrogram could be obtained when the cotton samples are measured with HVI for other important fiber quality parameters such as fiber Strength, UHML, UI, Micronaire, Color, and Trash. This measurement would not require any additional testing or any further infrastructure development. The only thing

needed would be a modification of the current HVI software. Therefore, the fibrogram fiber length measurement could be a convenient tool for characterizing fiber length variation for the entire cotton industry, including cotton breeders and other cotton researchers, merchants, and spinners.

The fiber length variation captured by the fibrogram could help breeders to develop new varieties with improved fiber length distributions that would perform better during processing resulting in higher quality yarns. Using the fibrogram fiber length information, if public breeders and private seed companies can develop germplasm with improved within-sample variation in fiber length, then farmers would get varieties with the potential to produce fiber able to better compete on the world market because of the potential for enhanced spinning efficiency and yarn quality. Other researchers, such as agronomists, could use data provided by the fibrogram to evaluate varieties and agronomic practices that result in cotton varieties with optimized fiber length distributions.

Fiber length variation captured by the fibrogram could also be beneficial for the spinning mills while purchasing raw cotton. Spinners use fiber length along with other fiber quality parameters to select the correct cotton bales to meet particular demands from their customers. Short fiber content is an essential fiber length parameter for spinning mills. A large amount of short fibers in a cotton bale will result in low-quality end products causing profit loss for the spinning mills. Current HVI length parameters do not have much information about short fiber content. The fiber length information characterized by the fibrogram could be used by the spinners to select cotton bales that would perform more efficiently during processing.

Another use of fiber length measurement in a spinning mill is machine setup. As UHML and UI do not provide all the required fiber length information, some spinning mills measure their cotton with AFIS, which is costly. The fibrogram fiber length information used to purchase the raw cotton could be used to determine the textile mill's textile machinery setup.

The demand for high-quality apparel and home furnishing products by the consumers, while keeping low costs, forces the textile mills to use new spinning technologies. Within-sample variation in fiber quality prohibits cotton from fitting some of the spinning systems such as the Airjet/Vortex spinning systems. Airjet spinning requires high-quality cotton and is very sensitive to the fiber length distribution. The fibrogram fiber length information could help the cotton breeders to release new germplasm that could fit this system. Airjet spinning is highly automated and very fast. It produces high-quality yarns similar in appearance to ring-spun yarns but with much lower tensile properties, which is one of the reasons why upland cotton is not competitive on that market. Therefore, if breeders could improve both the fiber length distribution and the tensile properties of upland cotton, 100% cotton airjet spun yarns could be produced. Due to the high automation of this system, manufacturing this type of yarn in the U.S. could be envisioned.

In summary, this dissertation presents possible improvements to the current HVI system by determining the within-sample variation in fiber length. The fibrogram fiber length measurement is important to develop and market new varieties that meet the international market demands without relying on a slower system of fiber quality measurement such as the AFIS.

Currently, only two data points are calibrated (UHML and UI) on HVIs. The whole fibrogram is not calibrated, which prevents its use by the industry. Therefore, a correction procedure for the entire fibrogram curve is required. With this doctoral research, it was possible to develop a process to correct the fibrogram across different HVIs, making its use by the industry possible in the future. To reach that point, calibration cottons need to be developed.