IMPROVEMENT OF WORK-TO-BREAK CHARACTERISTICS OF COTTON (*Gossypium hirsutum* L.) FIBERS AND YARN THROUGH BREEDING AND SELECTION FOR IMPROVED FIBER ELONGATION

A Dissertation

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ABSTRACT

The development of cottons with improved fiber quality has been a major objective in breeding programs around the world. Breeders have focused their attention on improving fiber strength and length, and have generally not used fiber elongation in the selection process. Although literature has reported a negative correlation between fiber elongation and tenacity, this correlation is weak and should not prevent breeders from simultaneously improving fiber tenacity and fiber elongation. Furthermore, the work of rupture property, important in the spinning process, could be best enhanced by improving both fiber tenacity and fiber elongation.

Fifteen populations were developed in 2007 by crossing good quality breeding lines with high elongation measurements to 'FM 958'; a High Plains standard cultivar with good fiber quality but reduced elongation. Samples in every generation were ginned on a laboratory saw gin, and the lint was tested on HVI (High Volume Instrument). The F_2 and F_3 generations showed a wide range of variation for elongation (6.9% - 12.8% for the F_2 and 4% - 9.20% for the F_3) allowing divergent selection for low and high fiber elongation. A correlation (r) of -0.32 between strength and elongation was observed in the F_2 individual plant selections. In the F_3, the correlation (r) between strength and elongation was -0.36, and in the F_4 the correlation (r) was -0.08. Nine lines were selected from the original 15 populations for spinning tests. The correlation between fiber elongation and strength for these lines was positive (r=0.424), indicating that with targeted selection, fiber elongation and strength can be simultaneously improved.

Fiber elongation was positively correlated with yarn tensile properties tenacity (r=0.11), work-to-break (r=0.68) and breaking elongation (r=0.87); and was negatively correlated with yarn evenness properties, number of thin places (r=-0.16), number of thick places (r=-0.9), nep count (r=-0.24), hairiness (r=-0.38) and total number of imperfections (r=-0.38). All selections for high elongation were superior for all tensile properties compared to the low selections and the check in the analysis over locations and in each location. Furthermore, selections for high elongation were significantly

different from the selections for low elongation and the check.

In addition to develop lines for fiber spinning tests with improved, or differentiated, fiber elongation, this project was amended to evaluate and determine the heritability of fiber elongation. Three different methodologies were used to obtain estimates of heritability; variance components, parent off-spring regression, and realized heritability using F_3, F_4, and F_5 generation. No inbreeding was assumed because there was no family structure in the generations within this study. Estimates of heritability by the variance component methods in the F_3, F_4 and F_5 were 69.5%, 56.75% and 47.9% respectively; indicating that 40-50% of the variation was due to non-genetic effects. Parent off-spring regression estimates of heritability were 66.1% for the $F_{3\text{-}4}$ and 62.8% for the $F_{4\text{-}5}$; indicating a high resemblance from parents to off-spring. Estimates of realized heritability were obtained to determine the progress realized from selection for the low and high selection for fiber elongation. Estimates were intermediate (0.44–0.55), indicating moderately good progress from selection.

The results from this project demonstrate that it is possible to improve fiber elongation and to break the negative correlation between elongation and strength. Furthermore, it has been demonstrated that improving fiber elongation results in the increase of length uniformity index and decreased short fiber content. Additionally, directed divergent selection was a successful methodology for the improvement of fiber elongation, and was useful to demonstrate that higher fiber elongation has a positive effect on yarn tensile properties, yarn evenness and processing. The development of new cultivars with improved fiber elongation will improve the quality and reputation of U. S.-grown cotton. The ultimate result will be better yarn quality and improved weaving efficiency, and particularly address current weaknesses in U. S. –grown cotton cultivars, especially from the High Plains of Texas, of more short fiber content, lower uniformity ratios, and weaker yarn strength.

DEDICATION

To my Mom, Dad and Sisters.

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1. INTRODUCTION

Cotton fiber is an important natural resource used for multiple purposes. It is widely used in industry for textile processing and for other uses. With the advancement and acceleration in spinning speed and processing, the requirement of improved cotton fiber quality is of great importance to the textile industry because it directly relates to processing performance, productivity and yarn quality.

This project is intended to improve the work-to-break characteristics of cotton fibers and yarns through breeding. The progress in a breeding program can be enhanced by understanding the genetics of cotton and its fiber properties. Elongation, an important property of cotton fibers, has usually been ignored during the selection process in breeding programs for improved fiber quality because the lack of calibration procedures for High Volume Instrument (HVI) elongation makes it impossible to rely on such data. In addition, the literature produced by cotton breeders shows that even when elongation measurements are available (stelometer instrument) their significance is not well understood. Since there is a perceived negative correlation between elongation and tenacity, they often conclude that there is no need to work specifically on improving elongation because it could result in lower tenacity. Nevertheless, the negative correlation is weak and does not preclude a simultaneous improvement of fiber tenacity and fiber elongation. The work of rupture, or combination of breaking strength and fiber elongation, is important to spinning quality. The most effective method of enhancing work of rupture is to improve the genetic contributions related to both tenacity and elongation. By genetically improving fiber properties, breeders contribute to productivity gains in the textile industry.

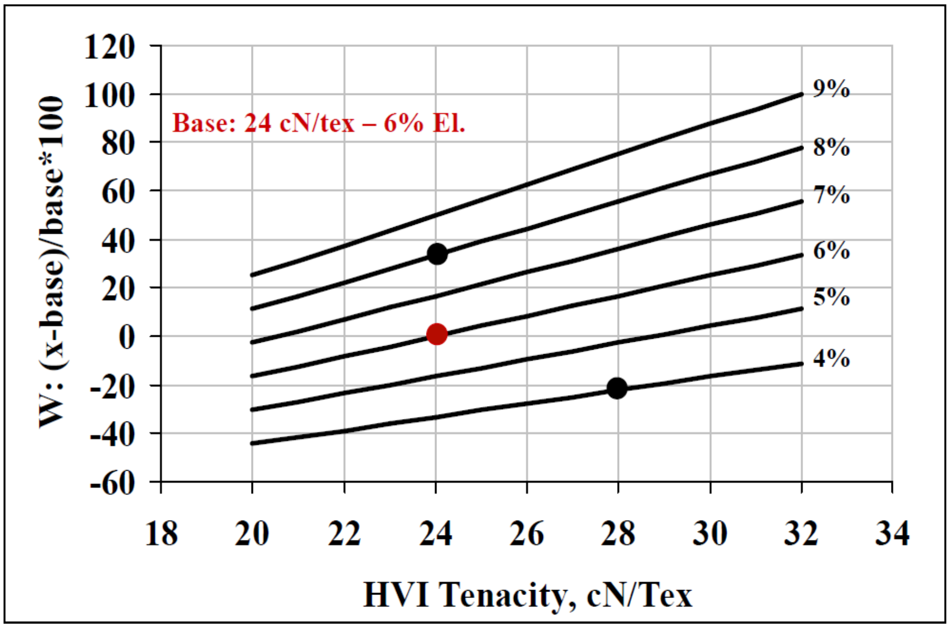
The elongation characteristics associated with fiber tenacity are of critical importance at three junctures: (1) Ginning – the cleaning and removal of fibers from the seeds create stresses that break fibers which lack sufficient tenacity and elongation, resulting in elevated short fiber content (SFC). (2) Opening and Carding – these indispensable steps prior to spinning achieve the final cleaning of the fibers and arranges them into a continuous bundle of parallel fibers (called a sliver). The SFC generated by these mechanical processes is correlated with both fiber strength and elongation properties. (3) Weaving – forming the spun yarns into a fabric on a weaving machine provides the ultimate test of yarn performance. Low levels of yarn breakage are required for achieving both the requisite weaving efficiency and fabric quality. Weaving has always been an abrasive and stressful process, but the speed of modern weaving machines magnifies these problems

1.1 Background

Elongation is an estimate of the elasticity of the bundle of fibers before breaking, and work-to-break refers to the total energy required to break a bundle of fibers, which is a function of the combination of elongation and tenacity. To better understand this concept, Figure 1 illustrates the relationship of elongation and tenacity in work-to-break. In the chart, the base is set to 24cN/tex with a 6% elongation; however, with the current marketing system the cultivar with higher strength and lower elongation would receive a premium while its performance in spinning and weaving (all other parameters being equal) would be lower. On the other hand, lower strength with higher elongation will require more energy to break the bundle of fibers. Therefore, its performance in processing will also improve.

The first question to be answered in order to improve fiber elongation is whether it is possible to obtain reliable elongation measurements from HVI instruments. A previous study was done to check the stability of HVI elongation measurements (Benzina et al., 2007). The results of this study demonstrated an excellent stability of the instrument to repeat elongation measurements during the test period. However, calibration of the HVI measurement for elongation is not currently available; therefore, measurements among HVI machines are not comparable. To solve this problem, Benzina et al. (2007), produced 3 standard cottons with known values of tenacity and elongation (measured with the instron). Reference material was created that could be used to calibrate the HVI instrument. This will allow elongation levels to be held constant over an extended period of time, which is indispensable for a breeding program selecting for the measured character.

Figure 1. Percent energy increase vs. HVI tenacity calculated for HVI base set at 24 g/tex and 6% elongation (Benzina et al., 2007).



Developing cottons with higher fiber quality has been, and is a main focus of breeding programs around the world. Fiber strength and length have been the main traits to improve in such programs. The elongation property of fibers has not been emphasized in breeding programs because it has shown to have inconsistent genetic contribution to fiber and yarn tenacity with the current measurement technology (High Volume Instruments). Additionally there is a perceived negative correlation between fiber elongation and strength, which make breeders more skeptical to focus on this particular trait. Nevertheless, Benzina et al. (2007), demonstrated this correlation is weak and does not preclude a simultaneous improvement of fiber tenacity and fiber elongation. On the other hand, it is possible that when breeding for one characteristic (i.e. elongation), an improvement of one or more other characteristics (i.e. strength) could be obtained. Therefore, the elongation trait, as a property of fiber quality, should be given more attention by breeders and manufacturers because the higher the fiber elongation, the higher the yarn quality and resistance to stress during processing (Backe, 1996).

When breeding for any character, it is important to consider the heritability and type of genetic variation involved in the expression of the trait which can facilitate further improvement of cotton fiber properties. The challenge for cotton breeders hence, is to exploit individual fiber characteristics, like fiber elongation, to develop germplasm with higher yarn work-to-break, and resistance to stresses during processing. Additionally, values of heritability are suggestive of the progress expected from selection. By breeding for higher fiber elongation, it is expected that new cultivars can withstand less fiber breakage during processing, perform better in spinning, and produce better yarn quality. Additionally, it is important to document the benefit for the cotton industry that developing cultivars with better elongation and work-to-break would have in sustaining a desirable quality reputation for U. S.-grown cotton.

2. REVIEW OF LITERATURE

Currently, there are 50 recognized *Gossypium* species (Ma et al., 2008; Stewart, 1995) distributed throughout the tropical and subtropical regions of the world (Brubaker et al., 1999; Fryxell, 1979). The fiber produced by cotton is unique, and therefore, it is widely used as a raw material in textiles and for many other industrial processes. Additionally, it is the third most important oilseed crop after soybean (*Glycine max*) and rapeseed (*Brassica napus*) (Brubaker et al., 1999).

Among the 50 species of *Gossypium*, 45 are diploid (2n=2x=26) and 5 are tetraploid (2n=4x=52) (Brubaker et al., 1999; Fryxell, 1979; Stewart, 1995; Zhang et al., 2005). The diploid *Gossypium* species are grouped into eight genomes (A, B, C, D, E, F, G, and K), and the 5 tetraploid species are grouped into one genome (AD). The separate genomes are assigned according to cytological characteristics and genome similarity of the species (Stewart, 1995). The tetraploid cottons arose from hybridization between an A (old world) and a D (new world) genome species (Brubaker et al., 1999). There are four cultivated species of cotton around the world; two diploids, *G. herbaceum* and *G. arboreum,* originally from Africa and India, respectively, and two tetraploids, *G. barbadense* and *G. hirsutum,* from Peru and Mexico, respectively. The tetraploids account for the major part of fiber production of the world (Stewart, 1995). The upland cotton, *G. hirsutum,* is the most widely cultivated cotton because of its high productivity and wide range of adaptation to the world's environmental conditions. On the other hand, *G. barbadense*, the other cultivated tetraploid cotton, is grown for its high fiber quality (Zhang et al., 2005).

In the U.S., cotton is grown in Alabama, Arizona, Arkansas, California, Florida, Georgia, Kansas, Louisiana, Mississippi, Missouri, New Mexico, North Carolina, Oklahoma, South Carolina, Tennessee, Virginia and Texas (Smith, 1999). Among them**,** Texas is the leading producer of cotton, producing 3.5 million bales (217.7 Kg per bale) in 2011, about 22% of the total U.S. production which in 2011 was 15.675 million bales (USDA-NASS). Most of the cotton produced in the United States, about 80%, is exported overseas. Therefore, with the increased competition in cotton production, the U.S. needs to improve cotton fiber quality to maintain its share in the global market. Other countries like Australia, Brazil, China, India, Turkey and Uzbekistan are leading producers of cotton. However, China is the major producer and consumer. In 2011 China produced 33.5 million bales and consumed more than 50% of the U.S. grown cotton (Cotton Council International).

The cotton plant has historically been modified to meet the requirements of the producing areas. Cotton plants are regarded as perennials, with indeterminate growth. However, the morphology and phenotype has been modified to meet the requirements of annual production systems. It has also been modified to be photoperiod insensitive to adapt to the temperate latitudes of the commercial production areas. World cotton production takes place primarily between latitudes 45°N and 30°S, with average temperature of 25°C (Acquaah, 2007). Cotton varieties are often classified as short-season or more determinate plants, medium-season, and long-or full-season which are more indeterminate plants (Silvertooth et al., 1999).

An optimum soil temperature of about 18°C during the day, and good forecast for at least five days are preferred planting conditions for good establishment of the crop. In the Texas High Plains planting usually starts between April and May. After establishment of the crop, the first developmental stage is the initiation of first reproductive sites, called squares. In general, in well-established non-stressed cotton, first squares begin to appear at 35 days after planting (Oosterhuis and Kerby, 2008). Then, approximately at 60 days after planting, first flowers start to appear. About three days elapse between the opening of one flower to the other on a different fruiting branch (Oosterhuis and Kerby, 2008). In the reproductive stage, about four to five weeks after planting, flowers open for several weeks followed by fruit development (Oosterhuis and Jernstedt, 1999).

Upland cotton flowers are creamy white on the day of flowering, and turn pink-red the following day, shedding one to two days after (Oosterhuis and Jernstedt, 1999). Pollination occurs during the flowering time, when pollen is transferred from the anthers to the stigma of the flower. Fertilization occurs after successful pollination from which fertilized seed develop in green pods called bolls. Fibers trichomes grow from epidermal cells on the seeds. Mature bolls split about 40 to 45 days after pollination, exposing fully developed fibers (Oosterhuis and Jernstedt, 1999).

Cotton development is sensitive to environmental changes. For instance, flowering does not take place if there is not sufficient soil moisture, or in a constant period of high temperatures or drought. Also a temperature differential between day and night is required for the correct development of the crop. Fiber development is also affected by changes in the environment. In the same cotton plant there are simultaneously open bolls, green bolls, and flowers. This means that different bolls on the same plant are developing in different growing conditions. Growing conditions determine the differences in fiber characteristics, which vary from one boll to another. Temperature, diseases, insect pressure, and water availability are the main factors that affect production of cotton. Furthermore, exposure to the environment once the bolls are open can degrade fiber characteristics.

Fibers are harvested approximately five to six months after planting. Mechanical cotton picker and stripper harvesters are used for such a task in the United States. In the Texas High Plains, stripper harvesters are more common than picker harvesters. Cultivars are usually storm proof type, and shorter in stature than in other growing regions in the U.S., well adapted to be harvested with strippers. Stripped cotton is collected and stored in modules with capacity of 13 to 15 bales of cotton. In a regular non-stressed season a farmer produces from two to four bales per acre (217.7 Kg/bale).

With the current marketing system, producers receive premiums and discounts based on the grade and quality of the fiber. Classing offices apply standardized procedures developed by the USDA (United States Department of Agriculture) for measuring physical characteristics of raw cotton that affect the quality of the end product. Such characteristics are measured with High Volume Instruments (HVI), and consist of the determination of fiber length, length uniformity, strength, micronaire, color, leaf and extraneous matter. However, properties like fiber elongation are usually ignored, because there is no standard calibration and a perceived negative correlation between fiber elongation and fiber strength (Benzina et al., 2007). Nonetheless, fiber elongation might play an important role in reducing short fiber content and increasing uniformity index (Backe, 1996).

To cope with changes in the market and production conditions, continuous efforts have been made for the improvement of cotton cultivars. Increased yields along with improved fiber quality have been the main objectives of breeding programs in the Texas High Plains and in the U.S. Nonetheless, the efforts should be constant to create and maintain sustainable cotton production.

2.1 Breeding

Plant breeding is defined as the art and science of genetic improvement of plants (Fehr, 1991). As art, it has been around since the beginning of human kind when humans started selecting for one plant type in preference to another. As science, plant breeding uses genetics and other disciplines to understand plants and to effectively select for superior types to improve their performance (Acquaah, 2007; Fehr, 1991). Thus, the overall objective of plant breeding is to improve plant characteristics that contribute to the economic value of the crop, as well as to improve the overall performance achieved by the crop in a growing environment (Acquaah, 2007; Bernardo, 2002; Campbell et al., 2011; Fehr, 1991; Hallauer and Miranda, 1981). To accomplish this goal, plant breeders manipulate plant structure and composition. However, breeders need to dispose of sufficient variation to be able to effectively select for superior types. Consequently, variation is by far one of the most important criteria for plant breeders to find useful traits that can be incorporated into breeding populations.

Genetic variation can be created by hybridizing genetically divergent parents, each one contributing characters of interest for the formation of a new population (Bernardo, 2002; Calhoun and Bowman, 1999; Fehr, 1991; Flavell, 2010). However, genetic variability in cultivated plants for breeding programs is sometimes limited, especially when there is not accessibility to diverse gene pools. Campbell et al. (2011) explained that "narrow genetic diversity is cause for alarm because genetic diversity must exist for effective plant breeding and genetic improvement efforts". Therefore, in some instances, exotic species are used as genetic resources to introduce new traits to increase yield potential, introduce pest and/or disease resistance, or to improve any trait of interest (Bowman, 1999; Brubaker et al., 1999; Flavell, 2010; Fryxell, 1984; Stewart, 1995). However, making crosses with dissimilar parents can carry useful genes, as well as deleterious genes (Flavell, 2010). Hence, before introducing exotic material into breeding programs, barriers to hybridization and introgression must be overcome. This task is usually an objective of pre-breeding and/or public breeding programs where useful traits are moved from exotic species to cultivated species while eliminating most of the undesirable traits (Bowman, 1999).

Populations for cultivar development can be created using different hybridization schemes; among them, single crosses (crossing two parent), three-way crosses (three-parent cross), four-way crosses (four parents), backcrosses, and more complex crosses (Fehr, 1991). Additionally, various mating schemes, like diallel mating design, and North Carolina design are used to evaluate gene action and heritability of a trait (Bowman and Jones, 1984; de Aguiar et al., 2007; Hussain et al., 2010). Diallel analysis allows breeders to separate and quantify the magnitude of genetic and non-genetic variances. Additionally, diallel analyses provide information on crosses that are more likely to perform better according to their general and specific combining ability, and thus produce desirable segregates (Braden et al., 2009; de Aguiar et al., 2007; Hussain et al., 2010).

In general, the improvement of crops follows a specific series of activities. First, the breeder must identify breeding objectives; second, identify or produce enough genetic variability to create a breeding population; and finally, identify and select the best strains/families which may become cultivars (Acquaah, 2007; Calhoun and Bowman, 1999; Meredith et al., 1991). The most critical step in cultivar development is the selection phase. Selection is a breeding methodology that allows breeders to choose individuals (artificial selection) with desirable characteristics that will be used as parents for the next cycle of selection (Hallauer and Miranda, 1981; Vallejo-Cabrera and Estrada-Salazar, 2002). The process is repeated for several generations until genetic variation is exhausted, or until the breeding objectives are met. Selection methodologies and breeding procedures depend on the availability of genetic variance, the trait and its heritability, the environmental effects, the biology of the plant and their reproductive mode among others (Fehr, 1991; Vallejo-Cabrera and Estrada-Salazar, 2002).

In cotton, as well as in other crops, breeders move from highly segregating populations towards more homozygous and uniform populations. Several methods including pedigree, bulk, single-seed descent, mass selection, recurrent selection and backcross are used by cotton breeders to manage segregating populations (Calhoun and Bowman, 1999). The most common method used by cotton breeders is the pedigree selection method. Pedigree breeding is used to attain uniformity of traits such as fiber quality, yield components, and disease and pest tolerance and/or resistance (Acquaah, 2007). Since the mid 1990's, changes in harvesting and ginning of upland cotton (*G. hirsutum*) and in speed of processing in the textile industry, have shaped the objectives of the improvement of cotton (Culp and Harrell, 1973). Cotton cultivars must meet the demands of high yields for producers, as well as provide fiber with good and high quality standards for textile manufactures (Culp and Harrell, 1973; May, 1999a; May, 2002). Therefore, cotton breeders play an important role in delivering superior cultivars for crop production systems that produce high yields with pest and disease tolerance and/or resistance, and superior fiber quality.

For instance, superior cotton yarns are required by the textile industry to increase efficiency and performance in spinning and weaving processes (Calhoun and Bowman, 1999; May and Taylor, 1998). However, yarn properties cannot be directly selected because of the lack of availability of large amounts of lint in early generations, the size and variability of the genetic population and the high cost of yarn testing (Braden et al., 2009; May, 2002). Therefore, breeders indirectly select for fiber properties in early generations that correlate with increased yarn strength and performance in later generations, which at the same time are less expensive to measure (Braden et al., 2009; Green and Culp, 1990; May and Taylor, 1998; May, 2002; Meredith et al., 1991). The correct identification of individual fiber properties that correlate to high yarn strength and performance, are the key path for a successful breeding program (May and Taylor, 1998). Moreover, as yarn manufacturing processes are updated to faster and more efficient spinning systems (Campbell et al., 2011; May, 2002), it is necessary to maintain and increase fiber quality that directly relates to yarn and weaving performance. Individual fiber properties like fiber length, length uniformity, strength, and micronaire, are the major fiber quality parameters that directly relate to yarn strength (Acquaah, 2007; May and Taylor, 1998; May, 2002; Meredith et al., 1991). However, other fiber properties like fiber elongation, maturity, and fineness also contribute to higher yarn strength (Backe, 1996; May and Taylor, 1998)**.** Even though individual fiber properties play a large role in the improvement of yarn tenacity, this is maximized by improving more than one fiber property at a time (May and Taylor, 1998). May and Taylor, (1998), reported that selecting for the combination of low micronaire, long 50% span length, and high fiber strength, results in greater improvement of yarn tenacity than selecting for individual fiber properties. Meredith et al. (1991), also reported that a combination of fiber length, stelometer strength and fineness, are better predictors of yarn tenacity of 27 tex yarn counts and lower. However, Meredith et al. (1991) concluded that stelometer strength is the single factor that most contributes to yarn tenacity. Other authors recognized the importance of fiber length as a critical predictor of yarn tenacity (Braden et al., 2009; May and Jividen, 1999)**.** On the other hand, May and Taylor, (1998) and Meredith et al. (1991), reported that selecting for high fiber elongation does not provide improvement in yarn tenacity. They concluded that the little improvement could be due to low genetic correlation, or to significant genotype x location x year interaction. However, Backe, (1996) reported that fiber elongation is an excellent predictor of yarn work-to-break.

Several researchers have worked on methods for simultaneous improvement of yield and fiber quality, strength in particular. For example, Meredith Jr, (1977), encouraged the use of backcross breeding for the simultaneous improvement of fiber quality and lint yield. He reported increases of 34.9, 36.9 and 37.6 lint percent on the BC_1F_5, BC_2F_4 and BC_3F_3 backcross populations respectively, as well as maintained satisfactory levels of fiber strength with little practical differences in lint yield among the three backcross populations. The average fiber strength for the BC_1F_5, BC_2F_4 and BC_3F_3 backcross populations was 220, 211, and 216 mN/tex, respectively. Other studies have proven that major improvement of lint yield and fiber quality is reached by hybridization and selection with the use of the pedigree method (Culp and Harrell, 1973). This method allows the evaluation of fiber quality traits in early generations, which according to Culp and Harrell, (1973) is more practical than evaluating large populations of undesirable material in later generations. Under the pedigree method, hybridization is followed by selection (Fehr, 1991). Selection usually starts in the F_2 generation, and continues until homozygosity is reached, or until the trait is fixed. Since the selection starts in early generations, traits can be quickly fixed. One of the major disadvantages of this method is the amount of record keeping. However, the major advantage is that it allows breeders to trace back the origin of the cross, and keep track of the development of the families and varieties (Acquaah, 2007; Fehr, 1991; Vallejo-Cabrera and Estrada-Salazar, 2002) .

A successful public breeding program in the U.S., the Pee Dee improvement program, was initiated in 1935 and is an excellent example of the continuous improvement of cotton fiber quality and yield (Campbell et al., 2011). The program used intercrossing and recurrent selection to obtain improved cultivars using the combination of alternative breeding methods such as random mating, modified backcrossing and composite crossing during 70 years of improvement; which at the same time allowed breeders to maintain genetic diversity (Campbell et al., 2009; Campbell et al., 2011). Campbell et al. (2011) selected eighty-two cotton germplasm lines from the Pee Dee cotton breeding program to evaluate agronomic data and fiber quality performance as well as to estimate the levels of genetic improvement. The overall percentage change from lines from the 1970s to the 2000s evaluated by Campbell et al. (2011) were, +9% lint percent, +21% lint yield, +10% bolls m^{-2}, -7% seed index, -4% fiber strength, -4%

fiber length, +16% fiber elongation, +4%micronaire, and +3% fiber fineness. Additionally, he reported superior values for fiber quality traits in comparison with commercial cultivars. The results suggested that hybridization followed by selection is successful for the improvement of agronomic and quality traits in cotton, and significant genetic gains can be achieved through breeding.

Breeders also use methodologies like divergent selection for the improvement of traits. Divergent selection is defined as the selection of high and low values of a trait (Bernardo, 2002). Divergent selection has been used in different studies to evaluate, for example, response progress from selection or for trait correlations. For instance, Cortez-Mendoza and Hallauer, (1979) conducted a study on 10 cycles of divergent mass selection for ear length in maize (*Zea mays* L.) to determine direct and correlated responses from selection. Albrecht and Dudley, (1987) working in lodging resistance in maize, conducted a study on divergent selection to evaluate progress from selection. Low and high selections (divergent selection) for a trait are also useful to obtain realized heritability estimates (Fehr, 1991; Guthrie et al., 1984; Ibrahim and Quick, 2001; Roumen, 1996; Smart et al., 2003). In addition, divergent selection has also been used in discovering significant variation, and in determining if traits like protein and oil in maize and soybean (*Glycine max* L.) can be changed by selection (Dudley and Lambert, 1992; Dudley and Lambert, 2004; Fasoula and Boerma, 2005).

There are several improvement strategies and techniques available for breeders to use. However, choosing the correct methodology depends on many factors. For instance, knowledge of the genetic effects, environmental influence, and testing methodologies, as well as identification of breeding objectives and availability of resources are key factors to develop accurate improvement strategies. Crosses made by breeders, specifically wide crosses (diverse parents), contribute to enhancement of cotton germplasm diversity as well as to its performance in general. Nevertheless, breeders have the task to keep and improve diversity at the same time, as well as to breed efficiently. A successful breeding program will deliver improved varieties that meet the needs of the production region while increasing crop performance.

2.2 Heritability

The concept of heritability first originated to describe the observed differences in phenotypes, whether they were due to genetic or environmental effects (Hanson, 1963). Heritability is defined as an estimate of the proportion of the genotypic variation to the phenotypic variation, which is attributable to the joint action of the genotype and the environment (Bernardo, 2002; Ceballos, 1998; Falconer and Mackay, 1996; Fehr, 1991; Hallauer and Miranda, 1981). Heritability measures the relative contributions of genetic and non-genetic factors to the phenotypic variances in a population, determining the degree of resemblance between relatives (Bernardo, 2002; Hallauer and Miranda, 1981; Holland et al., 2003). To obtain heritability estimates, phenotypes are evaluated in target environments. Consequently, values of heritability are specific to the experimental unit, the population under study, and the target environment (Hanson, 1963; Holland et al., 2003; Wagoire et al., 1999). However, defining and sampling the reference population and the environment is crucial to provide the correct circumstances of the estimation of heritability (Holland et al., 2003; Nyquist, 1991).

Heritability can be estimated in broad and narrow sense. Broad sense heritability measures the ratio of the total genetic contributions (additive, dominance, and epistasis) to the phenotypic variation. On the other hand, narrow sense heritability is the measure of or the ratio of the additive genetic component to the total phenotypic variance (Fehr, 1991; Hanson, 1963). Additive variance is desirable among breeders, because it measures the additive effects and therefore provides the value of the incremental accumulation of a quantitative trait in heterozygous state, and the increased value in the homozygous state (Falconer and Mackay, 1996; Fehr, 1991; Hallauer and Miranda, 1981). The values of narrow sense heritability are more useful in breeding programs, because it measures the genetic resemblance transmitted from parents to offspring (Fehr, 1991). On the other hand, broad sense heritability is generally higher than narrow sense heritability, because it measures all the genetic contributions (additive, dominance and epistatic) to the phenotype. However, dominance gene action is transmitted but can only be measured by the interaction of the alleles from both parents; therefore, it cannot be measured by breeders because it is not possible to discern between the heterozygous and the homozygous state (Falconer and Mackay, 1996; Fehr, 1991; Hallauer and Miranda, 1981). In general the lower the heritability value, a higher number of plants should be selected to ensure capture of the trait in question in the selected population (Poehlman, 1987).

Types of populations and mating designs for progeny evaluations need to be considered to evaluate family relations for the estimation of heritability. Because heritability is a measure of genetic and environmental effects on the phenotype, a measure of family relatedness is essential (Nyquist, 1991). Therefore, relationships between relatives can be obtained, and consequently genetic components of variances determined (Cockerham, 1963; Hallauer and Miranda, 1981; Hanson, 1963). Furthermore, to obtain unbiased estimates of heritability, samples from the progenies or individuals under study should be taken at random (Holland et al., 2003; Nyquist, 1991). Heritability can be estimated on single plant basis, plot basis, or entry mean basis (Fehr, 1991; Hallauer and Miranda, 1981). The heritability of a character depends on the evaluation process; therefore, its value and magnitude differ with the number of locations employed in the experiment, and whether it was evaluated in one or more years (Fehr, 1991).

A number of methods have been proposed to estimate heritability. Among them, the variance component method, based on the variance components obtained from the analysis of variance, is the most widely used (Bernardo, 2002; Cockerham, 1963; Fehr, 1991; Hallauer and Miranda, 1981; Hanson, 1963; Holland et al., 2003; Nyquist, 1991). Failure to estimate interactions of genotypes, years, and locations in the components of variance will influence the value of heritability, inflating its true value (Fehr, 1991). Parent offspring regression is based on the regression of the value of a character in the progeny upon the value for the same character in their parents. The regression of offspring on parents is a useful measure of the degree of resemblance between relatives (Bernardo, 2002; Falconer and Mackay, 1996; Fehr, 1991; Fernandez and Miller, 1985;

Foolad et al., 2002; Nyquist, 1991; Smalley et al., 2004; Smith and Kinman, 1965; Vogel et al., 1980). Realized heritability is obtained from the response realized from selection divided by the selection differential. Realized heritability expresses the gain from selection, and therefore depends on the unit used for selection (Bernardo, 2002; Falconer and Mackay, 1996; Fehr, 1991; Hanson, 1963; Holland et al., 2003; Nyquist, 1991).

Heritability is applicable in breeding programs for several reasons. It helps breeders in making decisions for the efficient allocation of resources (Hallauer and Miranda, 1981). It also facilitates in determining if the trait under study would benefit from breeding (Hanson, 1963; Nyquist, 1991), in determining the most convenient strategy for selection, and in predicting gains from selection (Holland et al., 2003; Nyquist, 1991). Furthermore, since the phenotype is due to the combined action of the genotypic and environmental effects, breeders are interested in determining which proportion is due to genotype and which to the environment (Hallauer and Miranda, 1981). Therefore, heritability gives a numerical description of the response from selection (Hanson, 1963).

In cotton, numerous studies have been conducted to estimate heritability of fiber properties such as length, strength, elongation, fineness, and maturity ratio. The availability of evaluation methods such as single instruments (i.e., fibrograph, stelometer, instron) and more recently the high volume instrument (HVI) and the Advance Fiber Information System (AFIS) have made possible the accurate assessment of fiber properties. Knowledge of heritability and genetic effects facilitate the further improvement of fiber properties (May and Green, 1994). Therefore, studies conducted to establish genetic variances and their effects are prompted to facilitate the overall improvement of cotton.

Even though fiber elongation is not currently a selection criterion in many cotton breeding programs, several efforts have been made to estimate its genetic components and heritability. May, (1999a), indicated that for fiber elongation, pedigree selection or early generation testing schemes should be an effective breeding tool. However, there is a weak negative correlation between fiber elongation and fiber strength, and therefore there is a reluctance to work on elongation because it could result in lower tenacity (Abdel-Nabi et al., 1965; Green and Culp, 1990; Meredith et al., 1991). Ulloa, (2006), estimated heritability for a number of fiber traits in two generations, $F_{2:3}$ and $F_{2:6}$, of okra-leaf type cotton. He obtained values of 0.83 and 0.74 using single-instruments to measure fiber elongation. This indicates that the inheritance of fiber elongation measured with single instruments is high, and therefore, selection should be highly effective. However, testing with HVI is necessary to reduce testing time and increase reliability. Yet, most breeders avoid working with elongation, because of the lack of calibration procedures for HVI-elongation (Benzina et al., 2007), and therefore the lack of agreement among HVI machines, and labs.

Conversely, numerous studies have been conducted to establish genetic effects, variances components, and heritability for yield and quality parameters like strength, length, uniformity, and maturity (Basal and Turgut, 2005; de Aguiar et al., 2007; Desalegn et al., 2009; Kaushik and Kapoor, 2010; Larik et al., 1997; May and Green, 1994). May and Jividen, (1999) report low to moderate estimates of heritability for most fiber properties. For example, parent-offspring regression estimate of heritability for strength measured with HVI, ranged from 0.12 to 0.39; indicating a significant genetic variation. The same authors reported low estimates of heritability for fiber elongation measured with HVI (0.17 – 0.18), concluding that HVI-instrument may not be as reliable in determining fiber elongation. However, Benzina et al., (2007) evaluated ways to calibrate the HVI to validate its measurement for elongation, and therefore obtain reliable estimates.

Abdel-Nabi et al., (1965), measured heritability of fiber strength and fiber elongation based on regression coefficients between the F_3 and F_2 lines. They obtained moderate values of heritability of 0.59 for fiber strength, and 0.80 for elongation. The authors suggested that the large proportion of the total genetic variance was due to additive variation, and therefore, selection for fiber elongation should be effective in early generations. Nevertheless, a high negative correlation of -0.60 between strength and elongation was also obtained. They concluded that it would be difficult to obtain high expressions for both characters on a single line. However, it is possible that with the use of targeted selection, fiber strength and elongation could be simultaneously improved.

Different studies reveal different values of heritability for fiber quality parameters. For example, values of 0.33 (Desalegn et al., 2009), 0.17 to 0.64 (May and Green, 1994), 0.40 (Tang et al., 1996), and 0.56 to 0.85 (Ulloa, 2006) have been reported for fiber strength. Except for Ulloa (2006), the values of heritability reported for strength tend to be moderate. Because fiber strength is an important component of selection for fiber quality, breeders spend a large amount of resources and time for its accurate evaluation. However, even though breeding programs have focused on improving fiber strength (Basal and Turgut, 2005; Gannaway, 1982; Singh et al., 1990), improving fiber elongation has been ignored (Backe, 1996; Benzina et al., 2007). Hence, more studies including fiber elongation are needed to indicate the importance of fiber elongation for fiber and yarn processing (Backe, 1996).

By improving yarn tenacity through fiber strength and elongation, it is expected to reduce the level of short fibers and increase uniformity ratio (Benzina et al., 2007). Uniformity ratio and short fiber content are also crucial components for the performance of fibers in textile processing (Deussen, 1992). Hence, genetic evaluation of those traits is important as well. Desalegn et al. (2009), obtain heritability estimates of 0.86 and 0.69 for short fiber content and uniformity ratio respectively. Ulloa (2006), reported values of 0.67 for the $F_{2:3}$ and 0.71 for the $F_{2:6}$ for short fiber content. High values of heritability for those two traits indicate that it is possible to decrease short fiber content and increase uniformity ratio.

Heritability of yield components is evaluated frequently as well. This allows breeders to determine yield traits that respond to selection. Some of the yield components usually evaluated include lint percent, lint yield, lint index, seed index, number of seed per boll, and boll weight. Desalegn et al. (2009), found high values of heritability for yield components; ranging from 0.72 to 0.97. The same authors measured the correlation between yield components and fiber quality parameters, and concluded that yield components could be considered as indicators of fiber quality improvement. However, it has been demonstrated that yield components, particularly lint yield, is negatively correlated to fiber quality parameters like length and strength (Desalegn et al., 2009; Green and Culp, 1990; Smith and Coyle, 1997; Ulloa, 2006). Nonetheless, Coyle and Smith, (1997); Green and Culp, (1990); and Schwartz and Smith, (2008), suggested that the use of more complex crosses like three way-crosses, modified backcross, inter-mating or recurrent selection can be used to improve quality characteristics and yield components at the same time. Additionally, general and specific combining ability effects are usually measured as a method of choosing the best parents for crossing in a breeding program (Green and Culp, 1990).

On the other hand, previous research indicated that in general, fiber elongation is positively correlated with lint yield and lint percentage (Tang et al., 1993). Therefore, knowledge on the heritability of fiber traits would facilitate the overall improvement of the cotton crop, and would allow breeders to choose effective selection schemes. However, reliable and less time consuming methods are required for the evaluation of such traits.

2.3 Fiber quality

Cotton fibers are single, elongated cells of the seed coat epidermis, or epidermal trichomes that arise from the protoderm of the ovule (Oosterhuis and Jernstedt, 1999). Fiber development can be divided into fiber initiation, fiber elongation, secondary wall formation and maturation (Ryser, 1999). The emergence of fiber initials takes place the day of anthesis (flowering) in upland cotton, or few days before anthesis in sea island cotton (Oosterhuis and Jernstedt, 1999). The initials elongate by a factor of 1000 to 3000 times the diameter of the fiber and then deposit a thick secondary cellulosic wall. Ryser, (1999), indicated that cotton fibers elongate by diffuse growth, which means that the cell growth occurs by extension of the cell wall all over its surface. Elongation of the fiber continues 20-30 days, depending on the genotype and environmental conditions, until the fibers reach their final length (about 20-60mm) (Oosterhuis and Jernstedt, 1999; Ryser, 1999). During the elongation phase, the primary cell wall is deposited. This consists of an accumulation of pectin, callose and a thin layer of cellulose, and cuticle on the surface (Oosterhuis and Jernstedt, 1999). The secondary cell wall formation, primarily composed of cellulose, starts at approximately 20 days after fiber initiation (Benedict et al., 1999). Deposition of the secondary cell wall continues for approximately 40-45 days after anthesis; then the boll splits open and the fibers become exposed to the environment and dry (Oosterhuis and Jernstedt, 1999). Therefore, the elongation phase and secondary wall formation overlaps (Benedict et al., 1999; Oosterhuis and Jernstedt, 1999). Additionally, the extent of the fiber elongation period determines the length of the fiber (Benedict et al., 1999). Secondary cell wall thickening and deposition determines fiber fineness and maturity (Benedict et al., 1999; Kohel, 1999). Secondary cell wall deposition (cellulose deposition) is also considered one of the major contributors of fiber strength (Benedict et al., 1999; Kohel, 1999). However, much variation is found from fiber to fiber due to environmental differences during the growing season, soil type, insect and disease pressure, rainfall, irrigation practices, and temperature among others (Ramey, 1999). Therefore, fiber development is highly influenced by the environment, which at the same time determines whether fiber length and strength reach their full genetic potential (Benedict et al., 1999).

Cotton fibers are used as raw material in the textile industry, and its value is currently measured based on fiber properties like length, strength, uniformity, micronaire, and grade. Fiber quality is not measured as a single trait, rather it can be defined as the combination of fiber properties that improve spinability and processing performance of cotton fibers in the textile industry (Kohel, 1999). The first attempts to measure fiber quality were done through visual assessment and feel (Kohel, 1999; Ramey, 1999). Even though these assessments were subjective, it helped estimate the ease of fiber processing. Visual assessment was made by graders who were able to identify fiber properties with great skill, classifying cotton according to its quality.

However, the cotton industry sought more objective measurements for fiber properties. Therefore, since the early 1900's scientist and institutes started developing instruments to measure fiber properties. The first instruments developed were capable of measuring single fiber properties; fibrograph measured fiber length, and the stelometer and pressley measured strength and elongation (May and Jividen, 1999; Ramey, 1999). However, in 1969, the U.S. Department of Agriculture developed the High Volume Instrument to obtain standardized and reliable measurements of fiber quality (Hsieh, 1999; Ramey, 1999), able to measure complete profiles of fiber properties in high volume (May and Jividen, 1999). With this system, cotton growers benefit from the USDA price support program by receiving premiums according to the quality of their cottons. The HVI, nonetheless, was designed as a marketing tool to determine the quality of fiber within cotton bales (Kelly et al., 2012). In spite of its initial purpose, HVI evaluates multiple fiber characteristics in high volume at low cost, higher speed and more accurately than hand classing. Therefore, breeders have used it since then to evaluate cotton fibers and make decisions for cotton quality improvement. Furthermore, as quantitative measurement techniques became available, fiber properties that correlate to spinning performance were more easily identified (Kohel, 1999). Additionally, with the advancement in speed and accuracy of new technological tools to measure fiber properties, breeders were able to study the genetics of quality parameters (May, 1999b).

Superior cotton yarns are required by the textile industry to increase the efficiency and performance in spinning and weaving processes (Calhoun and Bowman, 1999; May and Taylor, 1998). However, yarn properties cannot be directly selected because of the lack of availability of large amounts of lint in early generations of testing, the size and variability of the genetic population, and the high cost of yarn testing (Braden et al., 2009; May, 2002). Therefore, breeders indirectly select for fiber properties in early generations that correlate to increased yarn strength and performance in later generations, because more samples can be analyzed, fiber properties are less expensive to measure and require smaller quantities of fiber than yarn testing (Braden et al., 2009; Green and Culp, 1990; May and Taylor, 1998; Meredith et al., 1991).

Moreover, as yarn manufacturing processes are updated to faster and more efficient spinning systems (Campbell et al., 2011; May, 2002), it is necessary to maintain and improve fiber quality that directly relates to yarn and weaving performance.

To continue to produce superior and more competitive cottons, fiber characteristics like elongation, short fiber content, maturity, fineness and nep count, which are not currently measured by the industry, will become part of the market structure affecting the competitiveness of cotton. For instance, fiber elongation has been ignored as a measure of yarn performance, mainly because there is a perceived negative correlation with fiber strength (Backe, 1996). Also, breeding programs generally ignore fiber elongation because of a lack of calibration for high volume instrument (HVI) elongation, which make it difficult to rely on such data (Benzina et al., 2007). However, work to rupture is equally important as currently measured traits, and is determined by both strength and elongation. The work to rupture is defined as the total energy required to break a bundle of fibers. According to Benzina et al. (2007) , "it is calculated as the area under the curve between 0 (after removal of crimp) and the elongation corresponding to the peak load". Work to rupture becomes important, because as more energy is required to break the fibers, the short fiber content is reduced and therefore cottons would perform better in spinning and weaving (Benzina et al., 2007). Demonstrating that improved work-to-break will result in lower fiber breakage when the fibers are submitted to mechanical stresses (ginning, carding, spinning, weaving), will show the importance of including breeding lines with improved elongation and selection pressure for work-to-break characteristics in new variety development programs. Thus, as new spinning technologies are developed, fiber quality traits not measured before, that contribute to textile performance, become important in determining fiber quality for specific textile uses and for setting objectives in breeding programs (Kohel, 1999; May, 1999a).

2.4 Spinning

Textile industry uses yarns to create fabrics, and yarns are composed of cotton fibers. Yarns are made by twisting fibers into a cohesive structure in which fibers bind together having as much strength as possible (Smith and Zhu, 1999). The process by which fibers are bound together is known as fiber spinning (Joseph, 1981), and the goal is to produce yarns that are even, smooth, and free of defects (Smith and Zhu, 1999). Fiber properties determine the efficiency and performance of yarn processing and spinning (Faulkner et al., 2012). Two major spinning systems are available to produce cotton yarns: ring spinning, and rotor (open-end) spinning. The U.S. primarily uses the rotor system, while foreign industries primarily use ring spinning (Faulkner et al., 2012). Properties like fiber length and fineness determine the final count of the yarn, while properties like strength and maturity determine the ability of fibers to withstand stress during fiber processing. For instance, ring spinning requires longer fibers and high uniformity to produce superior yarns (Deussen, 1992). The force used to hold fibers together in ring spinning is lateral fiber-to-fiber friction, making length and fineness important properties because they affect the amount of contact between fibers (Deussen, 1992; Kelly, 2009). Conversely, rotor spinning requires stronger fibers able to resist the twist insertion to create the yarn. The major difference between the two systems is that ring spinning uses a traveler to create the twist, while rotor spinning uses rotating rotor (Joseph, 1981; Kelly, 2009). In rotor spinning yarn production is faster and more economical; also shorter fiber lengths can be used to produce yarns (Deussen, 1992). For this reason, rotor spinning became the most important technology used in the U.S. for fiber processing (Braden, 2005). However, a major disadvantage from rotor spinning is that it produces coarser yarns compared to those from ring spinning (Joseph, 1981).

In general, stronger fibers are needed, because they can withstand higher forces associated with higher speed in the textile industry (Deussen, 1992; Faerber and Deussen, 1994), as well as contributing to yarn strength (Meredith et al., 1991). Also, stronger fibers will reduce the amount of short fiber content from fiber breakage, which limits the efficiency of spinning and produces more defects and breakage. Fiber length and fineness, on the other hand, influence the forces between fibers that relate to the count of the yarn (Faulkner et al., 2012). Fiber length was the first property used to assess cotton quality, because of its recognized contribution to yarn strength and processing performance (May, 1999a).

Besides fiber strength and length, neps, short fiber content, maturity, fineness, and elongation are other fiber characteristics that influence the processing of yarns and textiles (May and Jividen, 1999). For instance, Backe (1996) reported that cotton fiber elongation contributes to yarn evenness, defect level, yarn strength and yarn elongation, work-to-rupture, hairiness and weaving performance. The author concluded that higher fiber elongation contributes to better yarn quality and resistance to stress reducing short fiber content and increasing uniformity index. Therefore, fiber elongation should be measured and considered during spinning setting, as pointed out by Benzina et al. (2007).

Each spinning system requires different fiber profiles to efficiently produce stronger yarns. Consequently, utilization of different spinning systems to produce yarns has resulted in the use of several different types of cotton varieties with fiber characteristics that supply the demand of the industry (El-Mogahzy, 1999). It is important that breeders use these profiles as guidelines for the improvement of cotton fiber quality. On the other hand, the U.S. production and use of cotton has changed in recent years, with increased exports taking over domestic consumption (Faulkner et al., 2012). The shift to foreign markets, coinciding with the shift to ring spinning over rotor spinning, has increased the competition and changed the objectives for cotton production (Braden, 2005; Faulkner et al., 2012). Therefore, fiber quality improvement and measurement techniques should keep working to meet the demands of the textile industry for superior cottons able to withstand the abrasive processing of ring spinning to produce finer yarns.

2.5 Objectives

2.5.1 Use divergent selection for fiber elongation to develop lines to test the hypothesis that elongation is important for spinning

2.5.2 Determine the response to selection for fiber elongation

2.5.3 Determine correlation coefficients among HVI fiber traits and yarn properties

2.5.4 Determine if work-to-break of cotton fiber bundle and yarn can be improved through classical breeding techniques

2.5.5 Determine if improving elongation in combination with breaking strength will significantly improve spinning quality of cotton

2.5.6 Evaluate and determine heritability of fiber elongation

3. MATERIALS AND METHODS

The research was conducted at the Texas AgriLife Research and Extension center in Lubbock, TX, (LREC) in partnership with Texas A&M University, Department of Soil and Crop Science, College Station, TX.

Fifteen populations were developed in 2007 by crossing high quality breeding lines with high elongation and good fiber characteristics to ‘FM 958’ (PVP 200100208), a High Plains standard cultivar with reduced fiber elongation. Pedigrees for these fifteen populations are listed in Table 1.

Divergent targeted selection was conducted on the F_2 and F_3 generations in 2008 and 2009 respectively. Final lines were selected and increased in 2010 in four replications to produce enough fiber for spinning test in 2011 and 2012. Selections for spinning include three paired selections, two additional selections from the entire population, and check cultivar ‘FM 958’.

Heritability was estimated using the variance component method, parent off-spring regression and realized heritability in 2011 and 2012, in three locations with three replications. Estimates of heritability were carried out using parents, F_3, F_4, and F_5 generations.

Table 1. Pedigrees for the original crosses made in 2007.

Entry/Family	Designation	Pedigree
1	FM958x3818	FM 958x{CA 3066x[(EPSM 1667-1-74-4-1-1xStahmanP)xEPSM 74-1094-76)}
2	FM958x3819	FM 958x{CA 3066x[(EPSM 1667-1-74-4-1-1xStahmanP)xEPSM 74-1094-76)}
3	FM958x3821	FM 958x{CA 3066x[(EPSM 1667-1-74-4-1-1xStahmanP)xEPSM 74-1094-76)}
4	FM958x3828	FM 958x[CA 3066x(CA 2267xM-8844-0243)]
5	FM958x3829	FM 958x(CA 3066xEPIg#826-1-75-1)
6	FM958x3830	FM 958x(CA 3066xEPIg#826-1-75-1)
7	FM958x3831	FM 958x(CA 3066xEPIg#826-1-75-1)
8	FM958x4009	FM 958x{[(EPSM 1667-1-74-4-1-1xStahman P)xMexico-CIAN-95]x[EPSM 1015-4-74xEPSM 1323-3-74]}
9	FM958x4027	FM 958x[(EPSM 1224-1-74xStahman P)xRanger Exp GXT 93]
10	FM958x4127	FM 958x(EPSM 1158-1-74-1-2-1-2xCA 3026)
11	FM958x4238	FM 958x[CA 3066x(CA 2267xM-8844-0243)]
12	FM958x4306	FM 958x"{(CA 3084xCA 1056)x[(EPSM 1667-1-74-4-1-1xStahman P)xEPSM 74-1094-4-76]}x(Deltapine 2156x82-DTT-822-2)"
13	FM958x4311	FM 958x(EPSM 1352-1-74-1-4xSTD Westburn M)
14	FM958x4332	FM 958x{[(EPSM 1667-1-74-4-1-1xStahman P)xMexico-CIAN-95]x[EPSM 1015-4-74xEPSM 1323-3-74]}
15	FM958x4404	FM 958xEPIg#826-1-75-1

3.1 F_2 generation

F_2 seed from the fifteen populations and a check (FM 958) were planted at LREC in Lubbock, TX, in a randomized complete block design (RCBD) with four-row plots and four replications on May 13, 2008. The soil type in the Lubbock location is Amarillo or Olton Loam. Every plot was thinned to approximately one plant every 20.32 cm approximately 30 days after emergence. Plots were 92.9 cm in length and each row was 101.6 cm wide. Test was irrigated using furrow irrigation. One boll per plant from the first position was harvested in October to determine family average. Four plants were selected per row (sixteen plants per plot)/replication based on agronomic traits, for a total of 64 plants per F_2 and harvested in November. Plants with similar fruiting pattern were selected to minimize variation in fiber development due to growth habit and environment. Selections and boll samples were ginned on a tabletop ten-saw box gin (Dennis Manufacturing, Athens, TX), and then tested on HVI for fiber properties. A total of 1,088 fiber samples were analyzed on HVI with 4 micronaire, 10 length/strength and 4 color determination per sample. In addition, three cottons standards for elongation (produced by the Fiber and Biopolymer Research Institute, FBRI) were tested several times per day to ensure that there was no instrument drift or malfunction. Fiber parameters measured by the HVI were micronaire, length (mm), uniformity (%), strength (g/tex), and elongation (%) (Table 2). All fiber testing was performed by the Fiber and Biopolymer Research Institute (FBRI) at Texas Tech University in Lubbock, TX. The same HVI, an Uster 1000 (Uster, Knoxville, TN) was used during the duration of the project.

From the 1,088 fiber samples, selections were done based on divergent selection for low and high fiber elongation within families using HVI data, while other fiber characteristics were kept stable.

Table 2. Fiber parameters measured by HVI.

Measurement	Unit
Micronaire	-
Length	mm
Uniformity	%
Strength	g/tex
Elongation	%

3.2 F_3 generation

Paired selection was conducted among the 1,088 individual plant selections (IPS) from the F_2 generation that represents divergent selection for low and high elongation in each cross keeping other fiber characteristics similar. One hundred fifty-six plants were selected based on HVI values. The 156 selections, representing at least one high elongation and one low elongation selection from each cross and FM 958 in each of 4 replications from 2008 were planted in one row progeny rows on May 14, 2009, at LREC in Lubbock, TX. Every plot was thinned to approximately one plant every 20.32 cm at approximately 30 days after emergence. Plots were 72.5 cm in length and 101.6 cm wide. Test was irrigated using furrow irrigation. A random sample of 10 first position bolls per row was taken prior harvest to evaluate fiber stability and to select for superior families. In this instance, superior inferred maintenance of divergence in elongation and similarity and acceptable quality in other fiber properties. From each of the superior families, six plants in each progeny row were selected based on visual assessment, and two plants in each progeny row were selected in the whole population to carry to the next generation. All samples were harvested during the first and second week of November. Seed cotton from boll samples and IPS was ginned on a tabletop ten-saw gin (Dennis manufacturing, Athens, TX), and the lint was tested on HVI with 4 micronaire, 10 length/strength and 4 color determinations per sample. In addition, three cotton standards for elongation (provided by the Fiber and Biopolymer Research Institute, FBRI) were tested several times per day to ensure that there was no instrument drift or malfunction. All fiber testing was performed by the Fiber and Biopolymer Research Institute (FBRI) at Texas Tech University in Lubbock, TX.

3.3 F_4 generation

From the initial 15 families, five families were selected based on fiber data for another round of divergent selection. Within each selected family two plants were chosen to advance, one for high and the other for low elongation, holding other properties similar. Two sister lines from family 10 (Table 1) were selected due its superior performance, meaning difference in elongation and similar in other fiber properties. Selections for high and low elongation from all selected families were planted in 1-row plots in an RCBD design with four replications in Lubbock, TX, on May 21, 2010. Additionally, four selections based on work-to-break and six selections based on high and low elongation from the entire population plus three checks were selected for a total of 25 entries (Table 3). Work-to-break was estimated by multiplying strength and elongation. Every plot was thinned to approximately one plant every 10.16 cm approximately 30 days after emergence. Plots were 70.1 cm in length and 101.6 cm wide. Test was irrigated using furrow irrigation.

Boll samples were taken from the first position in each row prior to harvest to determine stability of elongation. Samples were ginned on a tabletop ten-saw gin (Dennis manufacturing, Athens, TX), and the lint was tested on HVI with 4 micronaire, 10 length/strength and 4 color determinations per sample. In addition, three cotton standards for elongation (produced by the Fiber and Biopolymer Research Institute, FBRI) were tested several times per day to ensure that there was no instrument drift or malfunction. Additionally, fiber was tested on the Advance Fiber Information System (AFIS) to obtain data on fiber quality based on this system. Table 4 shows the fiber parameters measured with AFIS. The test was stripper harvested November 29, 2010. Seed was retained with the objective of planting large enough plots to obtain enough lint for spinning tests conducted in 2011 and 2012. Spinning data from 2012 are not reported, but will be used for future publications.

Table 3. HVI fiber data from increases planted on 2010 to conduct spinning studies.

Entry	Name	Reason	Family	Micronaire	Length (mm)	Uniformity (%)	Strength (g/Tex)	Elongation (%)	SXE[a]
1	09-2-211-5	Low	14	4.4	30.23	84.0	32.8	7.3	239.4
2	09-2-212-5	High	14	3.9	29.97	84.3	30.2	11.8	356.4
3	09-2-510-1	Low	10a	4.4	27.94	84.0	29.2	10.3	300.8
4	09-2-511-3	High	10a	4.6	27.43	84.2	30.6	13.0	397.8
5	09-2-707-6	Low	9	4.0	29.97	84.1	32.7	9.3	304.1
6	09-2-708-4	High	9	4.2	29.72	85.4	34.5	13.0	448.5
7	09-2-807-1	High	3	4.5	29.21	85.4	30.8	13.0	400.4
8	09-2-808-5	Low	3	4.5	29.21	84.6	29.4	10.8	317.5
9	09-2-1015-4	High	10b	4.3	29.72	84.7	33.4	12.6	420.8
10	09-2-1016-4	Low	10b	4.2	29.21	83.7	32.4	8.4	272.2
11	09-2-1111-5	Low	7	4.8	28.70	81.3	28.5	10.5	299.3
12	09-2-1112-1	High	7	4.2	28.19	82.7	28.2	16.0	451.2
13	09-2-207-2	LxL	11	4.4	28.70	84.3	29.4	6.6	194.0
14	09-2-1005-2	HxH	3	4.4	28.45	85.0	32.1	13.6	436.6
15	09-2-409-1	HxL	13	3.5	29.46	85.3	35.0	11.6	406.0
16	09-2-816-2	LxH	15	4.1	28.70	85.1	29.7	12.9	383.1
17	09-2-411-1	-E	7	4.1	30.73	85.5	33.8	8.4	283.9
18	09-2-415-2	+E	8	4.2	31.24	85.1	32.6	11.0	358.6

[a]Estimation of work-to-break obtained by multiplying strength and elongation
*The combination of L and H are for different levels of work-to-break
*The –E and +E selections were for different levels of elongation though they were not paired selections

Table 3. Continued.

Entry	Name	Reason	Family	Micronaire	Length (mm)	Uniformity (%)	Strength (g/Tex)	Elongation (%)	SXE
19	09-2-708-1	+E	9	3.8	30.73	87.8	35.5	13.1	465.1
20	09-2-612-2	-E	6	3.8	30.73	85.2	33.5	9.9	331.7
21	09-2-804-1	-E	10	3.8	31.75	83.9	36.6	8.4	307.4
22	09-2-912-1	+E	4	3.8	30.99	86.1	38.1	11.6	442.0
23	FM 958[b]	Check		4.7	28.96	83.2	33.8	9.6	324.5
24	DP 491[b]	Check		4.9	28.70	81.6	30.0	10.3	309.0
25	FM 989[b]	Check		4.9	25.91	81.3	26.3	11.1	291.9

[b]Fiber data come from different tests than the fiber data from the increases in the same field

Table 4. Fiber parameters measured with AFIS.

Measurement	Unit
Neps pr Gm	Count per gram
Length by weight	mm
Upper Quartile length	mm
Short fiber content by weight	%
Length by number	mm
Short fiber content by number	%
Visible foreign matter	%
Seed count per nep count	Cnt/g
Fineness	mTex
Maturity ratio	N/A

3.4 Spinning test

Spinning tests were conducted in 2011 to determine the influence of fiber elongation on yarn elongation, strength, work-to-break, and performance in general. All lines selected in 2010 were repeated in 2011 at four locations, though one location at Lamesa was not established and the location at the Texas Tech Quaker Avenue research farm did not produce enough fiber for spinning tests, leaving the Halfway and Lubbock Texas AgriLife Research locations.

The test in Lubbock, TX, was planted on May 5, 2011. Plots were 68.58 cm in length, four rows wide on 101.6 cm row spacing. Test was irrigated using furrow irrigation. A boll opener was applied on September 27, 2011, and a defoliant was applied on October 10, 2011. The test was harvested on October 26, 2011 using a two row mechanical stripper. The test in Halfway, TX, was planted under pivot irrigation in May 17, 2011. The soil type in this location is Pullman clay loam. Plots were 66.04 cm in length and four rows wide on 101.6 cm row spacing. A boll opener was applied on September 27, 2011, and a defoliant was applied on October 11, 2011. A ten boll sample was pre-harvested in Lubbock to select lines based on divergent elongation and other fiber characteristics for spinning tests. Nine entries were selected from the 25 entries planted (Table 5).

In order to obtain the adequate lint weight for the spinning process, field replications were combined (rep one with two, and rep three with four) for a total of two spinning test replications. Each sample was prepared using the protocol for carded yarn and machinery found in Figures 2 and 3. Due to shorter staple length on 2011, consequence of a severe drought, 30Ne count carded yarn could not be produced. Therefore, equipment settings were chosen for the production of 18Ne count carded yarn for all samples. The process was operated at high card speed (120 lbs/hour) and high traveler speed (38m/sec) to maximize the stress on fibers. After spinning, fibers were submitted to yarn quality testing. Yarn evenness was tested on a UT3 (Zellweger Uster, Knoxville, TN) with 400 meters of yarn per bobbin on 10 bobbins. Tensile testing was conducted using a Tensorapid 3 (Zellweger Uster, Knoxville, TN) with 10 breaks per bobbin on 10 bobbins. Yarn counts were determined using a Henry L. Scott Skein Tester, Model J-2 (Henry L. Scott, Providence, RI) with one skein per bobbin on 10 bobbins. Data on breaking elongation (%), tenacity (cN/tex), work-to-break (cN.cm), number of thin places (Km), number of thick places (Km), nep count (Km), hairiness and total number of imperfections were obtained.

Table 5. HVI data from F_4 boll samples from lines selected for spinning tests, 2011.

Entry	Name	Reason	Family	Micronaire	Length (mm)	Uniformity (%)	Strength (g/Tex)	Elongation (%)	SXE[a]
3	09-2-510-1	Low	10a	4.4	31.68	83.9	37.4	6.3	235.6
4	09-2-511-3	High	10a	4.8	28.19	83.4	35.7	8.4	299.8
9	09-2-1015-4	High	10b	4.9	27.94	82.6	36.3	7.9	286.7
10	09-2-1016-4	Low	10b	4.8	28.19	82.4	34.8	6.2	215.7
11	09-2-1111-5	Low	7	4.7	29.21	83.2	34.0	5.6	192.1
12	09-2-1112-1	High	7	4.8	28.95	83.0	35.9	8.3	297.9
19	09-2-708-1	+E	9	4.0	28.70	83.7	38.5	8.4	323.4
21	09-2-804-1	-E	10	4.0	32.25	84.3	38.4	5.6	215.0
23	FiberMax FM 958	Check		4.7	28.70	82.9	34.6	5.8	200.6

[a]Estimation of work-to-break obtained by multiplying strength and elongation
*The –E and +E selections were for different levels of elongation though they were not paired selections from the same family.

Figure 2. Process and equipment information for opening, blending, and carding.

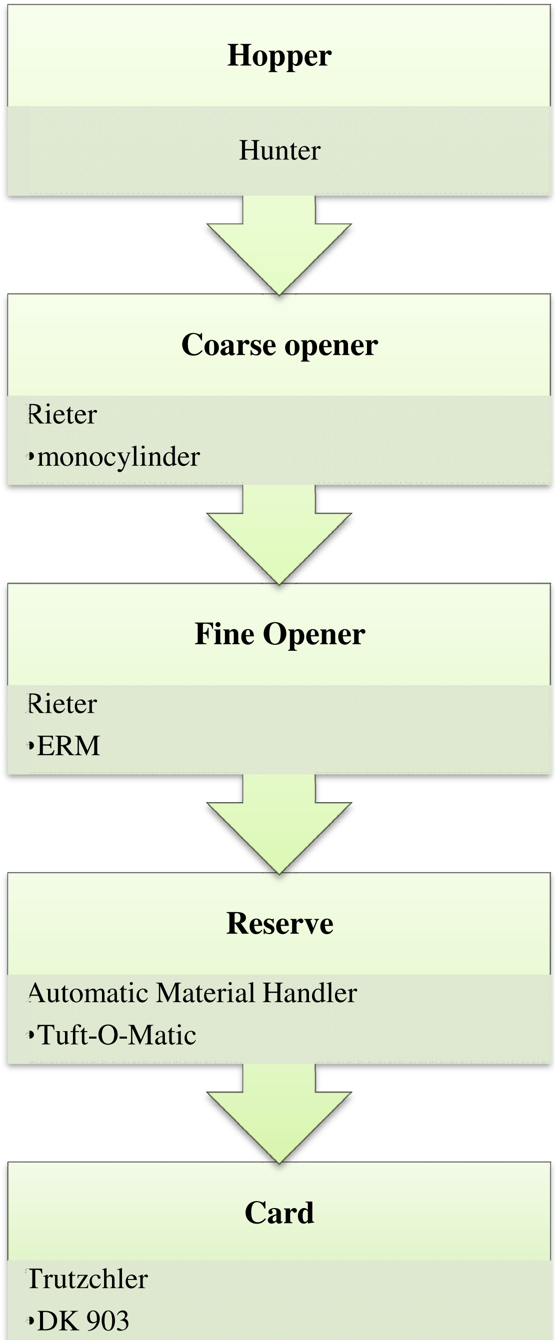
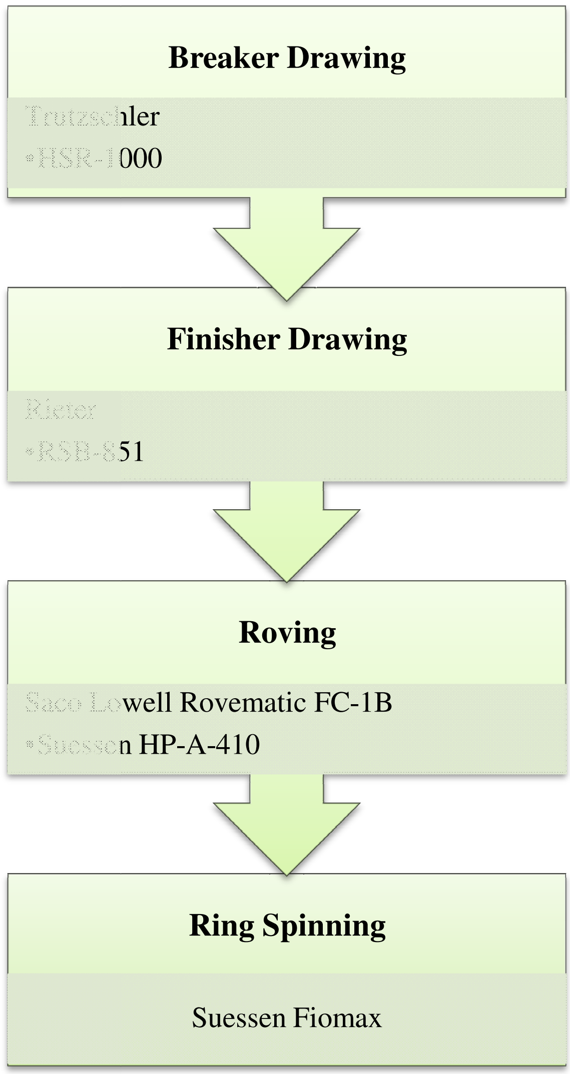


Figure 3. Process and equipment information for drawing, roving, and ring spinning (carded yarn production).



3.5 Yield test

A yield test was planted to evaluate the productivity of the selected lines. The seed source came from the selected F_4 lines in 2010. The test was 25 entries in total; 10 entries representing paired high and low elongation selections from five families out of the initial 15 crosses, four entries based on work-to-break values from different combinations of elongation and strength, and six entries based on high and low elongation (not paired) from the entire population plus three check cultivars. The test was a randomized complete block design with four replications planted initially in four locations in 2011; Halfway, Lamesa, Lubbock, and the Texas Tech Quaker Avenue research farm. However, one location at Lamesa was not successfully established, leaving the Halfway, Lubbock Texas AgriLife Research and the Texas Tech Quaker Avenue research locations. The Texas Tech Quaker Avenue research farm location did not produce enough lint for spinning tests, but was harvested for yield. Soil type at Lamesa is Amarillo fine sandy loam, and Amarillo Urban land complex at the Texas Tech Quaker Avenue research farm.

The test in Lubbock, TX, was planted on May 5, 2011. Plots were 68.58 cm in length, four rows wide on 101.6 cm row spacing. Test was irrigated using furrow irrigation. A boll opener was applied on September 27, 2011, and a defoliant was applied on October 10, 2011. The test was harvested on October 26, 2011, using a two row mechanical stripper. The test in Halfway, TX, was planted under pivot irrigation in May 17, 2011. Plots were 66.04 cm in length and four rows wide on 101.6 cm row spacing. A boll opener was applied on September 27, 2011, and a defoliant was applied on October 11, 2011. The test in the Texas Tech Quaker Avenue research farm was planted on May 31, 2011, and furrow irrigated. Plots were 82.55 cm in length, four rows wide on 101.6 cm row spacing. Harvest aids were applied on October 12, 2011, and the test was harvested using a two row mechanical stripper on November 3, 2011. The tests were harvested both by hand and machine in all locations. A 50 boll sample was taken in order to obtain data on picked lint %, pulled lint %, boll size, lint index, and seed per boll. Picked lint percent is the fraction of seed cotton, pulled lint percent is the lint fraction of the burr cotton, boll size is the weight in grams of seed cotton per boll. Then, all plots were harvested using a two row mechanical stripper on October 24, 2011. A grab sample was collected from the burr cotton to calculate lint turnout and seed turnout. Lint turnout is the percentage of a seed cotton sample that is actually useable lint; and seed turn out is percent seed by weight of the stripper-harvested grab sample. These turnouts were later used to calculate plot lint weight and yield. Yield was determined as the amount of kilograms of lint harvested per hectare. The remaining lint was ginned and kept for spinning test. Additionally, field notes on maturity, storm resistance, plant height and visual assessment were taken at a date where visual differences in crop maturity were evident. Maturity is the visual assessment of the percent of open bolls on a given date; storm resistance is a visual rating from 1(very loose boll type, considerable seed cotton loss) to 9 (very tight boll type, resistance to losses to late-season storm events); plant height is the average height of the plot; and visual assessment is rate based on breeder opinion on whether the line would be commercially acceptable, from 1-non-acceptable to 9-very attractive.

Prior to ginning, samples were de-burred using a two-saw cylinder stick machine and feeder-extractor. Then all samples were ginned on a ten-saw gin equipped with an incline cleaner, feeder extractor, and saw lint cleaner at the Texas AgriLife Research and Extension Center in Lubbock, TX. A fiber sample of approximately 30 g was taken to obtain fiber data using HVI with 4 micronaire, 10 length/strength and 4 color determination per sample. In addition, three cottons standards for elongation (produced by the Fiber and Biopolymer Research Institute, FBRI) were tested several times per day to ensure that there was no instrument drift or malfunction.

3.6 Heritability

3.6.1 Heritability by variance components

Broad sense heritability estimates were obtained by the components of variance method. Estimates were obtained for each generation available; F_3, F_4 and F_5. No inbreeding was assumed because there was not family structure present in the generations under study. Bulked F_2 IPS's constitute F_3 lines. F_4 lines were taken from F_3 boll samples, and F_5 was obtained by increasing the F_4 generation in a winter nursery in Mexico (Figure 4). Fiber samples were ginned on a tabletop ten saw-gin (Dennis manufacturing, Athens, TX), and the lint was tested on HVI with 2 micronaire, 10 length/strength per sample. In addition, three cottons standards for elongation (produced by the Fiber and Biopolymer Research Institute, FBRI) were tested several times per day to ensure that there was no instrument drift or malfunction. Analyses were carried out using PROC MIXED (SAS 9.2). Shapiro-Wilk and Kolmogorov-Smirnov tests for normality were carried out in each generation per location. Levene's test for homogeneity of variance across locations was used to determine if the data could be combined. Sixty one entries were planted in a RCBD with three replications in three locations, Lubbock, Halfway and Pecos, TX, for two years (2011 – 2012). The soil type at the Pecos location is Hoban silty clay. Every plot was thinned to approximately one plant every 20.32 cm approximately 30 days after emergence. Planting dates and plots lengths are described in table 6. Rows were 101.6 cm wide in Lubbock and Halfway, and 96.52 cm in Pecos, TX.

3.6.2 Heritability by parent off-spring regression

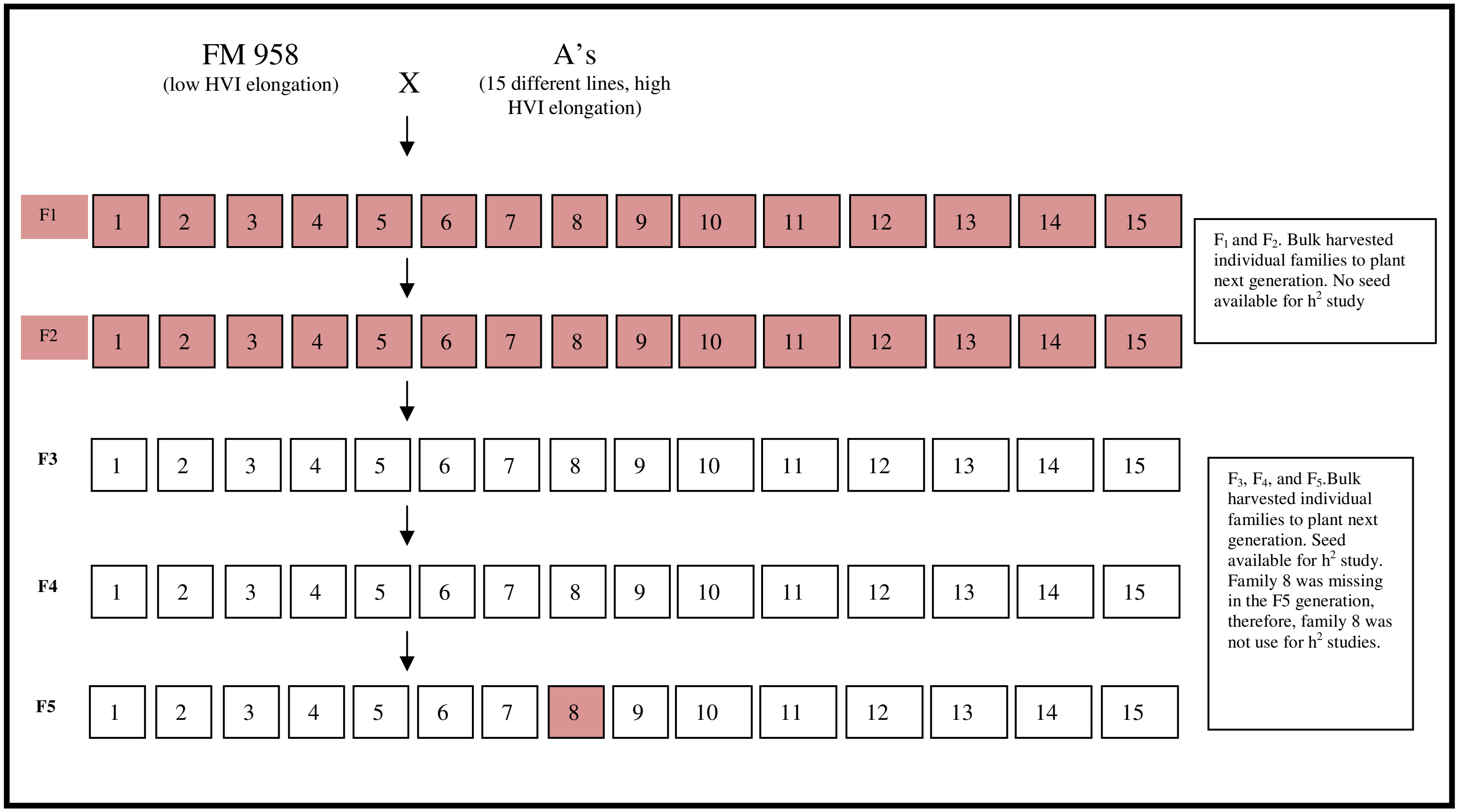
Heritability was estimated by the parent off-spring regression method to determine the degree of resemblance between parents and progenies. F_3, F_4, and F_5

generations were grown in a RCBD in three locations, Lubbock, Halfway and Pecos, TX in 2011and 2012. The fiber samples used to estimate heritability by variance components were also used to estimate heritability by parent off-spring regression (Figure 4). Linear correlation coefficients were calculated by regressing F_5 progeny means on F_4 parental values, and F_4 progeny means on F_3 parental values. Linear regression coefficients were obtained using PROC REG (SAS 9.2). Shapiro-Wilk and Kolmogorov-Smirnov tests for normality were carried out in each generation per location. Levene's test for homogeneity of variance across locations was used to determine if the data could be combined. Every plot was thinned to approximately one plant every 20.32 cm approximately 30 days after emergence. Planting dates and plots lengths are described in table 6. Rows were 101.6 cm wide in Lubbock and Halfway, and 96.52 cm in Pecos, TX.

Table 6. Planting dates and plot dimensions for heritability by variance components and parent off-spring regression.

Year	Location	Planting date	Plot length (cm)
2011	Lubbock	May 6	75.18
2011	Halfway	May 17	58.42
2011	Pecos	May 5	63.5
2012	Lubbock	May 8	75.18
2012	Halfway	May 17	40.64
2012	Pecos	May 4	78.74

Figure 4. Schematic representation of generations used for heritability study by the variance component analysis and parent off-spring regression.



3.6.3 Realized heritability

F_2 generation from 2008, F_3 generation from 2009 and F_4 generation from 2010, were used to estimate realized heritability using the divergent selections for high and low elongation. Realized heritability was expressed as the difference in mean performance of high and low progeny divided by the difference in the mean of the parents (Figure 5).

Figure 5. Formulas used to estimate realized heritability.

H^2_R for the high and low selection in the F_2-F_3

$$H^2_R = \frac{\overline{F_3 high} - \overline{F_3 low}}{\overline{F_2 high} - \overline{F_2 low}}$$

H^2_R for the high and low selection in the F_3-F_4

$$H^2_R = \frac{\overline{F_4 high} - \overline{F_4 low}}{\overline{F_3 high} - \overline{F_3 low}}$$

Where, $\overline{F_4 high}$= mean of high F_4 lines, $\overline{F_4 low}$ = mean for low F_4 lines, $\overline{F_3 high}$= mean of F_3 high selections, $\overline{F_3 low}$= mean of F_3 low selections. And, $\overline{F_3 high}$= mean of high F_3 lines, $\overline{F_3 low}$= mean for low F_3 lines, $\overline{F_2 high}$= mean of F_2 high selections, $\overline{F_2 low}$= mean of F_2 low selections.

3.7 Statistical analysis

Fiber, yarn and yield data were analyzed using PROC MIXED (SAS 9.2). Data for heritability estimates was analyzed using PROC MIXED and PROC REG (SAS 9.2). Shapiro-Wilk and Kolmogorov-Smirnov tests for normality were carried out in each generation per location. Levene's test for homogeneity of variance across locations was used to determine if the data could be combined. Mean separation was performed using Duncan's multiple range test, and was not performed when F-test values were non-significant at the probability level of 0.05.

4. RESULTS AND DISCUSSION

4.1 F_2 generation

The first year of the study began with the evaluation of 15 F_2 families and one check cultivar, ‘FM 958’planted in RCBD with four replications. Sixteen plants per plot, four row plots, were selected based on agronomic traits for a total of 64 plants per F_2 family. A total of 1,088 fiber samples, including the checks, were ginned on a tabletop ten-saw box gin (Dennis Manufacturing, Athens, TX), and then tested on HVI with 4 micronaire, 10 length/strength and 4 color determination per sample. However, there is a lack of calibration procedures for HVI elongation, making it difficult to rely on such data. Therefore, for this project, three cottons standards for elongation (produced by the Fiber and Biopolymer Research Institute, FBRI) were tested several times per day to ensure that there was no instrument drift or malfunction (Benzina et al., 2007). Table 7 shows the averages and coefficient of variation for the three elongation standards. The CV% for elongation are below the target value of 5% (5% is the maximum CV% allowable for fiber testing). No drift was observed during the testing period. The average value for HVI fiber elongation on the 1,088 individual plant selections (IPS) was 9.3%, with a minimum value of 6.9% and a maximum value of 12.8%. The average value for strength was 29.6 g/tex, with a minimum value of 23.9 g/tex and a maximum of 38 g/tex (Table 8). At this point, a wide range of fiber properties were observed, particularly for the tensile properties (strength and elongation), increasing the possibility for divergent selection. Divergent selection was the method of choice to test the hypothesis that elongation has a direct influence on yarn properties and fiber spinning, by attempting to develop similar lines that differ in elongation. Among the 1,088 IPSs, 156 plants were selected based on their HVI values for divergent fiber elongation, at least two elongation-divergent selections per cross. A negative correlation ($r = -0.32$, $p=<.0001$) was observed between fiber strength and elongation in the 156 selections (Figure 6). Nevertheless, the correlation was weak and targeted selection was used to focus on fiber elongation while keeping all other fiber properties constant. HVI elongation was also compared to HVI uniformity to determine the relationship between those two characteristics. The hypothesis is that increased fiber elongation will improve uniformity index and decrease short fiber content. However, at this point, no data on short fiber content was obtained. A positive correlation (r=0.3195, p=<.0001) was observed between fiber elongation and uniformity index (Figure 7) in the first generation of selection, indicating that there is a positive relationship between them. The complete data for the 156 selections from the 1,088 IPSs sorted by increasing elongation are presented in Appendix 1.

Table 7. Basic statistics on the standard elongation calibration cottons.

Sample ID		Micronaire	UHML (mm)	UI %	Strength (g/tex)	Elongation (%)
3104	Average	3.87	26.67	82.5	25.1	10.9
	CV%	0.8	0.8	0.5	1.4	3.4
3213	Average	4.28	29.21	83.4	30	7.7
	CV%	0.9	0.6	0.4	1.7	3.4
3289	Average	3.35	28.194	82.2	27.9	9.4
	CV%	0.8	0.8	0.5	1.3	3.4

Table 8. Basic statistics on the 1,088 F_2 IPSs harvested in 2008.

	Micronaire	Length (mm)	Unif (%)	Strength (g/tex)	Elongation (%)
Average	4.4	30.226	84.4	29.6	**9.3**
Std	0.4	2.54	1	1.8	0.9
CV %	9.6	4.3	1.2	5.9	9.7
Max	5.7	1.36	87.4	38	**12.8**
Min	3	1	80.2	23.9	**6.9**

Figure 6. Correlation between HVI strength and HVI elongation for F_2 plants selected in 2008.

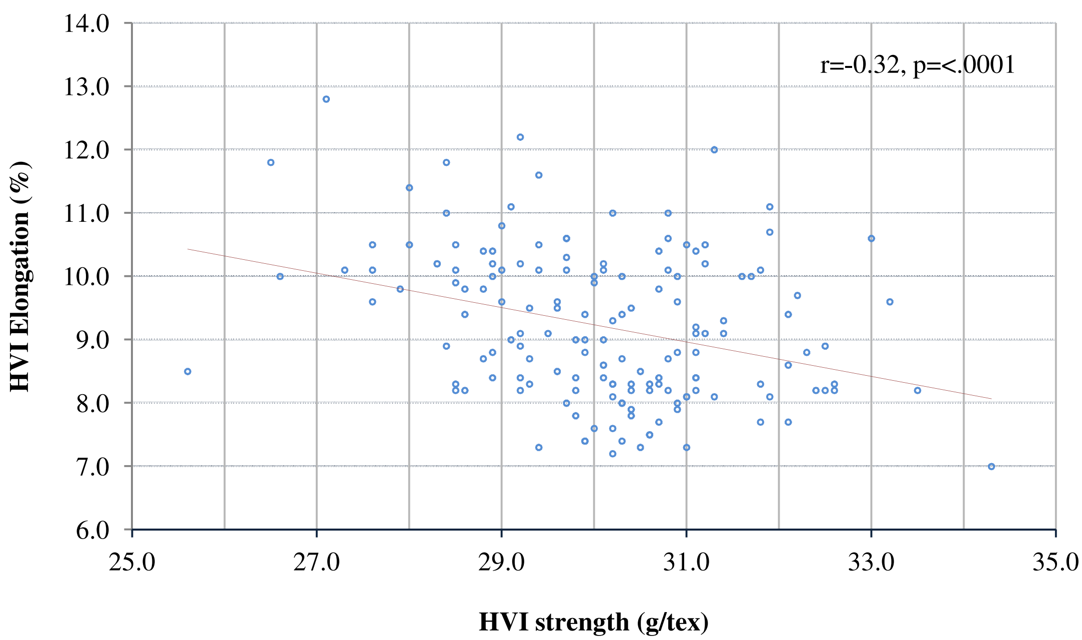
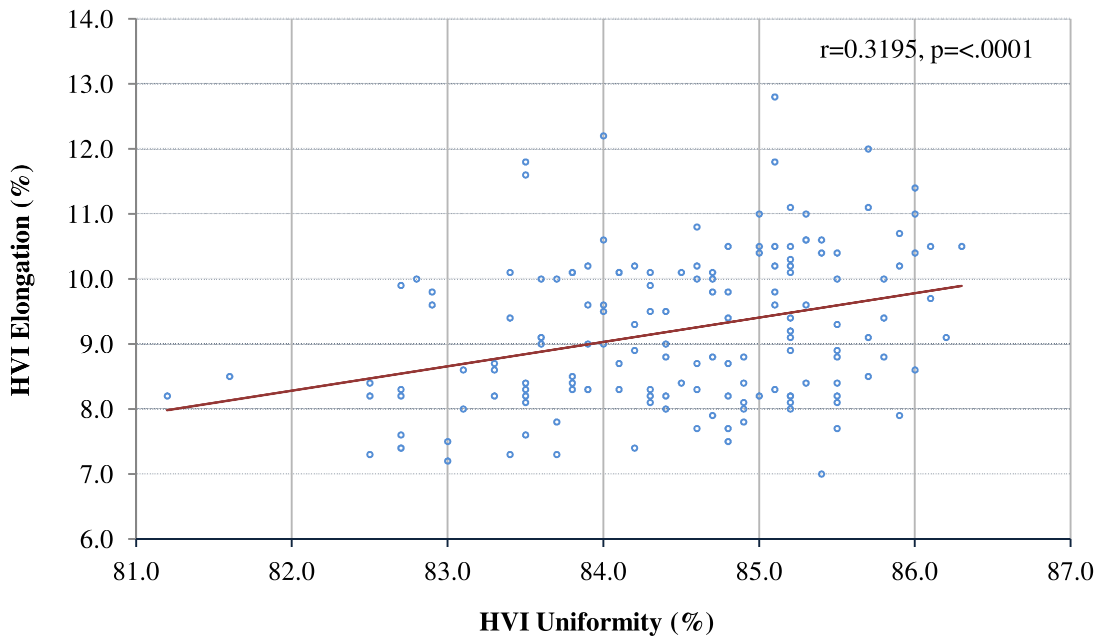


Figure 7. Correlation between HVI uniformity and HVI elongation for F_2 plants selected in 2008.



4.2 F_3 generation

The 156 paired selections among the F_2 plants were planted in 2009 to obtain an early evaluation of the effectiveness of the selections made in the previous generation. $F_{2:3}$ progeny rows representing at least one high and low elongation paired selections from each replication of each cross and a check variety (FM 958) were planted in one row plots. Ten boll samples were harvested from each progeny row to evaluate fiber quality for a second round of targeted divergent selection. Average value for HVI elongation on the 156 F_3 boll samples was 6.12% with a minimum value of 4.00% and a maximum value of 9.20%. Table 9 shows the basic statistics on the 156 F_3 boll samples, and the complete data sorted by low and high selections for fiber elongation are presented in Appendix 2. From five families showing strong divergence in elongation, six plants per row were selected based on visual assessment and two plants/row were selected from the additional rows to carry to the next generation (Table 10). Compared to the F_2 generation, the F_3 generation showed a more stable range for fiber elongation while maintaining variation of other fiber properties. Furthermore, an excellent diversity of fiber elongation was maintained (4% - 9.20%), enabling further divergent selection.

Table 9. Basic statistics on the 156 F_3 boll samples, 2009.

	Micronaire	Length (mm)	Uniformity (%)	Strength (g/tex)	Elongation (%)
Average	4.35	31.75	85.94	35.19	**6.12**
Std	0.29	1.01	0.94	1.91	0.79
CV%	6.58	80.51	1.09	5.42	12.89
Max	5.37	34.54	88.50	40.60	**9.20**
Min	3.53	29.46	83.00	30.70	**4.00**

Table 10. HVI properties for the individual plant selections from superior families in the F_3 generation, 2009.

Plot	Selection reason	Family	Micronaire	Length (mm)	Uniformity (%)	Strength (g/tex)	Elongation (%)
808-1	L	3	4.9	28.45	84.7	31.1	10.2
808-2	L	3	4.9	28.19	84.1	28.0	10.4
808-3	L	3	4.7	28.96	83.5	27.9	10.2
808-4	L	3	4.8	29.46	84.2	29.2	10.7
808-5	L	3	4.5	29.21	84.6	29.4	10.8
808-6	L	3	4.8	29.97	85.8	30.2	10.2
807-1	H	3	4.5	29.21	85.4	30.8	13.0
807-2	H	3	4.4	30.23	84.8	29.3	12.8
807-3	H	3	4.8	28.70	85.0	27.9	12.6
807-4	H	3	4.4	28.70	83.3	29.1	11.6
807-5	H	3	5.1	28.19	84.5	28.4	13.5
807-6	H	3	4.9	29.97	85.5	31.4	12.7
1111-1	L	7	4.9	28.45	83.2	29.3	11.2
1111-2	L	7	4.8	29.21	83.4	31.4	10.5
1111-3	L	7	4.4	28.70	83.9	30.2	12.6
1111-4	L	7	4.7	27.94	83.2	29.4	11.0
1111-5	L	7	4.8	28.70	81.3	28.5	10.5
1111-6	L	7	4.7	26.42	82.0	27.3	12.3
1112-1	H	7	4.2	28.19	82.7	28.2	16.0
1112-2	H	7	3.5	28.70	83.5	33.4	13.9
1112-3	H	7	3.5	28.70	82.3	30.6	13.4
1112-4	H	7	3.2	27.94	81.9	28.4	15.4
1112-5	H	7	3.4	27.94	82.0	29.6	13.4
1112-6	H	7	3.6	27.94	81.7	27.3	14.3
707-1	L	9	4.8	28.70	84.5	33.1	10.8
707-2	L	9	4.7	28.19	83.2	31.8	10.1
707-3	L	9	4.5	26.92	82.4	30.3	12.7
707-4	L	9	4.4	28.19	84.8	31.5	10.8
707-5	L	9	4.3	28.96	84.0	33.0	10.8
707-6	L	9	4.0	29.97	84.1	32.7	9.3
708-1	H	9	3.8	30.73	87.8	35.5	13.1
708-2	H	9	4.5	31.24	87.5	33.5	12.8
708-3	H	9	4.3	28.70	85.5	33.0	10.7
708-4	H	9	4.2	29.72	85.4	34.5	13.0
708-5	H	9	4.6	28.96	85.3	33.1	10.4
708-6	H	9	4.2	31.24	87.4	34.5	9.1

Table 10. Continued.

Plot	Selection reason	Family	Micronaire	Length (mm)	Uniformity (%)	Strength (g/tex)	Elongation (%)
510-1	L	10	4.4	27.94	84.0	29.2	10.3
510-2	L	10	3.8	29.46	84.6	32.6	9.8
510-3	L	10	4.5	27.18	83.8	32.1	10.1
510-4	L	10	4.8	28.45	83.4	32.7	9.1
510-5	L	10	4.9	28.19	85.1	31.8	9.6
510-6	L	10	4.6	28.45	84.6	32.2	9.5
1016-1	L	10	4.2	29.21	85.8	32.8	9.6
1016-2	L	10	3.9	28.19	83.0	30.6	10.1
1016-3	L	10	3.2	30.73	82.8	33.7	8.9
1016-4	L	10	4.2	29.21	83.7	32.4	8.4
1016-5	L	10	4.6	29.21	82.9	30.0	9.3
1016-6	L	10	4.3	28.45	83.1	31.1	9.1
511-1	H	10	4.6	28.19	85.0	29.3	11.3
511-2	H	10	4.7	27.43	85.0	30.9	12.1
511-3	H	10	4.6	27.43	84.2	30.6	13.0
511-4	H	10	4.5	27.43	83.3	29.7	13.2
511-5	H	10	3.6	27.94	84.2	30.4	12.3
511-6	H	10	4.5	27.43	83.8	29.9	12.6
1015-1	H	10	4.1	29.46	85.4	35.6	13.3
1015-2	H	10	4.5	29.46	85.1	34.1	13.1
1015-3	H	10	2.7	29.46	83.6	33.9	13.9
1015-4	H	10	4.3	29.72	84.7	33.4	12.6
1015-5	H	10	3.7	29.97	85.4	34.8	13.2
1015-6	H	10	4.1	29.97	85.6	32.6	12.8
211-1	L	14	4.4	30.99	85.7	34.4	7.7
211-2	L	14	4.2	32.00	85.5	32.8	7.9
211-3	L	14	4.9	28.96	85.0	31.3	8.3
211-4	L	14	3.9	30.99	84.4	33.2	7.5
211-5	L	14	4.4	30.23	84.0	32.8	7.3
211-6	L	14	4.6	30.48	85.2	33.9	7.8
212-1	H	14	4.6	27.94	84.0	28.1	9.6
212-2	H	14	4.3	30.23	82.7	28.5	9.3
212-3	H	14	4.7	27.18	83.9	28.2	11.2
212-4	H	14	4.2	29.97	82.2	29.0	8.8
212-5	H	14	3.9	29.97	84.3	30.2	11.8
212-6	H	14	3.6	30.48	84.4	32.3	10.3

A negative correlation (r=-0.362, p=<.0001) was still observed between fiber strength and fiber elongation in the F_3 generation (Figure 8). However, this correlation was weak enough to indicate that there could be potential improvement of both tensile properties, strength and elongation, using targeted selection. On the other hand, the correlation between uniformity and elongation was close to zero (r=0.0042, p=<.0001) (Figure 9). A high positive correlation (r=0.7172, p=<.0001) between the F_2 and the F_3 generation for fiber elongation indicate that progress from selection have been successful for the improvement of fiber elongation while keeping other fiber properties stable (Table 11, Figure 10).

Figure 8. Correlation between HVI strength and HVI elongation for 156 F_3 boll samples, 2009.

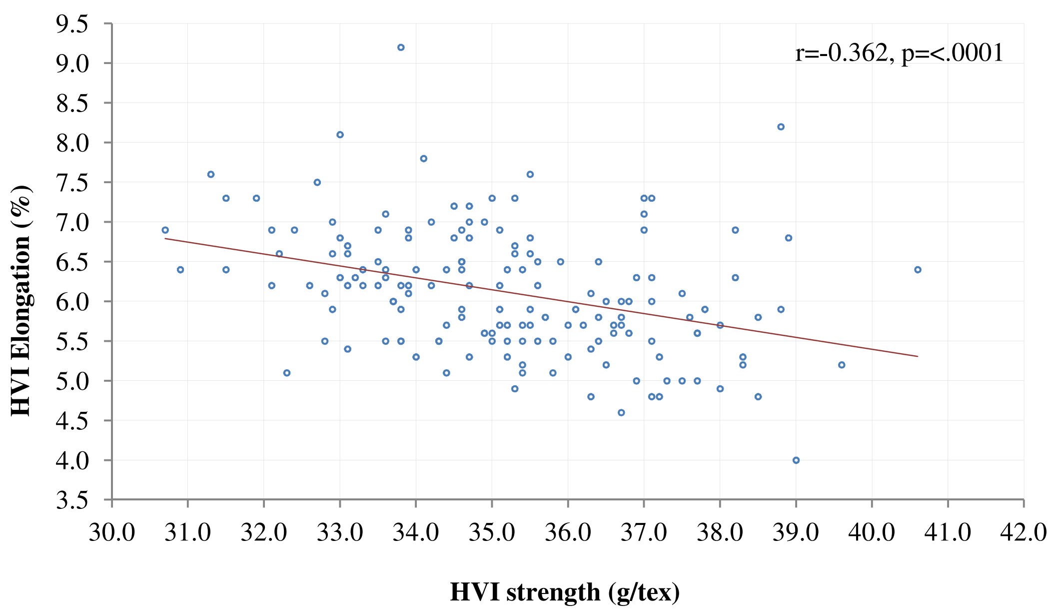


Figure 9. Correlation between HVI uniformity and HVI elongation for 156 F_3 boll samples, 2009.

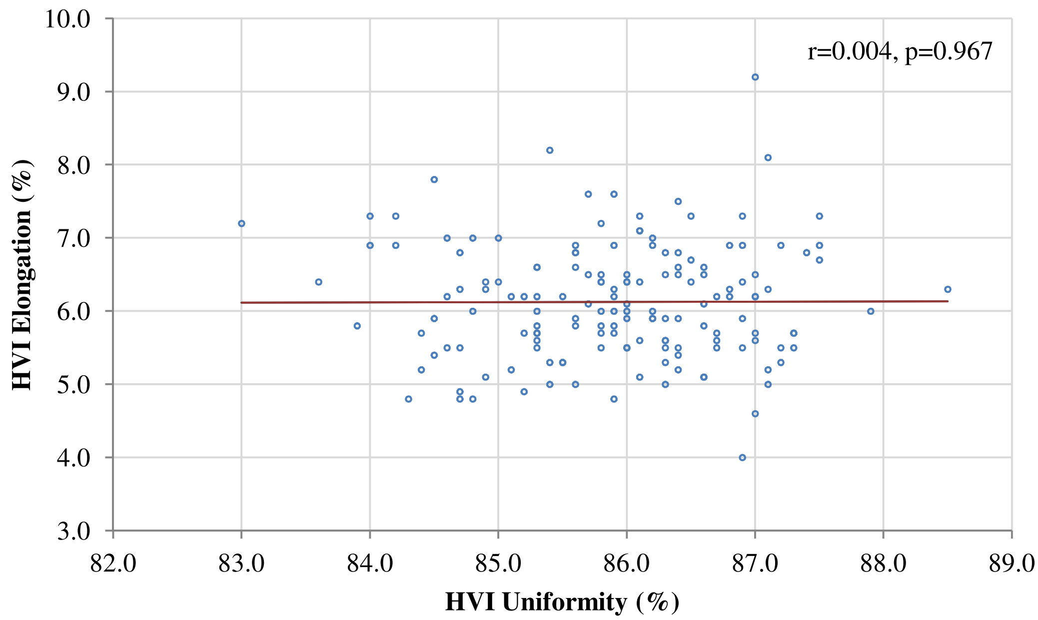
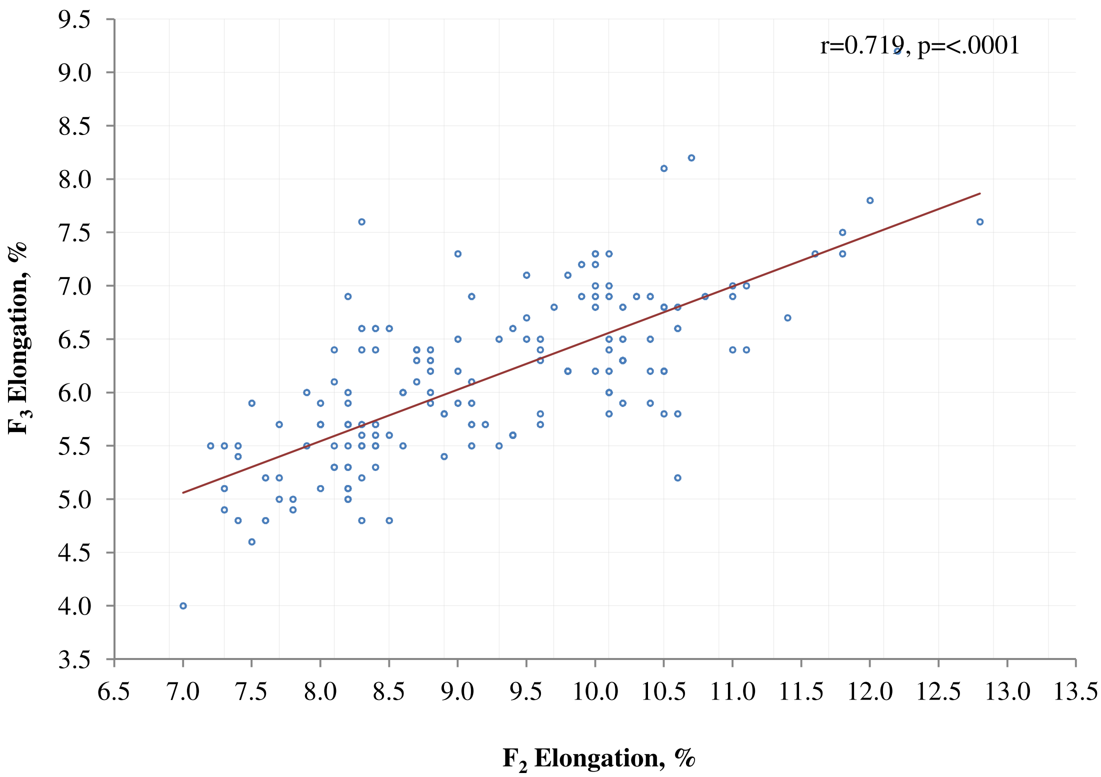


Table 11. HVI fiber properties correlation between F_2 IPS and F_3 boll samples.

Micronaire	0.5073	p=<.0001
Length (mm)	0.5980	p=<.0001
Uniformity (%)	0.3124	p=<.0001
Strength (g/tex)	0.5504	p=<.0001
Elongation (%)	0.7199	p=<.0001

Figure 10. Correlation between F_2 IPS and F_3 boll samples for fiber elongation.



4.3 F_4 generation

From the initial 15 families, five families were selected in the F_3 generation based on fiber data for another round of divergent selection. Within each selected family, two plants were chosen, one for high and the other for low elongation, holding other properties similar. Two additional paired selections from family 10 were advanced due its superior performance in regard to elongation divergence and high quality of other fiber parameters. Additionally, four selections based on work-to-break and six selections based on different combinations of high and low elongation and strength from the entire population plus three checks were advanced for a total of 25 entries (Table 12).

Selections were planted in 1-row plots in a RCBD with four replications in Lubbock, TX, in 2010. Boll samples were taken from each row to determine stability of elongation. The test was stripper harvested to conduct preliminary yield evaluations and to obtain agronomic data. After harvest, all seed was retained with the objective of planting enough seed in 2011 to obtain sufficient lint for spinning tests. Table 13 shows the basic statistics on the F_4 generation. The average elongation for the F_4 generation was 8.16%, with a minimum of 6.10% and a maximum of 11.40%, indicating that targeted divergent selection was a good method to improve fiber elongation while keeping other fiber properties constant. The basic statistics for the low and high selections are presented in table 14 and 15 respectively. The entry means HVI data from the F_4 generation is presented in table 16. Additionally, fiber data from the Advance Fiber Information System (AFIS) was obtained in the F_4 generation and the entry means are presented in table 17. A weak negative correlation (r=-0.0889, p=0.378) between fiber strength and elongation was observed in the F_4 generation (Figure 11). The correlation was weaker than in the F_2 and F_3 generation, possibly because selection pressure was applied to other fiber properties potentially contributing to spinning performance in addition to elongation. Additionally, a high positive correlation for elongation (r=0.8762, p=<.0001) between the F_3 and the F_4 generation was observed (Table 18, Figure 12). These, indicate that targeted selection was effective to improve fiber elongation while retaining good fiber strength and maintaining the quality of other fiber characteristics.

Table 12. HVI fiber properties for the selections planted in 2010.

Entry	Name	Reason	Family	Micronaire	Length (mm)	Uniformity (%)	Strength (g/Tex)	Elongation (%)	SXE[a]
1	09-2-211-5	Low	14	4.4	30.23	84.0	32.8	7.3	239.4
2	09-2-212-5	High	14	3.9	29.97	84.3	30.2	11.8	356.4
3	09-2-510-1	Low	10a	4.4	27.94	84.0	29.2	10.3	300.8
4	09-2-511-3	High	10a	4.6	27.43	84.2	30.6	13.0	397.8
5	09-2-707-6	Low	9	4	29.97	84.1	32.7	9.3	304.1
6	09-2-708-4	High	9	4.2	29.72	85.4	34.5	13.0	448.5
7	09-2-807-1	High	3	4.5	29.21	85.4	30.8	13.0	400.4
8	09-2-808-5	Low	3	4.5	29.21	84.6	29.4	10.8	317.5
9	09-2-1015-4	High	10b	4.3	29.72	84.7	33.4	12.6	420.8
10	09-2-1016-4	Low	10b	4.2	29.21	83.7	32.4	8.4	272.2
11	09-2-1111-5	Low	7	4.8	28.70	81.3	28.5	10.5	299.3
12	09-2-1112-1	High	7	4.2	28.19	82.7	28.2	16.0	451.2
13	09-2-207-2	LxL	11	4.4	28.70	84.3	29.4	6.6	194.0
14	09-2-1005-2	HxH	3	4.4	28.45	85.0	32.1	13.6	436.6
15	09-2-409-1	HxL	13	3.5	29.46	85.3	35.0	11.6	406.0
16	09-2-816-2	LxH	15	4.1	28.70	85.1	29.7	12.9	383.1
17	09-2-411-1	-E	7	4.1	30.73	85.5	33.8	8.4	283.9
18	09-2-415-2	+E	8	4.2	31.24	85.1	32.6	11.0	358.6

[a]Estimation of work-to-break obtained by multiplying strength and elongation
*The combination of L and H are for different levels of work-to-break
*The –E and +E selections were for different levels of elongation though they were not paired selections

Table 12. Continued.

Entry	Name	Reason	Family	Micronaire	Length (mm)	Uniformity (%)	Strength (g/Tex)	Elongation (%)	SXE
19	09-2-708-1	+E	9	3.8	30.73	87.8	35.5	13.1	465.1
20	09-2-612-2	-E	6	3.8	30.73	85.2	33.5	9.9	331.7
21	09-2-804-1	-E	10	3.8	31.75	83.9	36.6	8.4	307.4
22	09-2-912-1	+E	4	3.8	30.99	86.1	38.1	11.6	442
23	FM 958[b]	Check			4.7	28.96	83.2	33.8	9.6
24	DP 491[b]	Check			4.9	28.70	81.6	30.0	10.3
25	FM 989[b]	Check			4.9	25.91	81.3	26.3	11.1

[b]Fiber data come from different tests than the fiber data from the increases in the same field

Table 13. Basic statistics on the HVI fiber properties from boll samples in the F_4 generation, 2010.

	Micronaire	Length (mm)	Uniformity (%)	Strength (g/tex)	Elongation (%)
Average:	3.54	1.18	82.77	34.01	8.16
Std:	0.35	0.05	0.99	2.49	1.25
CV%	9.79	3.99	1.20	7.33	15.37
Highest:	4.34	1.30	85.10	380	11.40
Lowest:	2.75	1.05	80.30	26.30	6.10

Table 14. Basic statistics on the HVI fiber properties from boll samples in the F_4 for the low fiber elongation selections, 2010.

	Micronaire	Length (mm)	Uniformity (%)	Strength (g/tex)	Elongation (%)
Average:	3.67	30.22	82.83	34.23	7.10
Std:	0.22	0.03	0.81	1.59	0.57
CV%	5.93	2.71	0.98	4.66	8.10
Highest:	4.15	1.24	84.00	36.30	8.10
Lowest:	3.30	1.13	80.70	31.40	6.10

Table 15. Basic statistics on the HVI fiber properties from boll samples in the F_4 for the high fiber elongation selections, 2010.

	Micronaire	Length (mm)	Uniformity (%)	Strength (g/tex)	Elongation (%)
Average:	3.36	1.17	82.81	34.8	9.18
Std:	0.26	0.03	1.11	1.22	0.64
CV%	7.70	2.62	1.34	3.50	6.97
Highest:	3.78	1.22	84.60	36.70	10.40
Lowest:	2.81	1.12	80.30	32.10	8.20

Table 16. Entry means of HVI fiber properties for F_4 generation from 2010.

Entry	Name	Reason	Family	Micronaire	Length (mm)	Uniformity (%)	Strength (g/tex)	Elongation (%)
1	09-2-211-5	Low	14	3.64	31.31	83.08	35.58	6.20
2	09-2-212-5	High	14	2.99	30.35	81.58	33.68	8.40
3	09-2-510-1	Low	10a	3.57	28.96	82.68	33.83	7.95
4	09-2-511-3	High	10a	3.55	28.64	82.70	34.85	10.15
5	09-2-707-6	Low	9	3.57	30.86	83.40	35.53	6.85
6	09-2-708-4	High	9	3.37	29.78	83.58	36.28	8.65
7	09-2-807-1	High	3	3.46	30.54	84.20	34.05	9.20
8	09-2-808-5	Low	3	3.90	29.91	83.68	32.30	7.38
9	09-2-1015-4	High	10b	3.49	30.16	83.10	36.10	9.20
10	09-2-1016-4	Low	10b	3.61	30.54	82.65	35.83	6.95
11	09-2-1111-5	Low	7	3.75	29.85	81.48	32.30	7.28
12	09-2-1112-1	High	7	3.31	29.40	81.73	33.85	9.48
13	09-2-207-2	LxL	11	3.32	30.35	82.33	33.85	6.88
14	09-2-1005-2	HxH	3	4.04	29.34	83.20	34.55	8.93
15	09-2-409-1	HxL	13	3.55	29.53	83.38	36.40	9.08
16	09-2-816-2	LxH	15	3.75	28.96	83.25	32.60	9.75
17	09-2-411-1	-E	7	3.41	30.67	83.25	35.90	6.70
18	09-2-415-2	+E	8	3.82	31.56	84.68	35.53	8.48
19	09-2-708-1	+E	9	3.53	29.85	83.85	35.58	9.23
20	09-2-612-2	-E	6	3.09	30.42	82.48	34.63	7.63
21	09-2-804-1	-E	10	2.96	32.58	82.60	36.98	6.70
22	09-2-912-1	+E	4	3.34	31.18	84.08	37.48	7.43
23	FM 958	Check		3.44	29.21	82.00	33.28	7.15
24	DP 491	Check		3.59	29.97	81.68	34.08	7.58
25	FM 989	Check		3.34	29.46	82.13	34.30	7.45

Table 17. Entry means of AFIS fiber properties on the F_4 generation from 2010.

Entry	Name	Reason	Family	Neps per Gm	L(w) [mm]	UQL (w) [mm]	SFC (w) [%]	L(n) [mm]	SFC (n) [%]	VFM [%]	SCN (Cnt/g)	Fine [mTex]	Mat Ratio
1	09-2-211-5	Low	14	438	27.24	33.34	7.3	22.10	22.3	0.90	11	149	0.91
2	09-2-212-5	High	14	666	25.21	31.81	10.4	20.07	28.2	1.79	12	147	0.84
3	09-2-510-1	Low	10a	368	25.21	30.67	8.1	20.76	23.0	1.00	15	152	0.87
4	09-2-511-3	High	10a	404	25.08	30.16	8.1	20.57	23.0	1.45	13	148	0.85
5	09-2-707-6	Low	9	446	27.05	32.77	6.8	22.23	21.1	1.43	13	148	0.89
6	09-2-708-4	High	9	486	25.84	31.69	8.3	21.08	23.5	0.86	11	148	0.84
7	09-2-807-1	High	3	412	26.35	32.00	7.4	21.72	22.0	1.24	11	149	0.85
8	09-2-808-5	Low	3	361	26.29	31.69	6.9	21.84	20.8	0.63	10	156	0.88
9	09-2-1015-4	High	10b	454	25.78	31.43	8.4	21.02	24.0	1.27	12	148	0.86
10	09-2-1016-4	Low	10b	461	25.78	32.00	9.5	20.45	27.2	1.46	16	154	0.88
11	09-2-1111-5	Low	7	401	25.53	31.94	9.1	20.64	25.1	0.85	11	160	0.87
12	09-2-1112-1	High	7	434	25.53	31.31	8.1	21.15	22.5	0.72	9	153	0.85
13	09-2-207-2	LxL	11	500	26.04	32.00	8.3	21.02	24.1	0.86	10	142	0.87
14	09-2-1005-2	HxH	3	373	25.59	30.42	7.0	21.46	20.2	0.79	14	155	0.88
15	09-2-409-1	HxL	13	403	25.78	31.18	7.7	21.27	22.4	1.10	9	155	0.86
16	09-2-816-2	LxH	15	342	25.34	30.48	7.7	21.15	22.0	0.92	9	160	0.86
17	09-2-411-1	-E	7	411	26.73	32.64	7.3	21.84	22.1	1.01	8	149	0.88
18	09-2-415-2	+E	8	370	27.88	33.34	5.6	23.43	18.1	1.20	13	154	0.90
19	09-2-708-1	-E	9	435	26.42	31.69	7.1	21.84	21.2	1.12	11	151	0.86
20	09-2-612-2	+E	6	458	26.16	32.51	8.5	21.15	24.4	1.31	10	146	0.86
21	09-2-804-1	-E	10	692	27.37	34.29	8.5	21.53	25.6	3.10	16	137	0.86
22	09-2-912-1	+E	4	427	27.31	33.27	7.0	22.48	21.3	1.12	12	149	0.87
23	FM 958	Check		477	25.02	30.73	9.3	20.26	25.7	0.98	13	146	0.86
24	DP 491	Check		479	25.53	31.75	9.6	20.38	26.7	1.37	10	149	0.87
25	FM 989	Check		470	25.27	30.92	8.8	20.51	24.7	1.10	16	150	0.87

Figure 11. Correlation between HVI strength and HVI elongation in the F_4 generation.

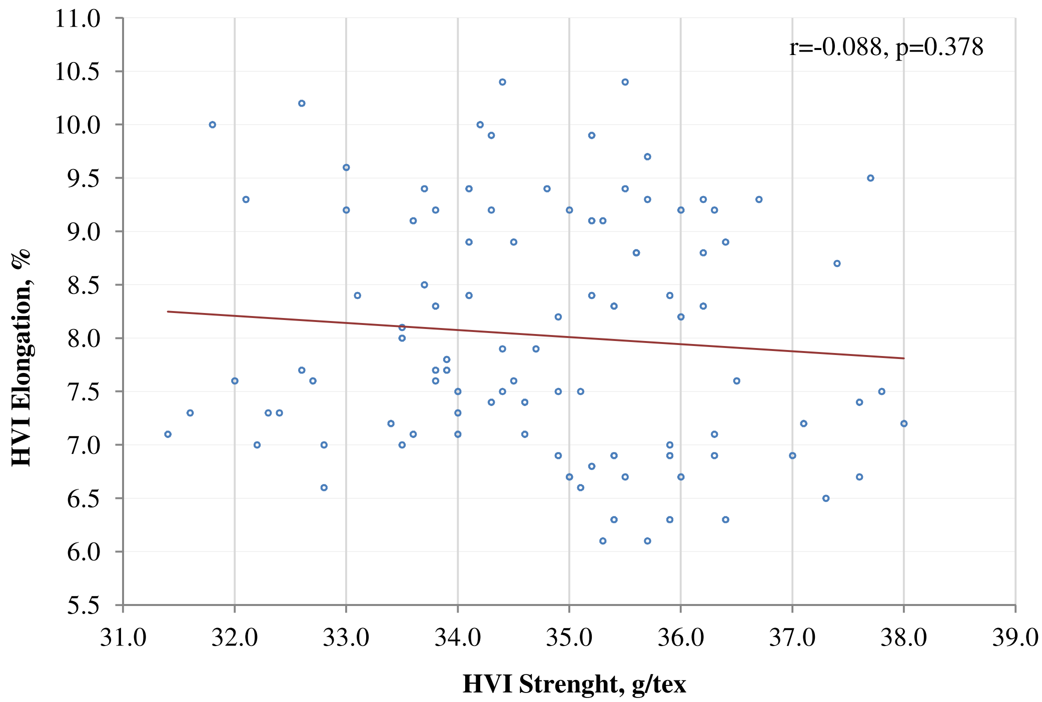
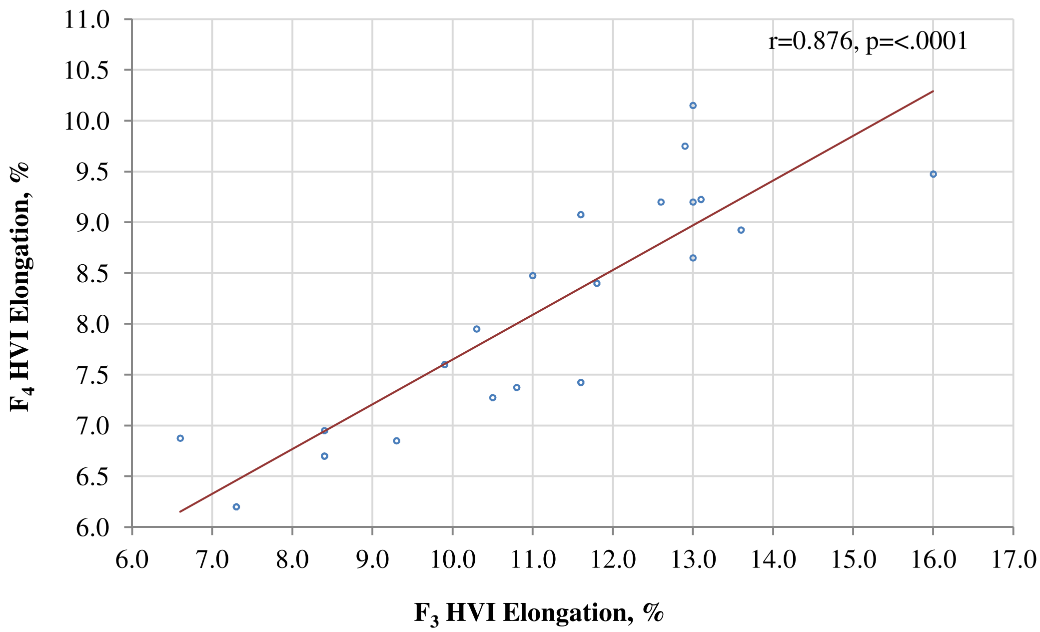


Table 18. HVI fiber properties correlation between F_3 and F_4 generations.

Micronaire	0.4726	p=0.0263
Length (mm)	0.6785	p=0.0005
Uniformity (%)	0.7079	p=0.0002
Strength (g/tex)	0.8958	p=<.0001
Elongation (%)	0.8762	p=<.0001

Figure 12. Correlation for HVI Elongation between F_3 and F_4 generation.



An analysis of variance was carried out to determine if there were significant differences among selections for low and high fiber elongation in the F_4 generation. The results indicate significant differences among entries for fiber elongation ($p=0.0001$, $\alpha=0.05$) (Table 19). Separation mean analysis showed significant differences for the low and high selections within families (Table 20). Selections for high elongation were significantly different from selection for low elongation. This indicates divergent selection was effective in separating low and high values for fiber elongation. Table 21 shows the least square means for the divergent selections. Fiber elongation was group for low and high selections within each family. The low selection remained low and the high selections remained high. The values for fiber elongation among families ranged between 6.2% (family 14 low selections) and 10.15% (family 10a high selection).

Table 19. Analysis of variance among the divergent selections (low-high) for fiber elongation in the F_4 generation.

Source	df	MS	F-value	Pr>F
Total	47			
Rep	3	0.119	1.87	0.1546
Entry	11	6.04	95.06	**0.0001 ***
Residual	33	0.064		

*significant at 0.05 level

Table 20. Differences of least square means for the divergent selections (low-high) for fiber elongation in the F_4 generation .

Entry	Family	Elongation (reason)	Estimate*
4	10a	High	10.15a
12	7	High	9.48b
7	3	High	9.20b
9	10b	High	9.20b
6	9	High	8.65c
2	14	High	8.40c
3	10a	Low	7.95d
8	3	Low	7.38e
11	7	Low	7.28ef
10	10b	Low	6.95fg
5	9	Low	6.85g
1	14	Low	6.20h

*Equal letters indicate no significant differences at 0.05 level

Table 21. Least squares means for the divergent selections (low-high) for fiber elongation in the F_4 generation.

Entry	Family	Elongation (reason)	Estimate	Std. Error	t-value
1	14	Low	6.2	0.1305	47.51
2	14	High	8.4	0.1305	64.37
3	10a	Low	7.95	0.1305	60.92
4	10a	High	10.15	0.1305	77.78
5	9	Low	6.85	0.1305	52.49
6	9	High	8.65	0.1305	66.28
7	3	High	9.2	0.1305	70.5
8	3	Low	7.38	0.1305	56.51
9	10b	High	9.2	0.1305	70.5
10	10b	Low	6.95	0.1305	53.26
11	7	Low	7.28	0.1305	55.75
12	7	High	9.48	0.1305	72.6

Pearson correlations were carried out among fiber properties to determine the strength of linear dependence between variables (Table 22). Elongation was negatively correlated with HVI length (r=-0.520, p=<.0001) and HVI strength (r=-0.089, p=0.379), and positively correlated with micronaire (r=0.122, p=0.200) and uniformity (r=0.162, p=0.108) (Figure 13). However, correlations were non-significant between elongation and strength, micronaire and uniformity. Elongation was negatively correlated with the AFIS properties length by weight (r=-0.336, p=0.001), short fiber content by weight (r=-0.080, p=0.431), length by number (r=-0.074, p=0.465), short fiber content by number (r=-0.178, p=0.077) and maturity ratio (r=-0.441, p=<.0001); and was positively correlated with fineness (r=0.281, p=0.005) (Figure 14). Nevertheless, correlations were non-significant between elongation and the AFIS properties short fiber content by weight, length by number and short fiber content by number. It is evident that length characteristics cannot be ignored when selecting for improved tensile properties, as elongation has been disregarded while selecting for improved fiber length. Positive correlation between elongation and uniformity was maintained through generations of selections. Therefore, it is possible that while improving elongation, length uniformity index improves at the same time, indicating a possible causal relationship. Data from HVI shows a steady improvement of fiber length and strength; however, length uniformity remained stagnant. Nevertheless, this research shows the ability to select for improved fiber elongation has the potential to impact length uniformity indirectly. Additionally, as elongation increases, short fiber content by weight and by number decrease as expected. However, these correlations are weak and although they are a good indication of the relationships between elongation and length uniformity index, and between elongation and short fiber content, future studies should focus on increasing the understanding and importance of such relationships.

Table 22. Pearson correlations among HVI and AFIS fiber properties in the F_4 generation.

	Micronaire	Length (mm)	Uniformity (%)	Strength (g/tex)	Elongation (%)	L(w) (mm)	SFC (w) (%)	L(n) (mm)	SFC (n) (%)	Fine (mTex)	Mat Ratio
Micronaire	1	-0.222	0.364	-0.276	0.129	0.105	-0.477	0.354	-0.523	0.747	0.604
		0.027	0.000	0.005	ns	ns	<.0001	0.000	<.0001	<.0001	<.0001
Length (mm)	-0.222	1	0.348	0.505	-0.520	0.797	-0.247	0.510	-0.106	-0.322	0.323
	0.027		0.000	<.0001	<.0001	<.0001	0.013	<.0001	ns	0.001	0.001
Uniformity (%)	0.364	0.348	1	0.414	0.162	0.597	-0.688	0.699	-0.637	0.159	0.331
	0.000	0.000		<.0001	ns	<.0001	<.0001	<.0001	<.0001	ns	0.001
Strength (g/tex)	-0.276	0.505	0.414	1	-0.089	0.484	-0.184	0.031	-0.077	-0.035	0.045
	0.005	0.000	0.000		ns	0.000	ns	0.002	ns	0.000	ns
Elongation (%)	0.122	-0.520	0.162	-0.089	1	-0.336	-0.080	-0.074	-0.178	0.281	-0.441
	ns	<.0001	ns	ns		0.006	ns	ns	ns	ns	<.0001
L(w) [mm]	0.105	0.797	0.597	0.484	-0.336	1	-0.729	0.896	-0.613	-0.071	0.509
	ns	<.0001	<.0001	<.0001	0.001		<.0001	<.0001	<.0001	ns	<.0001
SFC (w) [%]	-0.477	-0.247	-0.688	-0.184	-0.080	-0.729	1	-0.941	0.982	-0.320	-0.539
	<.0001	0.013	0.000	ns	ns	0.000		0.000	0.000	0.001	0.000
L(n) [mm]	0.354	0.510	0.698	0.308	-0.074	0.896	-0.941	1	-0.890	0.209	0.556
	0.000	<.0001	<.0001	0.002	ns	<.0001	<.0001		<.0001	0.037	<.0001
SFC (n) [%]	-0.523	-0.106	-0.637	-0.077	-0.178	-0.613	0.982	-0.890	1	-0.398	-0.497
	<.0001	ns	<.0001	ns	ns	<.0001	<.0001	<.0001		<.0001	<.0001
Fine (mTex)	0.747	-0.322	0.159	-0.351	0.281	-0.071	-0.320	0.209	-0.398	1	0.468
	<.0001	0.001	ns	0.000	0.005	ns	0.001	0.037	<.0001		<.0001
Mat Ratio	0.604	0.323	0.331	0.045	-0.441	0.509	-0.539	0.556	-0.497	0.468	1
	<.0001	0.001	0.001	ns	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	

Figure 13. Correlations between HVI elongation and other HVI fiber properties in the F_4 generation, 2010.

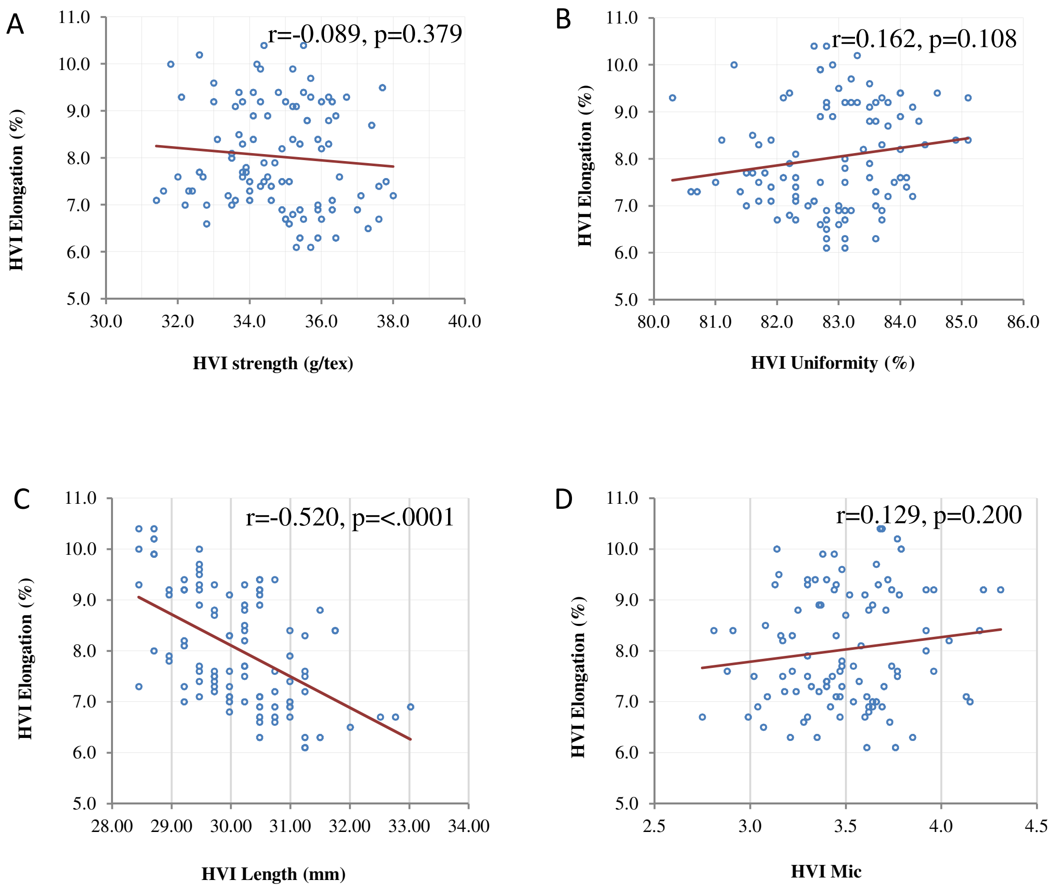
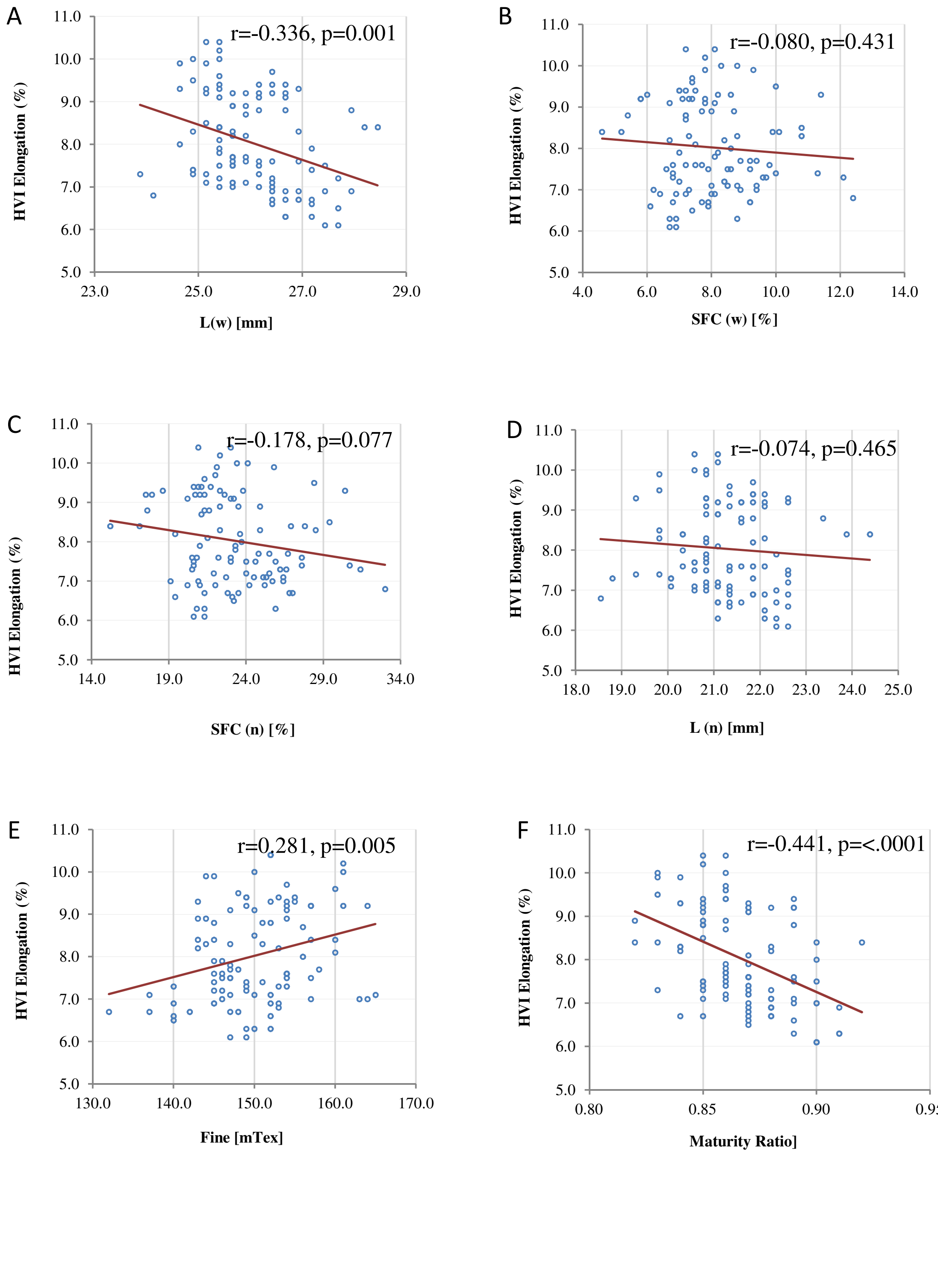


Figure 14. Correlations between HVI elongation and AFIS properties in the F_4 generation, 2010.



Family averages per generation (F_2, F_3, and F_4) for the divergent selections indicated that the relative difference between the low elongation selections and the high elongation selections remained constant over years; the lines selected for low elongation remained low, and the selections for high elongation remained high (Figure 15). The mean values were lower in the F_3 generation (2009), therefore it can be observed that the elongation level changed with the environment and possible because of instrument effect, but the relative differences between divergent selections were constant. Within selected families, the difference level between low and high selections for elongation was constant with no interactions (Figure 16). Figure 17 shows the relationship between HVI elongation among entries and field replications. It can be observed that there is little variation among replications and entries, suggesting stability of fiber elongation.

Figure 15. Family average per generation for divergent selections (low-high) elongation.

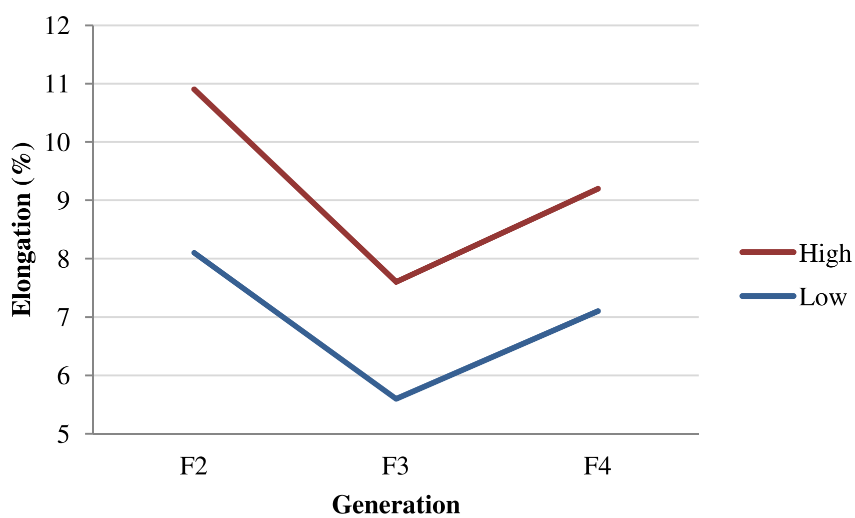


Figure 16. Average per selected family in each generation for divergent selection (low-high elongation).

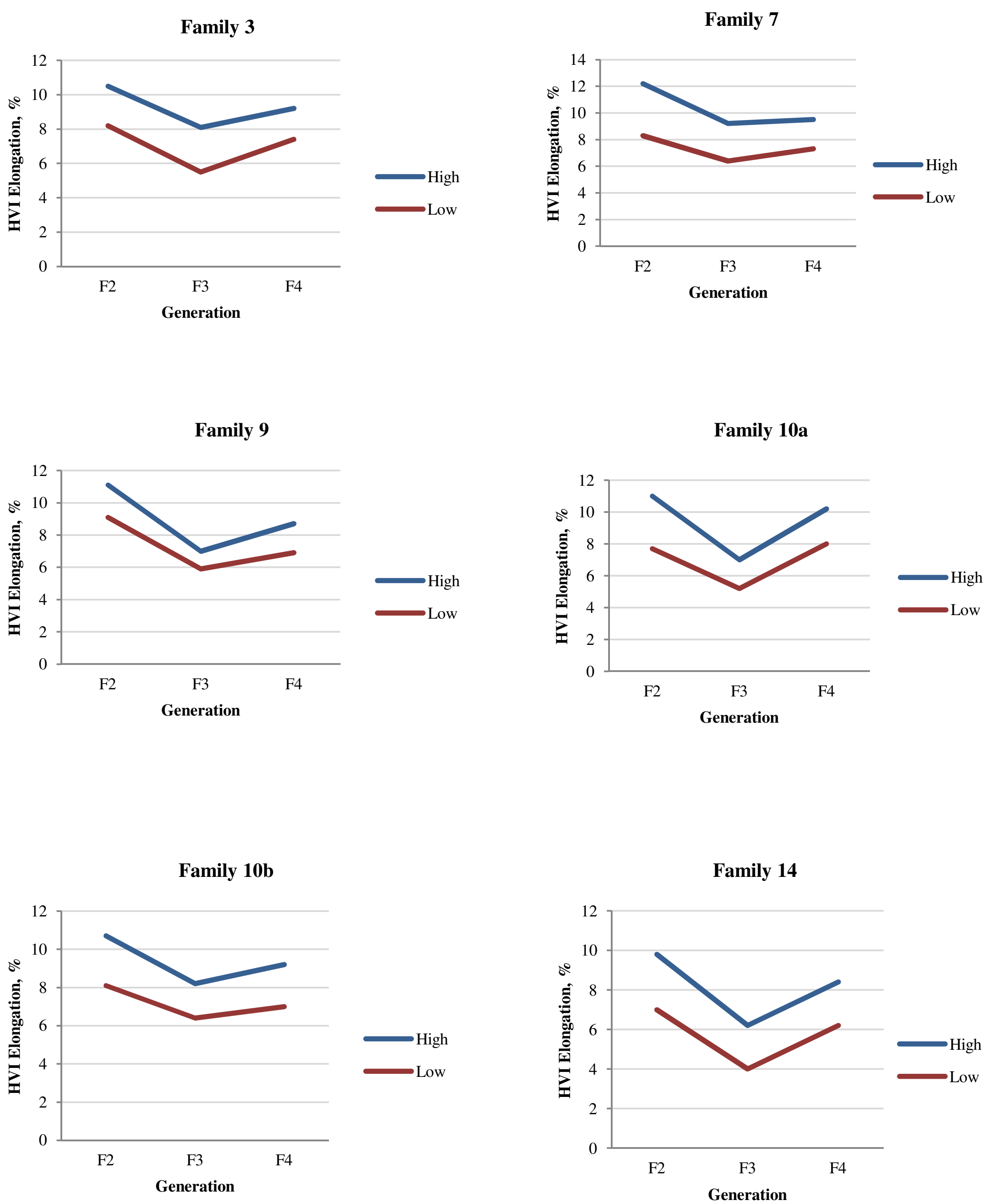
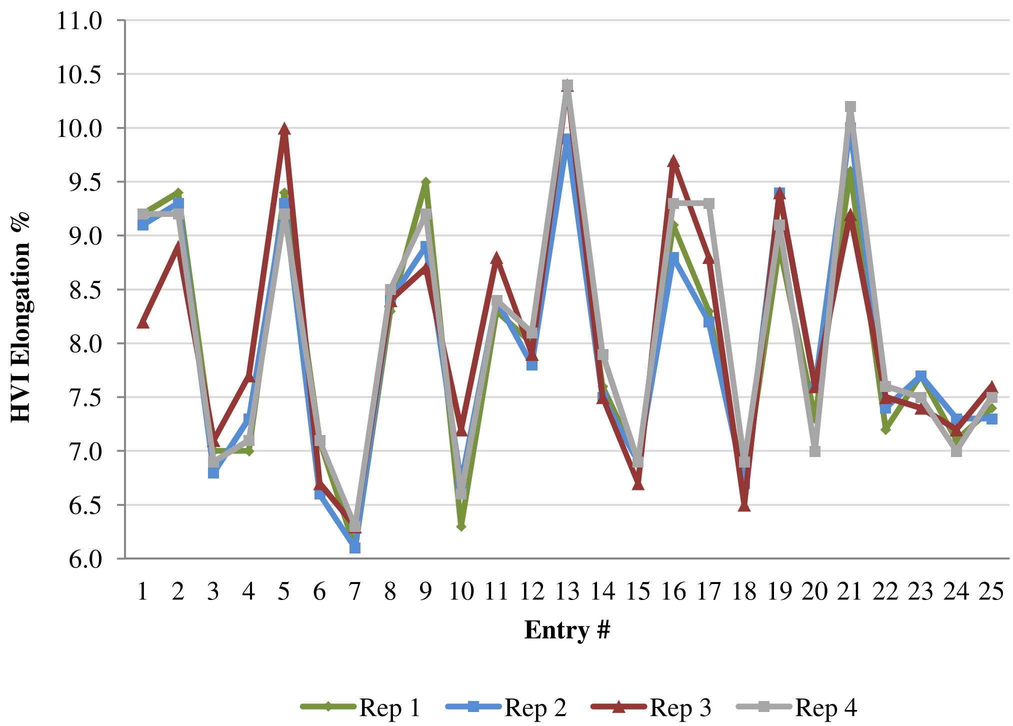


Figure 17. HVI elongation among entries and field replications in the F_4 generation.



4.4 Spinning test

Spinning tests were conducted in 2011 to determine the influence of fiber elongation on yarn elongation, strength, work-to-break, and performance in general. Selected lines were planted in a RCBD with four replications in 2011in four locations; though one location at Lamesa was not established and the location at the Texas Tech Quaker Avenue research farm did not produce enough fiber for spinning tests, leaving the Halfway and Lubbock Texas AgriLife Research locations. Nine entries were selected from the lines evaluated in the F_4 generation in 2010 to conduct spinning tests; four entries represented paired selections from one family, two entries represented paired selections from another family, two selections were based on high and low elongation and other fiber properties considered good for spinning potential from the entire population and a check ‘FM958’ (Table 23).

Analysis of variance from HVI and AFIS fiber data over locations are presented in table 24 and table 25 respectively. Entry means over location are presented in each table and means separation was conducted when there were significant differences among entries. There were significant differences among entries for fiber elongation and all other HVI fiber properties over combined locations. However, there were no significant differences among entries with high fiber elongation, but they were significantly different from entries with low elongation and the check. Family 7 had the highest elongation value (9.7%), followed by family 10a (9.6%) and 10b (9.2%). Fiber strength was not significantly different among entries with higher fiber elongation, and was higher than entries with low elongation and the check; except for the selection for low elongation from the entire population (-E) which had the highest strength value (32.4g/tex). This indicates that divergent targeted selection was a successful methodology for the improvement of fiber elongation while keeping high levels of strength. Additionally, looking at AFIS fiber properties, there were significant differences among entries for all properties.

Table 26 shows significant differences for fiber properties from HVI and AFIS for each location. In Halfway, entries were significantly different for all HVI and AFIS fiber properties. In Lubbock, entries were non-significant for HVI uniformity and the AFIS properties short fiber content by weight, length by number and seed count per nep count. Entry means for fiber properties in each location are presented; additionally, mean separation was conducted when there were significant differences among entries (Table 27 and Table 28).

Table 23. HVI fiber data for lines selected for spinning tests, 2011.

Entry	Name	Reason	Family	Micronaire	Length (mm)	Uniformity (%)	Strength (g/Tex)	Elongation (%)	Work-to-break
3	09-2-510-1	Low	10a	4.4	31.68	83.9	37.4	6.3	235.6
4	09-2-511-3	High	10a	4.8	28.19	83.4	35.7	8.4	299.8
9	09-2-1015-4	High	10b	4.9	27.94	82.6	36.3	7.9	286.7
10	09-2-1016-4	Low	10b	4.8	28.19	82.4	34.8	6.2	215.7
11	09-2-1111-5	Low	7	4.7	29.21	83.2	34.0	5.6	192.1
12	09-2-1112-1	High	7	4.8	28.95	83.0	35.9	8.3	297.9
19	09-2-708-1	+E	9	4.0	28.70	83.7	38.5	8.4	323.4
21	09-2-804-1	-E	10	4.0	32.25	84.3	38.4	5.6	215.0
23	FiberMax FM 958	Check		4.7	28.70	82.9	34.6	5.8	200.6

*The –E and +E selections were for different levels of elongation though they were not paired selections from the same family.

Table 24. Analysis of variance for HVI fiber properties over locations sorted by entries with high to low elongation.

Family	Reason	Entry	Micronaire		Length (mm)		Uniformity (%)		Strength (g/tex)		Elongation (%)	
7	High	12	4.1	c	27.1	cd	80.6	bc	31.2	bc	9.7	a
10a	High	4	4.2	c	26.4	e	80.7	abc	31.4	bc	9.6	a
10b	High	9	4.1	c	27.3	bcd	81.0	ab	31.4	bc	9.2	a
9	+E	19	3.8	d	27.7	bc	81.5	a	33.4	a	8.7	b
10a	Low	3	4.4	a	26.7	de	80.9	abc	29.8	d	7.2	c
10b	Low	10	4.2	c	28.0	b	80.5	bc	30.8	cd	6.8	cd
10	-E	21	3.6	e	30.3	a	81.1	ab	32.4	ab	6.6	d
FM958	Check	23	4.3	b	27.2	cd	80.6	bc	28.1	e	6.6	d
7	Low	11	4.5	a	27.6	bc	80.1	c	26.5	f	6.4	d

*Means with the same letter indicate no significant difference at the 0.05 level

Table 25. Analysis of variance for AFIS fiber properties over locations sorted by entries with high to low elongation.

Family	Reason	Entry	nepgm (g)		lw (mm)		uqlw (mm)		sfcw (%)		ln (mm)		sfcn (%)		vfm (%)		scn (Cnt/g)	
7	High	12	340.6	cd	23.7	bc	28.6	bc	8.9	cd	19.5	a	24.6	e	0.57	b	17	bc
10a	High	4	343.0	cd	22.8	d	27.4	d	9.7	abc	18.6	b	26.3	cde	0.62	b	19	b
10b	High	9	352.8	c	23.6	bcd	28.6	b	9.7	abc	19.1	ab	26.6	cd	0.73	b	21	b
9	+E	19	407.8	b	24.3	b	29.3	b	8.5	d	19.7	a	25.0	de	0.79	b	27	a
10a	Low	3	305.9	de	23.1	cd	27.9	cd	9.9	ab	18.8	b	27.0	bc	0.52	b	19	b
10b	Low	10	353.0	c	23.7	bc	29.2	b	10.6	a	18.7	b	29.6	a	0.69	b	20	b
10	-E	21	516.4	a	25.2	a	31.3	a	9.6	abc	19.7	a	28.6	ab	1.20	a	18	bc
FM958	Check	23	316.5	cde	24.1	b	29.3	b	8.6	d	19.7	a	24.9	de	0.58	b	13	c
7	Low	11	302.3	e	23.8	bc	29.1	b	9.6	bc	19.2	ab	26.5	cd	0.55	b	17	bc

*Means with the same letter indicate no significant difference at the 0.05 level

Table 25. Continued.

Family	Reason	Entry	fine (mTex)		mat ratio		Hs (mTex)	
7	High	12	169	bc	0.89	d	190	a
10a	High	4	165	de	0.88	d	186	b
10b	High	9	163	de	0.90	cd	182	c
9	+E	19	158	f	0.89	d	178	d
10a	Low	3	171	bc	0.92	ab	186	b
10b	Low	10	163	de	0.90	bc	180	cd
10	-E	21	149	g	0.88	d	169	e
FM958	Check	23	166	cd	0.92	a	181	cd
7	Low	11	174	a	0.92	a	189	a

Table 26. P-values from the analysis of variance for fiber properties from HVI and AFIS for each location.

	Halfway		Lubbock	
Micronaire	<.0001	*	<.0001	*
Length (mm)	<.0001	*	<.0001	*
Uniformity	0.0001	*	0.5513	ns
Strength (g/tex)	<.0001	*	<.0001	*
Elongation (%)	<.0001	*	<.0001	*
nepgm (g)	<.0001	*	<.0001	*
lw (mm)	0.0017	*	0.0399	*
uqlw (mm)	<.0001	*	0.0055	*
sfcw (%)	0.0031	*	0.3023	ns
ln (mm)	0.0085	*	0.2358	ns
sfcn (%)	0.0002	*	0.0117	*
vfm (%)	0.0003	*	0.0409	*
scn (Cnt/g)	<.0001	*	0.4007	ns
fine (mTex)	<.0001	*	<.0001	*
mat ratio	0.0017	*	<.0001	*
Hs (mTex)	<.0001	*	<.0001	*

*significant at 0.05 level

[ns] non-significant at 0.05 level

Table 27. Analysis of variance for HVI properties in each location sorted by entries with high to low elongation.

Location	Family	Reason	Entry	Micronaire		Length (mm)		Uniformity (%)		Strength (g/tex)		Elongation (%)	
Halfway	7	High	12	3.5	c	26.5	cd	79.8	b	29.2	bc	9.5	a
Halfway	10a	High	4	3.5	c	25.8	e	79.8	b	29.7	bc	9.3	a
Halfway	10b	High	9	3.5	c	26.8	bcd	80.1	b	29.8	bc	9.1	ab
Halfway	9	+E	19	3.4	c	26.9	bcd	81.4	a	32.9	a	8.7	b
Halfway	10a	Low	3	3.8	ab	26.3	ed	80.3	b	28.6	c	7.3	c
Halfway	10b	Low	10	3.6	bc	27.3	b	79.8	b	29.2	bc	7.1	cd
Halfway	FM958	Check	23	3.8	ab	26.7	bcd	80.1	b	26.9	d	6.7	d
Halfway	10	-E	21	3.1	d	29.4	a	79.9	b	30.4	b	6.7	d
Halfway	7	Low	11	3.9	a	27.1	bc	79.0	c	25.5	d	6.6	d
Lubbock	10a	High	4	4.9	b	26.9	c	81.7	ns	33.2	ab	10.0	a
Lubbock	7	High	12	4.7	c	27.8	bc	81.4	ns	33.2	ab	9.8	a
Lubbock	10b	High	9	4.8	bc	27.9	bc	81.9	ns	32.9	ab	9.3	ab
Lubbock	9	+E	19	4.2	d	28.4	bc	81.7	ns	34.0	a	8.7	b
Lubbock	10a	Low	3	5.1	a	27.1	c	81.5	ns	30.9	bc	7.1	c
Lubbock	10	-E	21	4.1	d	31.2	a	82.3	ns	34.4	a	6.5	c
Lubbock	10b	Low	10	4.8	bc	28.8	b	81.3	ns	32.4	ab	6.5	c
Lubbock	FM958	Check	23	4.8	bc	27.8	bc	81.1	ns	29.3	cd	6.5	c
Lubbock	7	Low	11	5.1	a	28.1	bc	81.2	ns	27.5	d	6.2	c

*Means with the same letter indicate no significant difference at the 0.05 level

Table 28. Analysis of variance for AFIS properties in each location sorted by entries with high to low elongation.

Location	Family	Reason	Entry	nepgm (g)		lw (mm)		uqlw (mm)		sfcw (%)		ln (mm)		sfcn (%)		vfm (%)	
Halfway	7	High	12	450.75	bc	23.1	bcd	28.2	bc	10.6	ab	18.5	abc	28.2	c	0.52	b
Halfway	10a	High	4	452.25	bc	22.0	d	26.8	d	11.4	bc	17.8	cd	29.3	bc	0.51	b
Halfway	10b	High	9	441.5	bcd	22.8	bcd	28.0	bcd	11.4	bc	18.2	abc	29.7	bc	0.76	b
Halfway	9	+E	19	487.75	b	23.4	cb	28.2	bc	9.8	ab	18.7	ab	27.5	c	0.57	b
Halfway	10a	Low	3	404.75	cd	22.3	cd	27.3	cd	12.0	c	17.7	cd	31.0	b	0.49	b
Halfway	10b	Low	10	476.75	b	22.8	bcd	28.4	bc	12.6	c	17.5	c	33.7	a	0.79	b
Halfway	FM958	Check	23	389.25	cd	23.8	ab	29.2	b	9.7	a	19.2	a	27.1	c	0.62	b
Halfway	10	-E	21	660.5	a	24.5	a	30.8	a	11.1	ab	18.9	a	31.4	ab	1.35	a
Halfway	7	Low	11	376.5	d	23.0	bcd	28.4	bc	11.2	abc	18.2	bcd	29.7	bc	0.50	b
Lubbock	10a	High	4	233.75	cd	23.6	c	28.1	c	8.0	ns	19.4	ns	23.4	abc	0.74	abc
Lubbock	7	High	12	230.5	cd	24.4	cb	29.1	bc	7.1	ns	20.4	ns	21.0	c	0.63	abc
Lubbock	10b	High	9	264	c	24.3	cb	29.3	bc	7.9	ns	20.0	ns	23.4	abc	0.70	abc
Lubbock	9	+E	19	327.75	b	25.3	ab	30.4	ab	7.2	ns	20.7	ns	22.6	c	1.00	ab
Lubbock	10a	Low	3	207	d	23.9	cb	28.6	bc	7.9	ns	19.8	ns	23.1	abc	0.55	c
Lubbock	10	-E	21	372.25	a	26.0	a	31.8	a	8.1	ns	20.4	ns	25.8	a	1.06	a
Lubbock	10b	Low	10	229.25	cd	24.7	abc	30.0	b	8.5	ns	19.9	ns	25.5	ab	0.60	c
Lubbock	FM958	Check	23	243.75	cd	24.4	cb	29.4	bc	7.5	ns	20.1	ns	22.6	c	0.53	c
Lubbock	7	Low	11	228	cd	24.6	abc	29.8	bc	7.9	ns	20.3	ns	23.4	abc	0.61	bc

*Means with the same letter indicate no significant difference at the 0.05 level

Table 28. Continued.

Location	Family	Reason	Entry	scn (Cnt/g)		fine (mTex)		mat ratio		Hs (mTex)	
Halfway	7	High	12	19	cd	156	bcd	0.86	cd	183	a
Halfway	10a	High	4	18	cd	153	bcd	0.85	d	180	ab
Halfway	10b	High	9	25	b	153	bcd	0.86	cd	177	bc
Halfway	9	+E	19	34	a	152	cd	0.87	bcd	176	bc
Halfway	10a	Low	3	21	bcd	158	abc	0.88	abc	180	ab
Halfway	10b	Low	10	24	bc	151	dc	0.87	bcd	174	c
Halfway	FM958	Check	23	15	d	158	abc	0.90	a	176	bc
Halfway	10	-E	21	21	bcd	139	e	0.85	cd	164	d
Halfway	7	Low	11	16	d	162	a	0.88	ab	184	a
Lubbock	10a	High	4	20	ns	176	b	0.92	cd	192	b
Lubbock	7	High	12	15	ns	182	a	0.92	cd	198	a
Lubbock	10b	High	9	16	ns	173	b	0.93	bc	186	c
Lubbock	9	+E	19	20	ns	164	c	0.91	d	180	d
Lubbock	10a	Low	3	17	ns	184	a	0.96	a	193	b
Lubbock	10	-E	21	16	ns	158	d	0.91	d	175	e
Lubbock	10b	Low	10	16	ns	175	b	0.94	ab	186	c
Lubbock	FM958	Check	23	12	ns	175	b	0.94	ab	186	c
Lubbock	7	Low	11	18	ns	186	a	0.96	a	195	b

In the analysis in each location, entries with high elongation were not significantly different from each other, but were significantly different from entries with low elongation and the check. In Lubbock, fiber elongation values were higher than those observed from samples from the Halfway location. In Lubbock, the high elongation selection from family 10a had the highest value (10%), followed by family 7 (9.8%) and family 10b (9.3%). In Halfway, the highest elongation value was for the high elongation selection from family 7 (9.5%), followed by family 10a (9.3%) and family 10b (9.1%). In both locations, the low selection from family 7 had the lowest value for elongation.

In addition, fiber strength was not significantly different among entries with higher fiber elongation in both locations. On the other hand, fiber strength was no significantly different among entries selected for low fiber elongation including the check. For some entries, fiber strength was no significantly different for entries selected for low elongation and high elongation. Higher strength values were found in the Lubbock location compared to the Halfway location. In both locations, the check 'FM958' had low fiber strength values, 26.9 g/tex in Halfway and 29.3 g/tex in Lubbock. For AFIS properties, there were significant differences among entries in Halfway. In Lubbock, only short fiber content by weight, length by number and seed coat number were not significantly different.

In the analysis over locations, there were significant differences among entries for all HVI and AFIS fiber properties. For the HVI properties, there were significant differences between locations for micronaire, length, length uniformity, and strength. Locations were not significantly different for elongation. Interaction between entries and location was only found for micronaire (Table 29). Looking at the AFIS properties, there were significant differences between locations for nep count per gram, length by weight, short fiber content by weight, length by number, short fiber content by number, fineness, maturity ratio and standard fineness. There was also interaction between entry and location for nep count per gram, seed count per nep count, fineness and standard fineness (Table 29).

Table 29. P-values from the analysis of variance over locations for HVI and AFIS fiber properties.

	Entry		Location		Loc x entry	
Micronaire	<.0001	*	0.0002	*	<.0001	*
Length (mm)	<.0001	*	0.0035	*	ns	
Uniformity	0.0172	*	0.0182	*	ns	
Strength (g/tex)	<.0001	*	0.0076	*	ns	
Elongation (%)	<.0001	*	0.7952	ns	ns	
nepgm (g)	<.0001	*	0.0015	*	0.0018	*
lw (mm)	<.0001	*	0.0252	*	ns	
uqlw (mm)	<.0001	*	0.0569	ns	ns	
sfcw (%)	0.0002	*	0.0026	*	ns	
ln (mm)	0.0008	*	0.0117	*	ns	
sfcn (%)	<.0001	*	0.0033	*	ns	
vfm (%)	<.0001	*	0.6409	ns	ns	
scn (Cnt/g)	0.0001	*	0.1166	ns	0.0186	*
fine (mTex)	<.0001	*	0.0002	*	0.0002	*
mat ratio	<.0001	*	0.0001	*	ns	
Hs (mTex)	<.0001	*	0.0005	*	0.0232	

*significant at 0.05 level

[ns] non-significant at 0.05 level

Family average across locations from divergent selections for lines selected for spinning tests indicate that the relative difference between low and high fiber elongation remained constant (Figure 18). Lines selected for low elongation during the three cycles of selection (F_2, F_3 and F_4) remained low, and the selections for high elongation remained high. Relative differences for low and high elongation selections within families remained constant in each environment (Figure 19). Therefore environment did not have a major influence on fiber elongation. Additionally, all selections for high elongation were higher than the check 'FM958'.

Figure 18. Family average for low and high selection for fiber elongation across locations from lines selected for spinning tests, 2011.

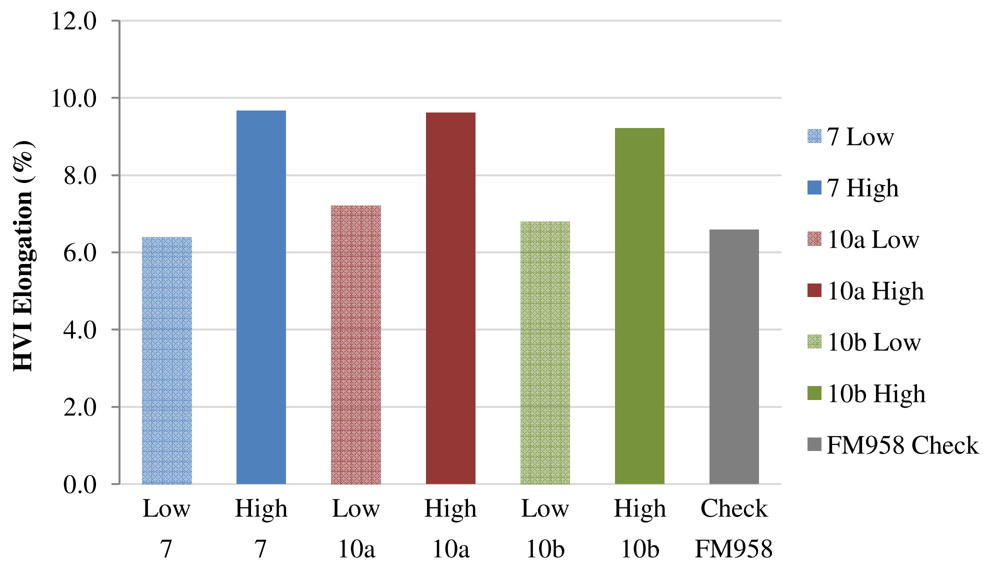
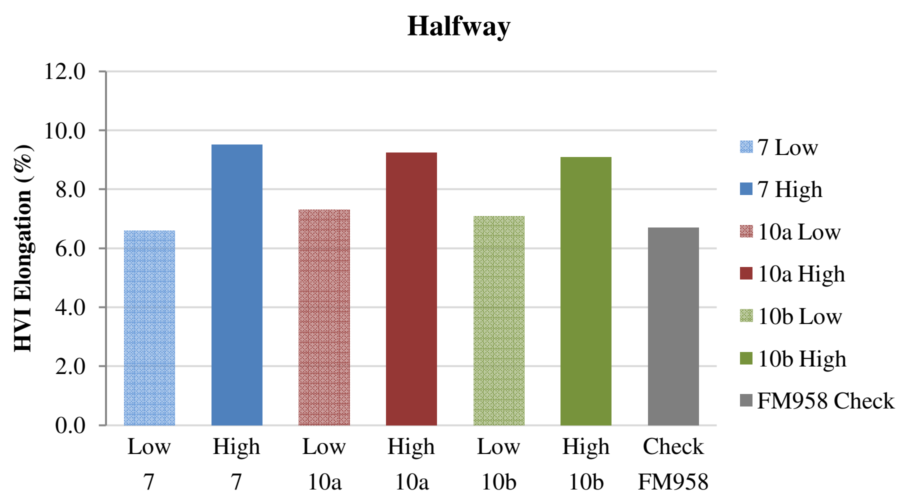
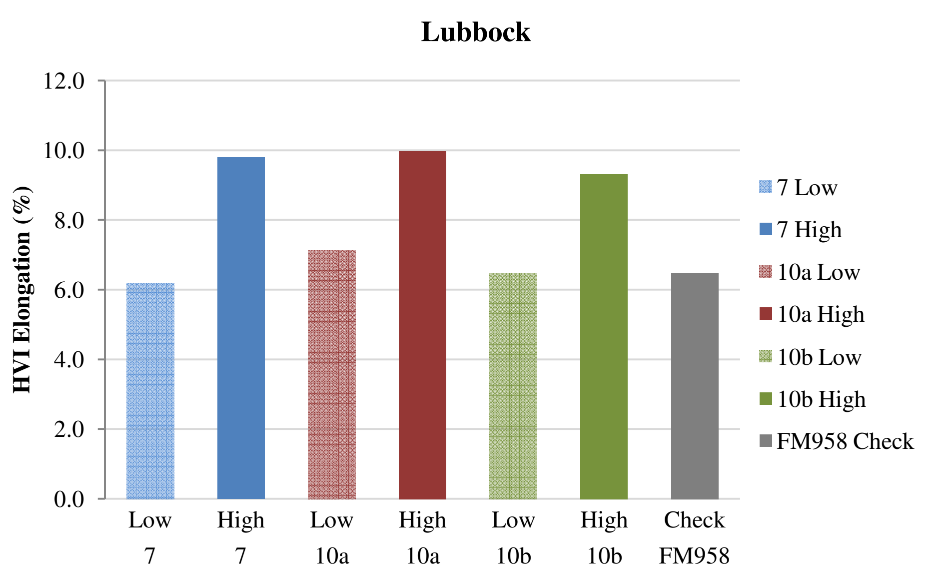


Figure 19. Family averages for low and high selections for fiber elongation in each location from lines selected for spinning tests, 2011.





Pearson correlations were carried out among HVI and AFIS fiber properties in the selected lines to determine the strength of linear dependence between variables. Fiber elongation was positively correlated to strength (r=0.424, p=0.010) (Table 30 and Figure 20). This indicated that continuous selection for elongation while keeping strength values constant influenced the relationship between them. As seen in the previous generations, the relationship between elongation and strength was negative but weak; -0.32 in the F_2, -0.36 in the F_3 and -0.0889 in the F_4. However, with constant targeted selection this relationship changed towards a positive relationship. In the early generations, selection pressure was applied only to elongation attempting to keep other fiber properties constant, for the purpose of developing lines for spinning that isolate the influence of elongation specifically. However, in the final round of selections, other fiber properties were considered. Therefore, the positive correlation between fiber strength and elongation at the end, compared to negative correlation in the early generations, indicates that the two properties that constitute the work-to-break can be improved simultaneously. Additionally, elongation was also positively correlated to uniformity (r=0.182, p=0.289) (Figure 21), indicating that while improving fiber elongation, uniformity increases as well. On the other hand, fiber elongation was negatively correlated to micronaire (r=-0.066, p=0.704) and length (r=-0.375, p=0.024). Table 30 shows the correlation among HVI fiber properties. Table 31 shows the correlation among AFIS properties, and table 32 shows the correlations between HVI and AFIS fiber properties. The correlation between fiber elongation and short fiber content by weight (r=-0.111, p=0.519) and by number (r=-0.230, p=0.177) were negative, indicating that while fiber elongation increases, short fiber content decreases (Figure 22). Therefore, it has been demonstrated that while improving fiber elongation, uniformity index increases and short fiber content decreases. Hence, future improvement of cotton should include fiber elongation in their breeding objectives, since it is possible to obtain lines with increased uniformity, decreased short fiber content and at the same time improved fiber strength.

Table 30. Pearson correlations among HVI fiber properties for the lines selected for spinning tests, 2011.

	Micronaire	Length (mm)	Uniformity (%)	Strength g/tex)	Elongation (%)
Micronaire	1	0.163	0.579	0.218	-0.066
		ns	0.000	ns	ns
Length (mm)	0.163	1	0.515	0.478	-0.375
	ns		0.001	0.003	0.024
Uniformity (%)	0.579	0.515	1	0.773	0.182
	0.000	0.001		<.0001	ns
Strength (g/tex)	0.218	0.478	0.773	1	0.424
	ns	0.003	<.0001		0.010
Elongation (%)	-0.066	-0.375	0.182	0.424	1
	ns	0.024	ns	0.010	

Figure 20. Correlation between fiber elongation and fiber strength in the selected lines for spinning tests.

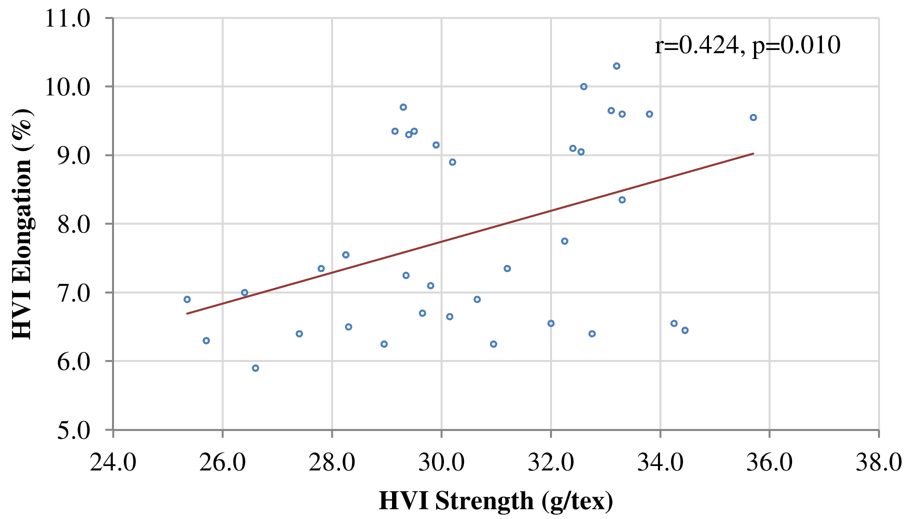


Figure 21. Correlation between fiber elongation and fiber uniformity in the selected lines for spinning tests.

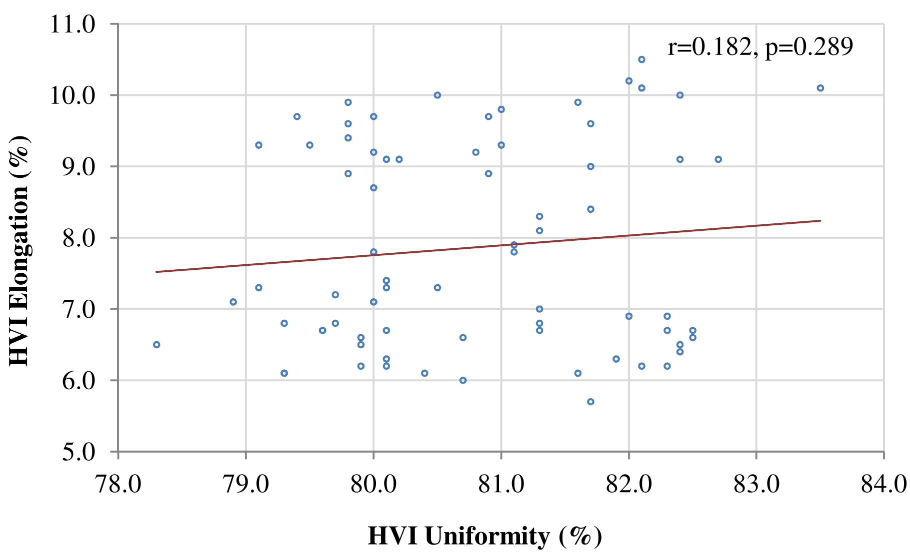


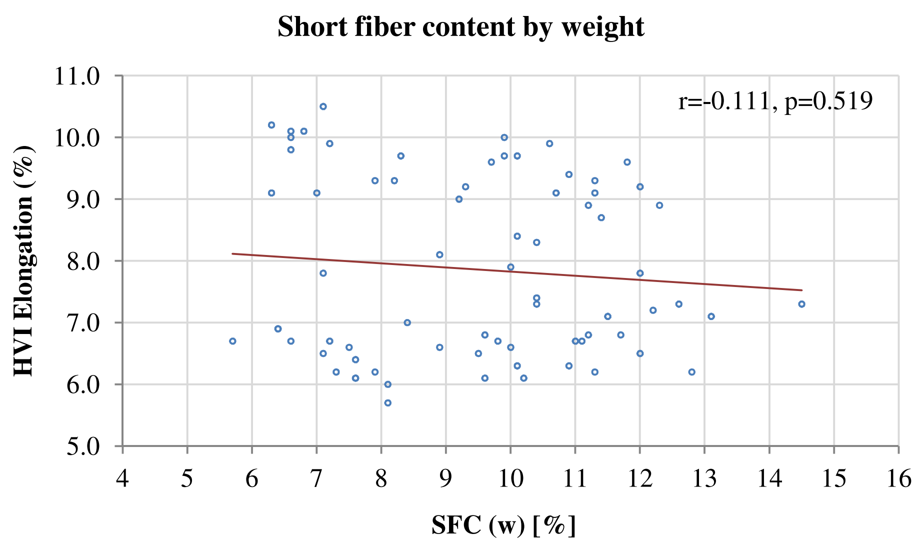
Table 31. Pearson correlations among AFIS fiber properties for the lines selected for spinning tests.

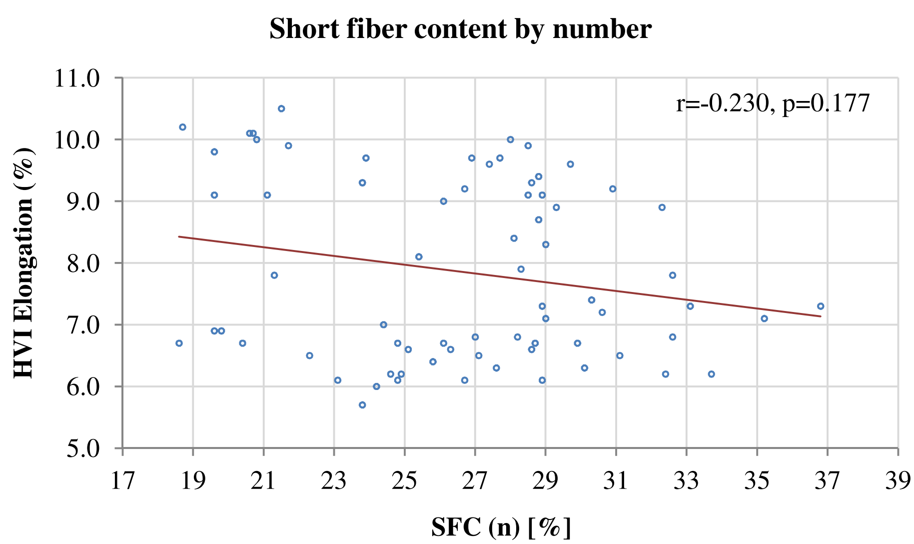
	Neps per Gm	L(w) (mm)	uql(w) (mm)	sfc(w) (%)	L(n) (mm)	sfc(n) (%)	vfm (%)	scn (Cnt/g)	fine (mTex)	ifc (%)	mat ratio	Hs (mTex)
Nep per Gm	1	-0.330	-0.090	0.730	-0.600	0.780	0.230	0.510	-0.950	0.930	-0.890	-0.860
		0.050	ns	<.0001	0.000	<.0001	ns	0.000	<.0001	<.0001	<.0001	<.0001
L(w) (mm)	-0.330	1	0.944	-0.778	0.904	-0.636	0.261	-0.275	0.325	-0.540	0.570	0.053
	0.050		<.0001	<.0001	<.0001	<.0001	ns	ns	ns	0.001	0.000	ns
uql(w) (mm)	-0.090	0.944	1	-0.538	0.729	-0.360	0.336	-0.232	0.086	-0.304	0.371	-0.193
	ns	<.0001		0.001	<.0001	0.031	0.045	ns	ns	ns	0.026	ns
sfc(w) (%)	0.730	-0.778	-0.538	1	-0.953	0.974	0.024	0.349	-0.712	0.853	-0.803	-0.536
	<.0001	<.0001	0.001		<.0001	<.0001	ns	0.037	<.0001	<.0001	<.0001	0.001
L(n) (mm)	-0.600	0.904	0.729	-0.953	1	-0.893	0.067	-0.341	0.583	-0.756	0.728	0.372
	0.000	<.0001	<.0001	<.0001		<.0001	ns	0.042	0.000	<.0001	<.0001	0.025
sfc(n) (%)	0.780	-0.636	-0.360	0.974	-0.893	1	0.113	0.354	-0.759	0.861	-0.780	-0.641
	<.0001	<.0001	0.031	<.0001	<.0001		ns	0.034	<.0001	<.0001	<.0001	<.0001
vfm (%)	0.230	0.261	0.336	0.024	0.067	0.113	1	0.044	-0.201	0.119	-0.090	-0.277
	ns	ns	0.045	ns	ns	ns		ns	ns	ns	ns	ns
scn (Cnt/g)	0.510	-0.275	-0.232	0.349	-0.341	0.354	0.044	1	-0.464	0.521	-0.514	-0.372
	0.000	ns	ns	0.037	0.042	0.034	ns		0.004	0.001	0.001	0.026
Fine (mTex)	-0.950	0.325	0.086	-0.712	0.583	-0.759	-0.201	-0.464	1	-0.937	0.914	0.924
	<.0001	0.053	ns	<.0001	0.000	<.0001	ns	0.004		<.0001	<.0001	<.0001
ifc (%)	0.930	-0.540	-0.304	0.853	-0.756	0.861	0.119	0.521	-0.937	1	-0.974	-0.762
	<.0001	0.001	ns	<.0001	<.0001	<.0001	ns	0.001	<.0001		<.0001	<.0001
Mat ratio	-0.890	0.570	0.371	-0.803	0.728	-0.780	-0.090	-0.514	0.914	-0.974	1	0.693
	<.0001	0.000	0.026	<.0001	<.0001	<.0001	ns	0.001	<.0001	<.0001		<.0001
Hs (mTex)	-0.860	0.053	-0.193	-0.536	0.372	-0.641	-0.277	-0.372	0.924	-0.762	0.693	1
	<.0001	ns	ns	0.001	0.025	<.0001	ns	0.026	<.0001	<.0001	<.0001	

Table 32. Pearson correlations among HVI and AFIS fiber properties for the lines selected for spinning tests.

	Neps per Gm	L(w) (mm)	uql(w) (mm)	sfc(w) (%)	L(n) (mm)	sfc(n) (%)	vfm (%)	scn (Cnt/g)	fine (mTex)	ifc (%)	mat ratio	Hs (mTex)
Micronaire	-0.952	0.413	0.186	-0.746	0.630	-0.761	-0.080	-0.499	0.967	-0.956	0.950	0.832
	<.0001	0.012	ns	<.0001	<.0001	<.0001	ns	0.002	<.0001	<.0001	<.0001	<.0001
Length (mm)	-0.051	0.835	0.895	-0.427	0.598	-0.252	0.364	-0.214	0.040	-0.219	0.287	-0.195
	ns	<.0001	<.0001	0.009	0.000	ns	0.029	ns	ns	ns	ns	ns
Uniformity (%)	-0.529	0.664	0.446	-0.802	0.778	-0.757	0.080	-0.029	0.492	-0.623	0.595	0.332
	0.001	<.0001	0.006	<.0001	<.0001	<.0001	ns	ns	0.002	<.0001	0.000	0.048
Strength (g/tex)	-0.179	0.470	0.331	-0.498	0.468	-0.426	0.275	0.160	0.133	-0.218	0.192	0.078
	ns	0.004	0.049	0.002	0.004	0.010	ns	ns	ns	ns	ns	ns
Elongation (%)	-0.051	-0.246	-0.410	-0.111	-0.017	-0.230	-0.119	0.233	-0.002	0.074	-0.234	0.239
	ns	ns	0.013	ns	ns	ns	ns	ns	ns	ns	ns	ns

Figure 22. Correlation between fiber elongation and short fiber content by weight and by number in the selected lines for spinning tests.





In order to obtain adequate lint weight for the spinning process, field replications were combined (rep one with two, and rep three with four) for a total of two spinning test replications for each location. Each sample was prepared using the protocol for carded yarn. Due to shorter staple length in 2011, consequence of a severe drought, 30Ne count carded yarn could not be produced. Therefore, equipment settings were chosen for the production of 18Ne count carded yarn for all samples.

Analyses of variance were carried out over locations for yarn properties to determine if there were significant differences among entries (Table 33). Location was not significant for any of the yarn properties in the combined analysis. Interaction between entries and location was only evident for tenacity (Table 34). Entry means over locations are presented, and means separation was conducted when there were significant differences among entries. There were significant differences among entries for breaking elongation (brkel, %), work-to-break (work cN.cm), tenacity (cN/tex), number of thin places (tn50 Km), number of thick places (tk50 Km), nep count (np200 Km), hairiness (hair) and total number of imperfections (ipi). Yarns produced from lines developed from selections for high fiber elongation had a higher breaking elongation and higher work-to-break, compare to the lines develop from the selections for low elongation and the check. An improvement of 71.5% was observed from the low elongation selection to the high elongation selection for breaking elongation. Additionally, an improvement of 93.3% was observed from the low elongation selection to the high elongation selection for work-to-break. This indicates that selecting for high fiber elongation has a direct positive influence on spinning tensile properties and performance.

Entry means for fiber properties in each location are presented; additionally, mean separation was conducted when there were significant differences among entries (Table 35). The results were similar for combined analysis over locations; high fiber elongation selections had higher breaking elongation and work-to-break. However, some of the lines selected for low elongation had higher tenacity than the lines selected for high elongation; and the check was intermediate between the low and high selections.

Table 33. Analysis of variance for yarn properties over locations sorted by breaking elongation.

Family	Reason	Entry	tena (cN/tex)		brkelo (%)		work (cN.cm)		tn50 (Km)		tk50 (Km)		np200 (Km)		hair		ipi	
9	+E	19	16.96	a	5.48	a	883.91	a	2	bc	51	b	38	cd	6	d	91	c
10a	High	4	13.71	d	5.47	a	752.98	b	2	bc	73	b	63	a	7	bc	138	abc
7	high	12	13.96	cd	5.22	b	732.34	b	4	bc	69	b	27	d	6	cd	99	bc
10b	High	9	14.44	b	5.17	b	743.89	b	5	ab	84	b	46	cb	6	cd	135	abc
10	-E	21	16.81	a	4.60	c	731.29	b	1	c	84	b	63	a	7	cd	147	ab
10a	Low	3	13.53	d	4.26	d	581.00	cd	5	ab	83	b	48	bc	7	cd	136	abc
10b	low	10	14.25	bc	4.22	d	596.54	c	3	bc	89	ab	59	ab	7	cd	150	ab
FM958	check	23	13.79	cd	4.02	e	545.41	d	3	bc	71	b	31	d	7	ab	105	bc
7	low	11	12.28	e	3.83	e	473.69	e	8	a	122	a	54	ab	7	a	184	a

*Means with the same letter indicate no significant difference at the 0.05 level
^{ns} non-significant

Table 34. P-values from the analysis of variance over locations for yarn properties.

	Entry		Location[a]		Loc x entry	
Tena (cN/tex)	<.0001	*	0.2656	ns	0.0047	*
Brkelo (%)	<.0001	*	0.2475	ns	ns	
work (cN.cm)	<.0001	*	0.3462	ns	ns	
tn50 (Km)	0.0091	*	0.2284	ns	ns	
tk50 (Km)	0.0284	*	0.1531	ns	ns	
np200 (km)	<.0001	*	0.2554	ns	ns	
hair	0.0013	*	0.0561	ns	ns	
ipi	0.0082	*	0.2427	ns	ns	

*significant at 0.05 level
[ns] non-significant at 0.05 level
[a]Locations include Halfway and Lubbock, TX.

Table 35. Analysis of variance for yarn properties in each location sorted by breaking elongation.

Family	Reason	Location	Entry	tena cN/tex		brkelo (%)		work cN.cm		tn50 (Km)		tk50 (Km)		np200 (Km)		hair		ipi	
10a	High	Halfway	4	13.88	cd	5.42	a	758.76	b	2	ns	78	ns	47	abc	7	ns	127	ns
9	+E	Halfway	19	16.76	a	5.34	ab	873.95	a	3	ns	63	ns	42	bc	7	ns	107	ns
7	High	Halfway	12	13.82	cd	5.18	ab	735.46	bc	3	ns	74	ns	29	c	7	ns	105	ns
10b	High	Halfway	9	14.28	c	5.10	b	739.45	bc	7	ns	105	ns	46	abc	6	ns	157	ns
10	-E	Halfway	21	15.85	b	4.51	c	684.08	c	1	ns	103	ns	65	a	7	ns	168	ns
10a	Low	Halfway	3	13.36	d	4.21	d	564.13	d	5	ns	79	ns	48	abc	7	ns	131	ns
10b	Low	Halfway	10	14.11	cd	4.20	d	602.27	d	4	ns	92	ns	54	ab	7	ns	148	ns
Check	Check	Halfway	23	13.44	d	4.09	de	544.39	d	2	ns	66	ns	30	c	7	ns	97	ns
7	Low	Halfway	11	11.71	e	3.81	e	458.31	e	10	ns	135	ns	55	ab	7	ns	200	ns
9	+E	Lubbock	19	17.15	a	5.62	a	893.88	a	1	ns	39	c	35	de	7	abc	74	d
10a	High	Lubbock	4	13.55	d	5.52	ab	747.19	b	3	ns	67	b	79	a	6	cd	148	ab
7	High	Lubbock	12	14.11	bcd	5.26	b	729.22	b	4	ns	65	b	25	e	7	abc	94	cd
10b	High	Lubbock	9	14.60	b	5.24	b	748.33	b	3	ns	64	bc	47	cd	6	cd	113	bcd
10	-E	Lubbock	21	17.77	a	4.69	c	778.50	b	1	ns	66	b	62	bc	7	ab	127	abc
10a	Low	Lubbock	3	13.70	cd	4.31	d	597.88	c	5	ns	88	ab	48	cd	6	d	141	ab
10b	low	Lubbock	10	14.40	bcd	4.23	de	590.82	c	3	ns	86	ab	65	ab	7	bcd	153	ab
Check	Check	Lubbock	23	14.13	bcd	3.95	ef	546.44	cd	4	ns	77	b	33	de	7	a	113	bcd
7	low	Lubbock	11	12.86	e	3.86	f	489.06	d	6	ns	110	a	53	bc	7	bcd	168	a

*Means with the same letter indicate no significant difference at the 0.05 level
[ns] non-significant

Pearson correlations among HVI fiber properties and yarn properties for lines selected for fiber spinning tests were carried out (Table 36). Fiber elongation was positively correlated to tenacity (r=0.1067, p=0.536) (Figure 23), work-to-break (r=0.6899, p=<.0001) (Figure 24) and breaking elongation (r=0.8789, p=<.0001) (Figure 25). On the other hand, fiber elongation was negatively correlated to number of thin places (r=-0.1616, p=0.346) (Figure 26), number of thick places (r=-0.3939, p=0.017) (Figure 27), nep count (r=-0.2402, p=0.158) (Figure 28), hairiness (r=-0.3846, p=0.020) (Figure 29) and total number of imperfections (r=-0.3801, p=0.022) (Figure 30). The correlations are significant for work-to-break and breaking elongation, indicating that as the values of elongation increase, work-to-break and breaking elongation increase as well. The correlation between fiber elongation and yarn tenacity is also positive although non-significant; nevertheless, increases in fiber elongation produce stronger yarns. Likewise as the values of elongation increase, the number of imperfections, thin places, thick places and hairiness decreases. The correlations between fiber elongation and hairiness, and elongation and total number of imperfections were significant, indicating that high fiber elongation reduces hairiness and imperfections producing more even yarns. Consequently, yarn evenness and spinning performance improve with increased fiber elongation. Hence, high fiber elongation is contributing to better performance during processing. At the same time, fiber strength was positively correlated to breaking elongation (r=0.6512, p=<.0001), tenacity (r=0.7170, p=<.0001) and work-to-break (r=0.7464, p=<.0001). Even though fiber strength was not considered during early generations of selection, it can be observed that strength is important in the development of stronger yarns, as evident by the significance of the correlation coefficients between strength and yarn tensile properties. Changing fiber elongation has been successful in the development of breeding lines with higher fiber elongation that impact spinning performance and yarn quality in a positive way.

In addition, correlations for high and low elongation selections were done separately to determine the differences between low and high selections (Table 37 and 38). Low and high fiber elongation selections were positively correlated to tenacity

(Figure 31), breaking elongation (Figure 32) and work-to-break (Figure 33). Low and high selections were negatively correlated to thin places (Figure 34), thick places (Figure 35), hairiness (Figure 36) and total number of imperfections (Figure 37). However, for the high selections, elongation was positively correlated to nep count (Figure 38). Either for the low or high selections, elongation was positively correlated to yarn tensile properties, and negatively correlated to evenness properties. Therefore, it has been demonstrated that elongation is an important fiber property that contributes to yarn strength and evenness. An improvement of 71.5% and 93.3% was reach for yarn breaking elongation and yarn work-to-break respectively with lines with high values of fiber elongation. These results demonstrated the importance of including fiber elongation in breeding programs to improve yarn tensile properties and quality.

Table 36. Pearson correlations among HVI fiber properties and yarn properties.

	Micronaire	Length (mm)	Uniformity (%)	Strength g/tex	Elongation (%)	brkelo (%)	tena (cN/tex)	work (cN.cm)	tn50 (Km)	tk50 (Km)	np200 (Km)	hair	ipi
Micronaire	1	0.163	0.579	0.218	-0.066	-0.143	-0.215	-0.242	0.059	-0.134	0.052	-0.104	-0.073
		ns	0.000	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Length (mm)	0.163	1	0.515	0.478	-0.375	-0.077	0.624	0.159	-0.311	-0.085	0.271	-0.397	0.013
	ns		0.001	0.003	0.024	ns	<.0001	ns	ns	ns	ns	0.017	ns
Uniformity (%)	0.579	0.515	1	0.773	0.182	0.347	0.543	0.438	-0.390	-0.483	0.038	-0.587	-0.362
	0.000	0.001		<.0001	ns	0.038	0.001	0.008	0.019	0.003	ns	0.000	0.030
Strength (g/tex)	0.218	0.478	0.773	1	0.424	0.651	0.717	0.746	-0.468	-0.484	0.145	-0.615	-0.327
	ns	0.003	<.0001		0.010	<.0001	<.0001	<.0001	0.004	0.003	ns	<.0001	ns
Elongation (%)	-0.066	-0.375	0.182	0.424	1	0.879	0.107	0.690	-0.162	-0.394	-0.240	-0.385	-0.380
	ns	0.024	ns	0.010		<.0001	ns	<.0001	ns	0.017	ns	0.020	0.022
brkelo (%)	-0.143	-0.077	0.347	0.651	0.879	1	0.481	0.925	-0.399	-0.520	-0.148	-0.484	-0.454
	ns	ns	0.038	<.0001	<.0001		0.003	<.0001	0.016	0.001	ns	0.003	0.006
tena (cN/tex)	-0.215	0.624	0.543	0.717	0.107	0.481	1	0.764	-0.641	-0.519	-0.047	-0.614	-0.437
	ns	<.0001	0.001	<.0001	ns	0.003		<.0001	<.0001	0.001	ns	<.0001	0.008
work (cN.cm)	-0.242	0.159	0.438	0.746	0.690	0.925	0.764	1	-0.528	-0.579	-0.148	-0.600	-0.507
	ns	ns	0.008	<.0001	<.0001	<.0001	<.0001		0.001	0.000	ns	0.000	0.002
tn50 (Km)	0.059	-0.311	-0.390	-0.468	-0.162	-0.399	-0.641	-0.528	1	0.771	0.144	0.461	0.679
	ns	0.065	0.019	0.004	ns	0.016	<.0001	0.001		<.0001	ns	0.005	<.0001
tk50 (Km)	-0.134	-0.085	-0.483	-0.484	-0.394	-0.520	-0.519	-0.579	0.771	1	0.486	0.652	0.952
	ns	ns	0.003	0.003	0.017	0.001	0.001	0.000	<.0001		0.003	<.0001	<.0001
np200 (Km)	0.052	0.271	0.038	0.145	-0.240	-0.148	-0.047	-0.148	0.144	0.486	1	0.349	0.727
	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.003		0.037	<.0001
hair	-0.104	-0.397	-0.587	-0.615	-0.385	-0.484	-0.614	-0.600	0.461	0.652	0.349	1	0.629
	ns	0.017	0.000	<.0001	0.020	0.003	<.0001	0.000	0.005	<.0001	0.037		<.0001
ipi	-0.073	0.013	-0.362	-0.327	-0.380	-0.454	-0.437	-0.507	0.679	0.952	0.727	0.629	1
	ns	ns	0.030	ns	0.022	0.006	0.008	0.002	<.0001	<.0001	<.0001	<.0001	

Figure 23. Correlation between fiber elongation and yarn tenacity.

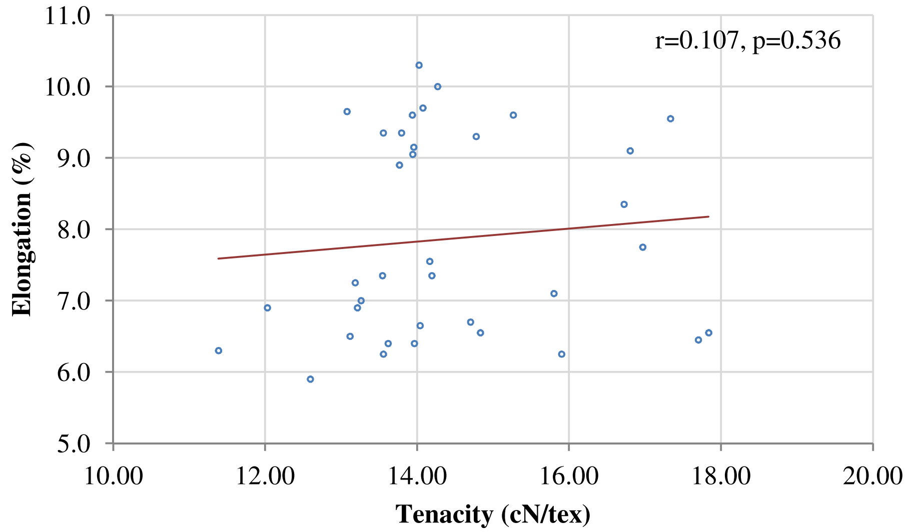


Figure 24. Correlation between fiber elongation and yarn work-to-break.

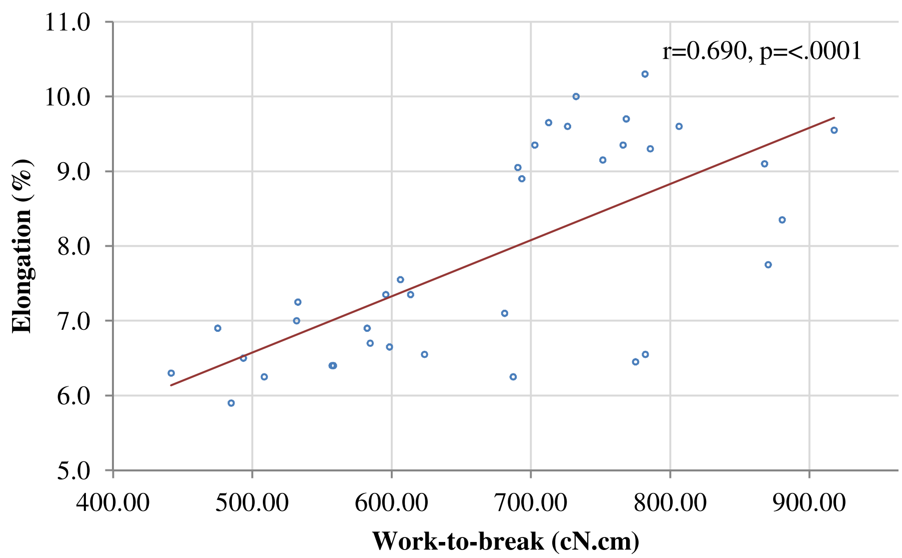


Figure 25. Correlation between fiber elongation and yarn breaking elongation.

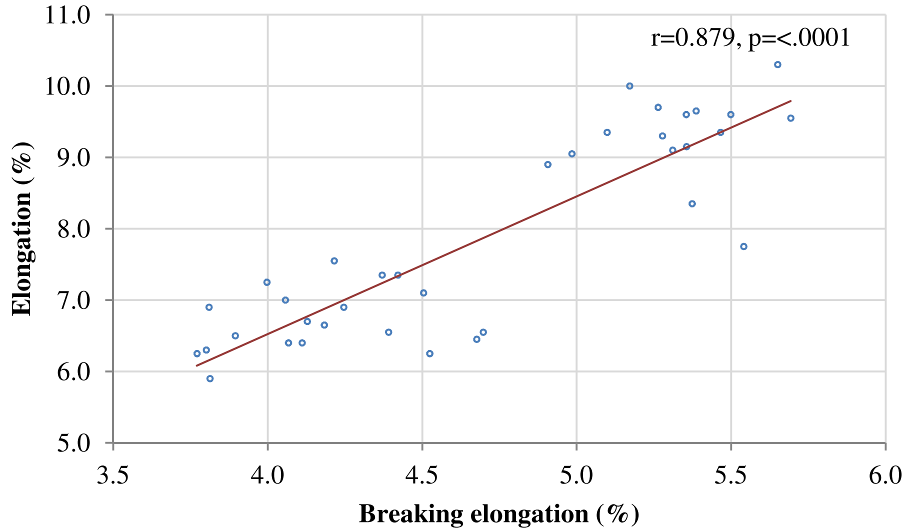


Figure 26. Correlation between fiber elongation and yarn thin places.

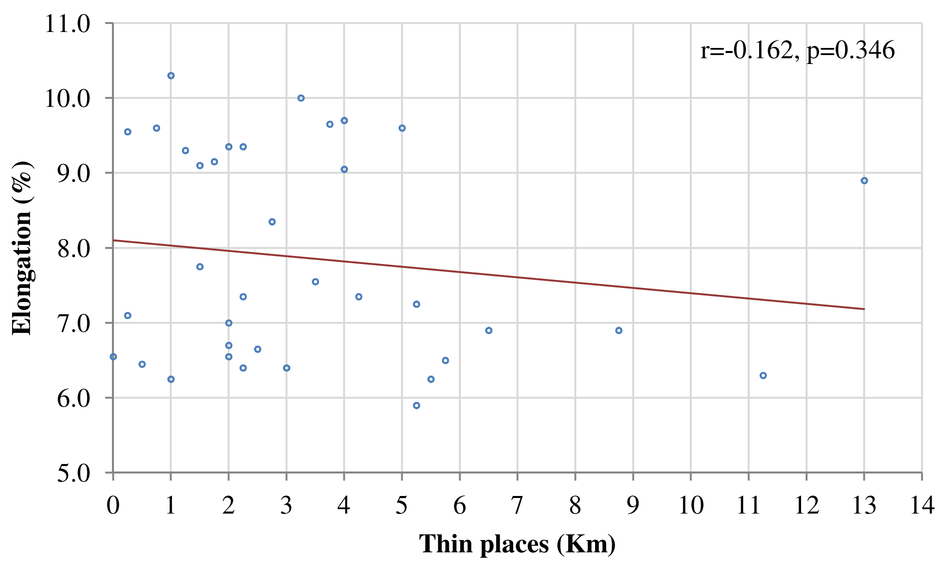


Figure 27. Correlation between fiber elongation and yarn thick places.

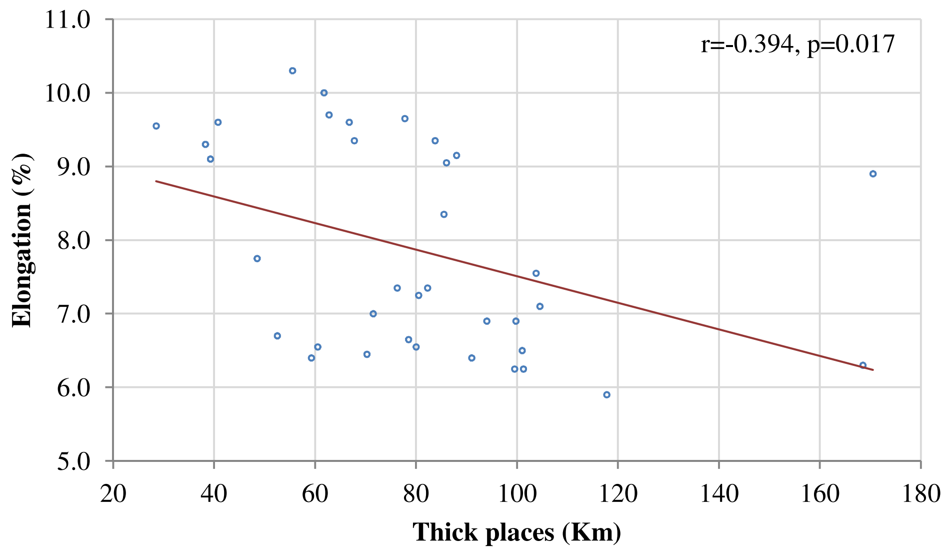


Figure 28. Correlation between fiber elongation and nep count.

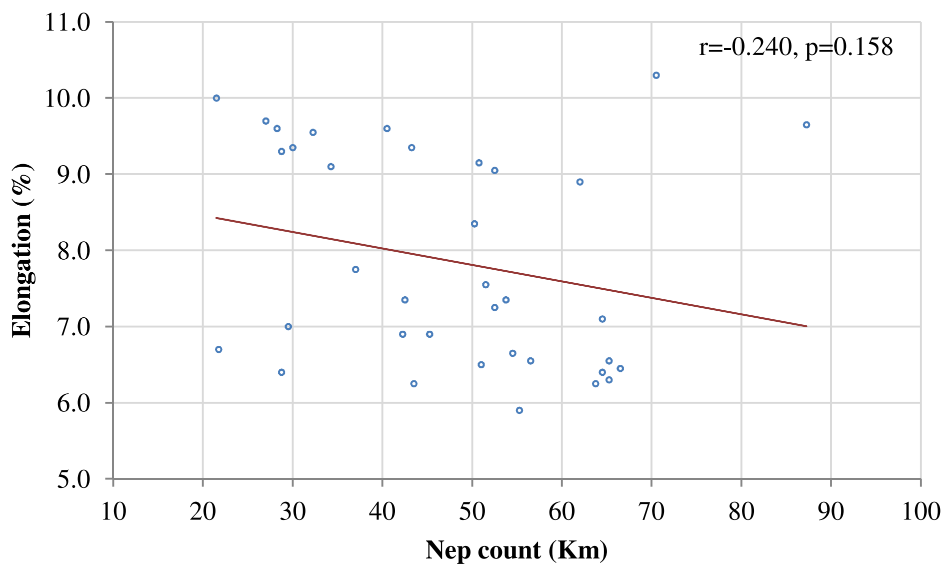


Figure 29. Correlation between fiber elongation and hairiness.

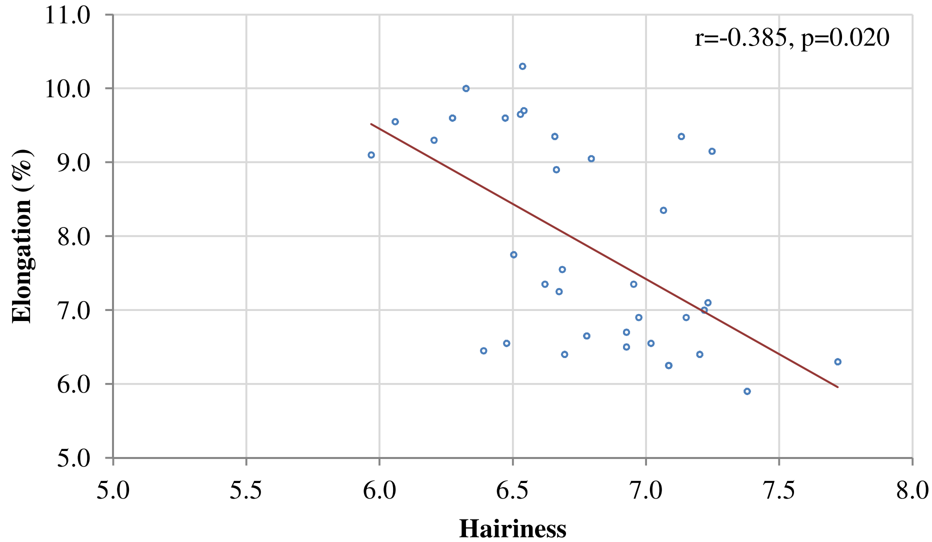


Figure 30. Correlation between fiber elongation and total number of imperfections.

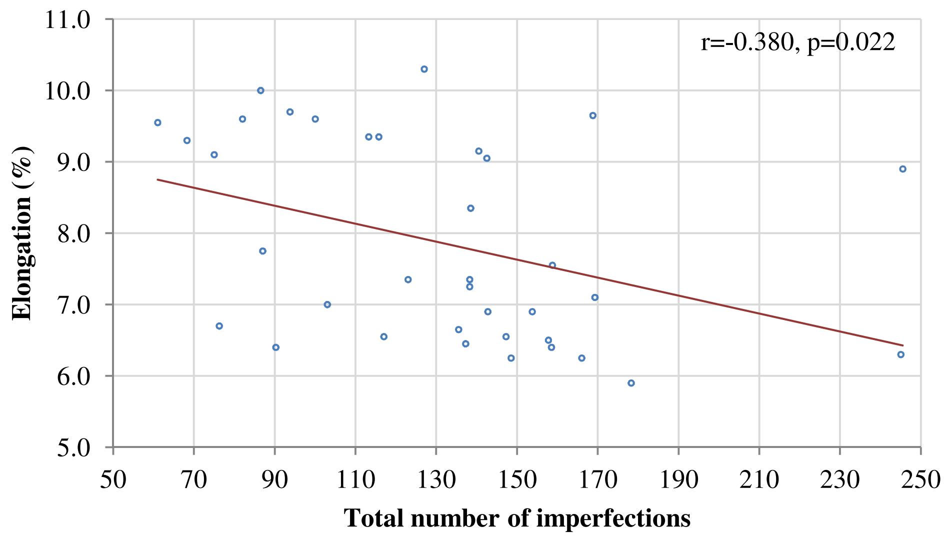


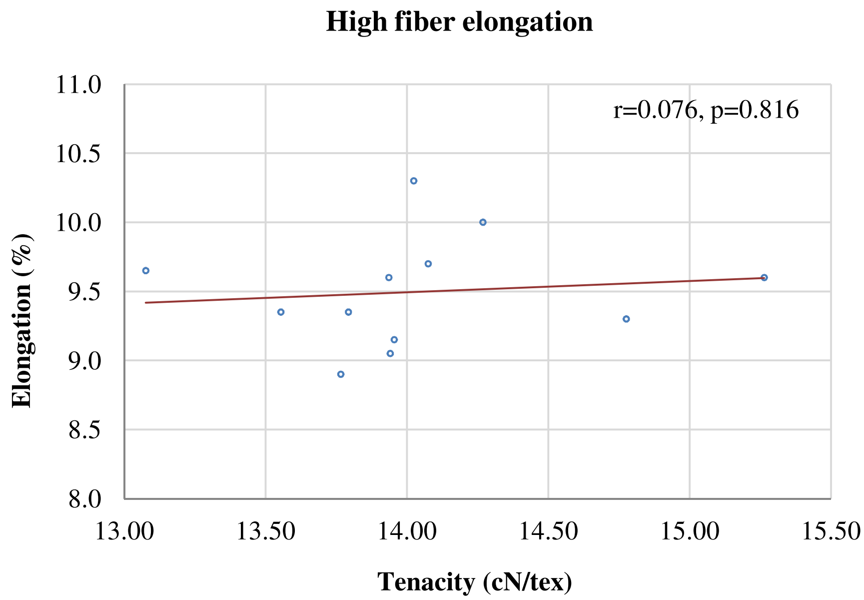
Table 37. Correlations between high fiber elongation and yarn properties.

	tena (cN/tex)	brkelo (%)	work (cN.cm)	tn50 (Km)	tk50 (Km)	np200 (Km)	hair	ipi
Elongation (%)	0.076	0.653	0.425	-0.484	-0.591	0.019	-0.403	-0.450
p-value	0.816	0.021	0.169	0.111	0.043	0.953	0.194	0.142

Table 38. Correlations between low fiber elongation and yarn properties.

	tena (cN/tex)	brkelo (%)	work (cN.cm)	tn50 (Km)	tk50 (Km)	np200 (Km)	hair	ipi
Elongation (%)	0.383	0.594	0.569	-0.272	-0.494	-0.493	-0.635	-0.563
p-value	0.219	0.041	0.053	0.392	0.102	0.103	0.026	0.056

Figure 31. Correlation between high and low elongation and yarn tenacity.



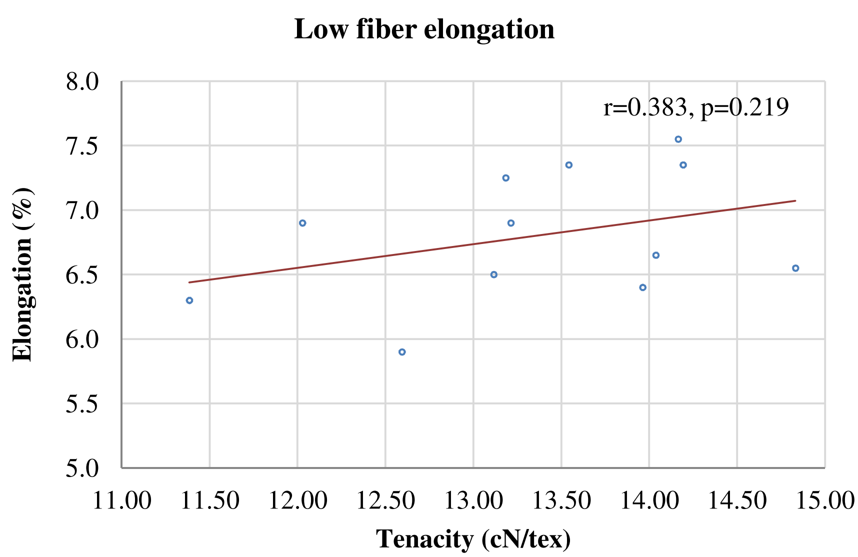
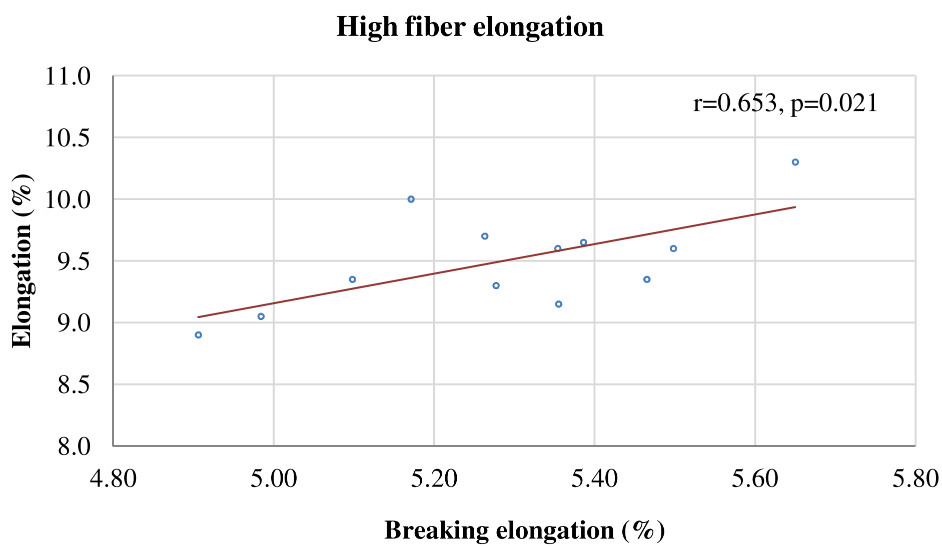


Figure 32. Correlation between high and low elongation and yarn breaking elongation.



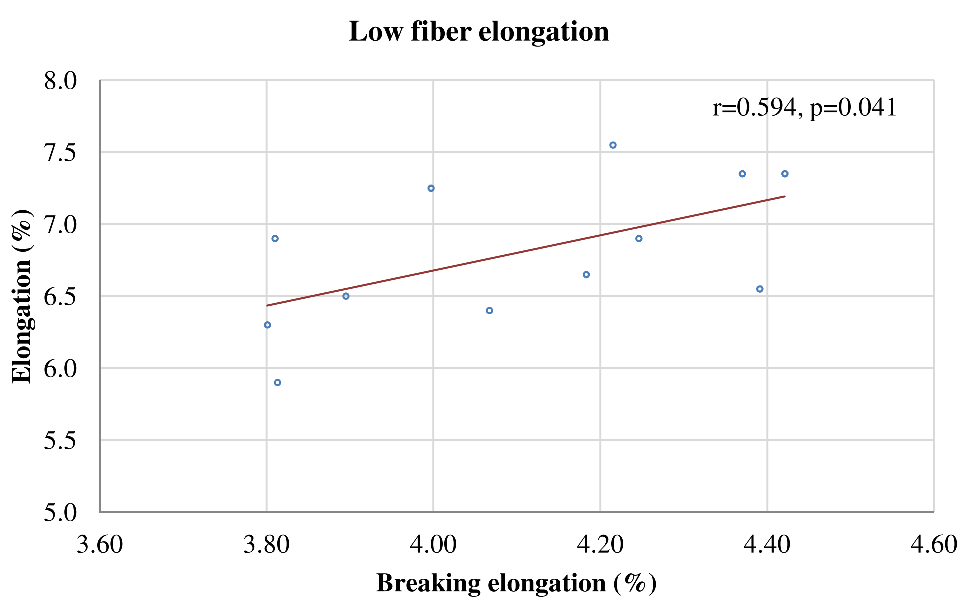
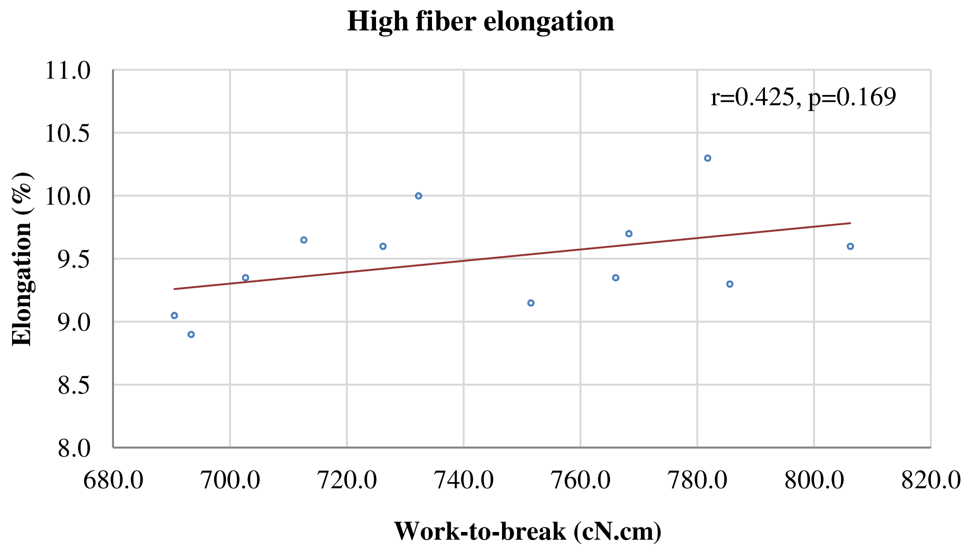


Figure 33. Correlation between high and low elongation and yarn work-to-break.



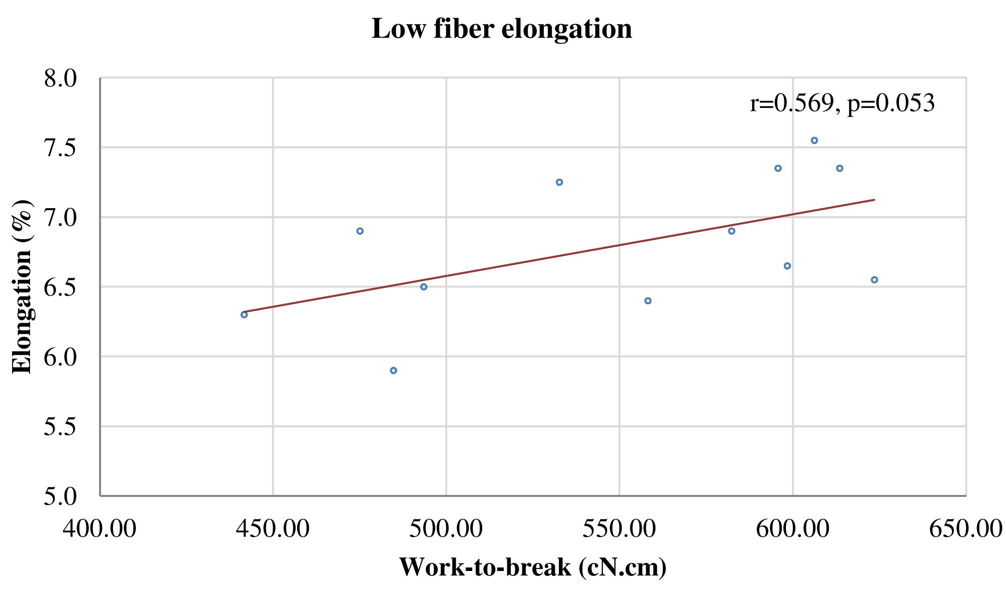
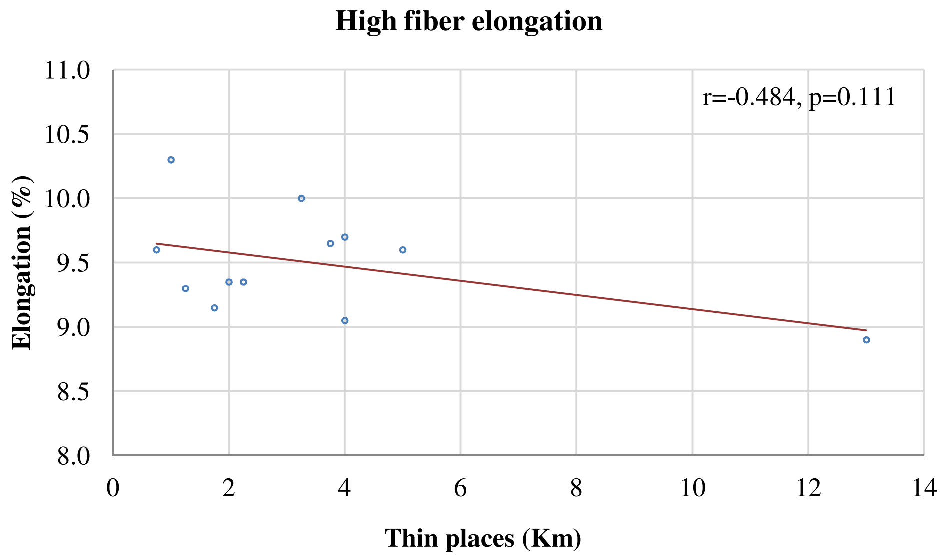


Figure 34. Correlation between high and low fiber elongation and yarn thin places.



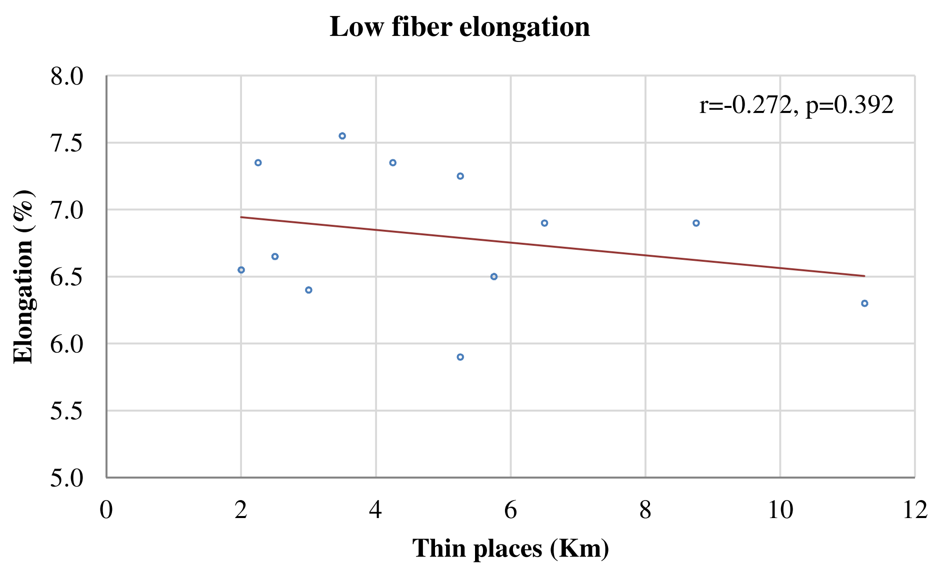
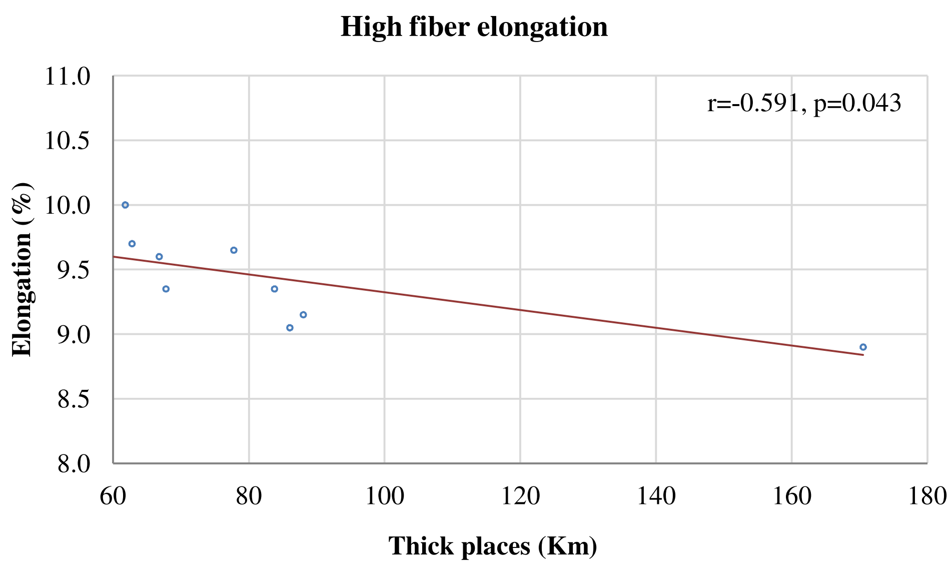


Figure 35. Correlation between high and low fiber elongation and yarn thick places.



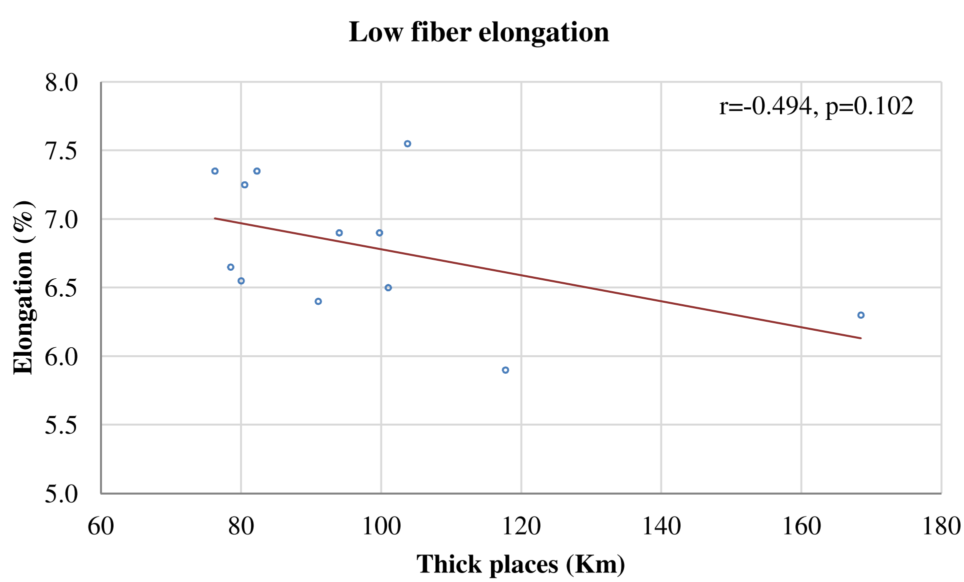
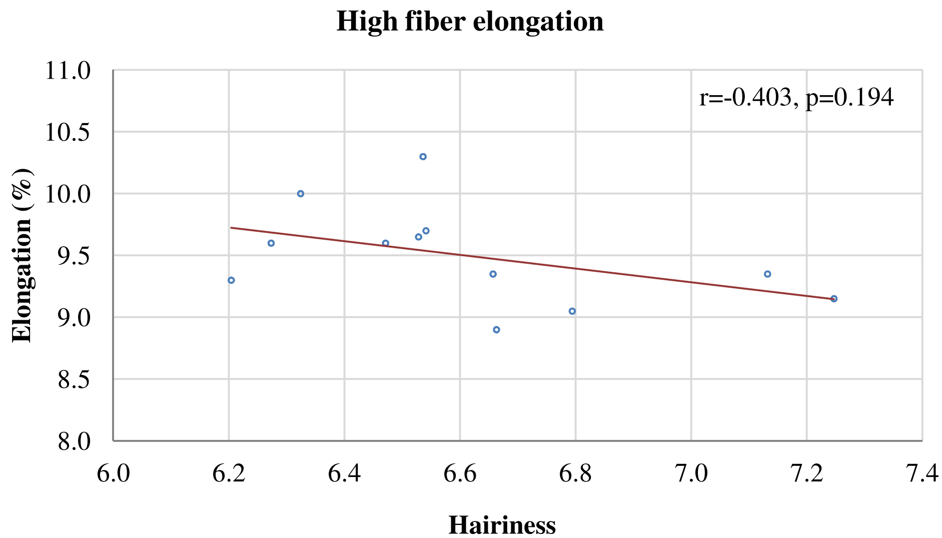


Figure 36. Correlation between high and low fiber elongation and yarn hairiness.



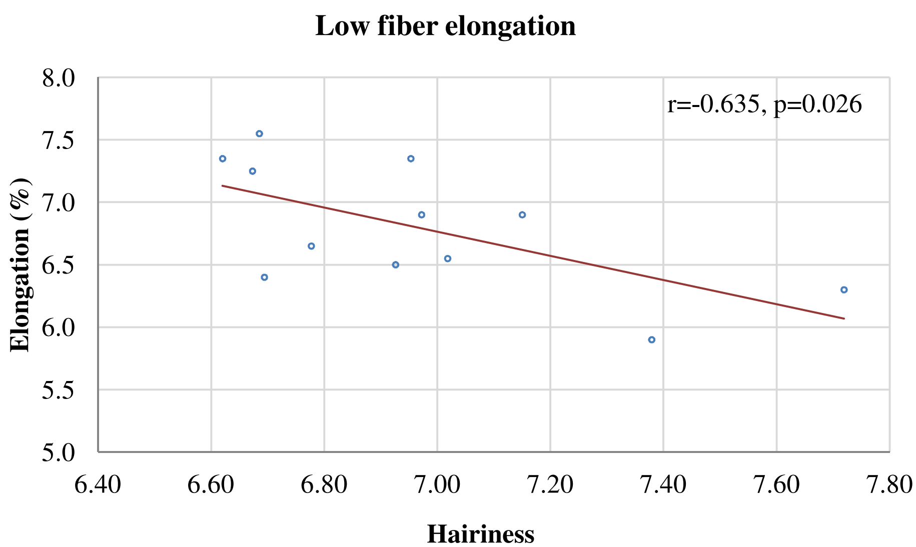
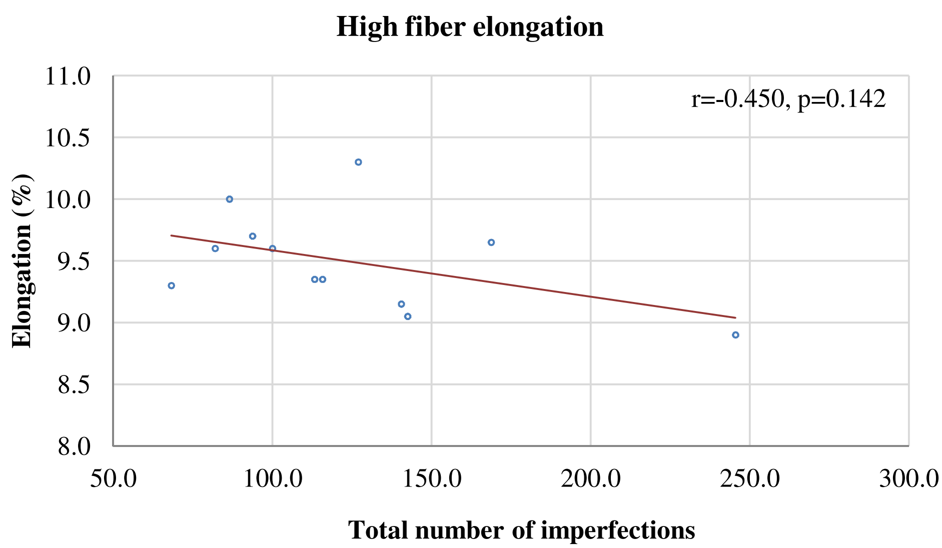


Figure 37. Correlation between high and low elongation and yarn total number of imperfections.



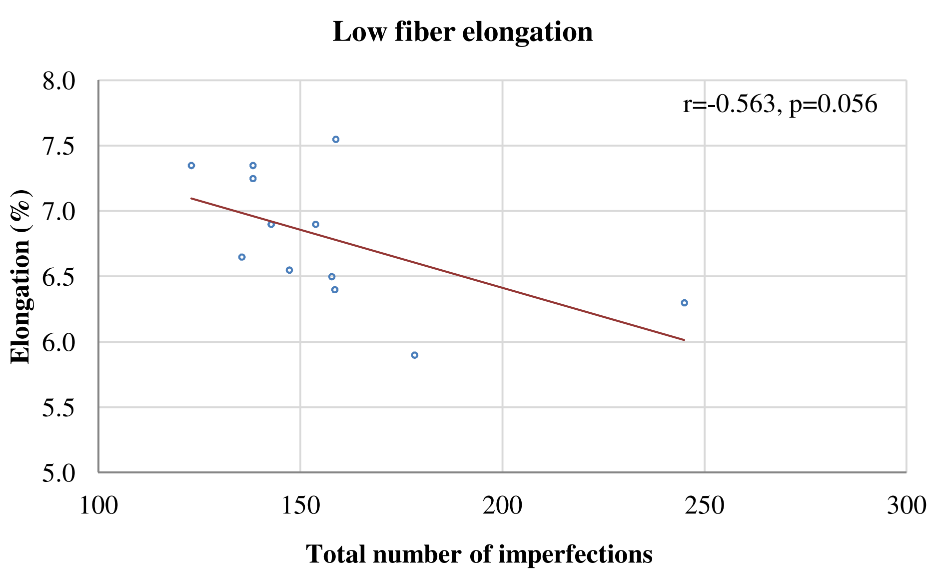
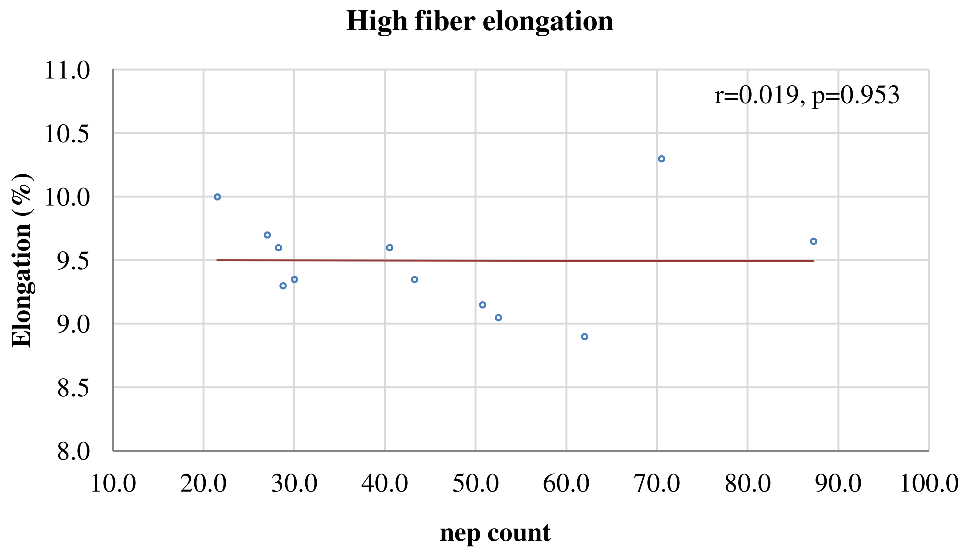
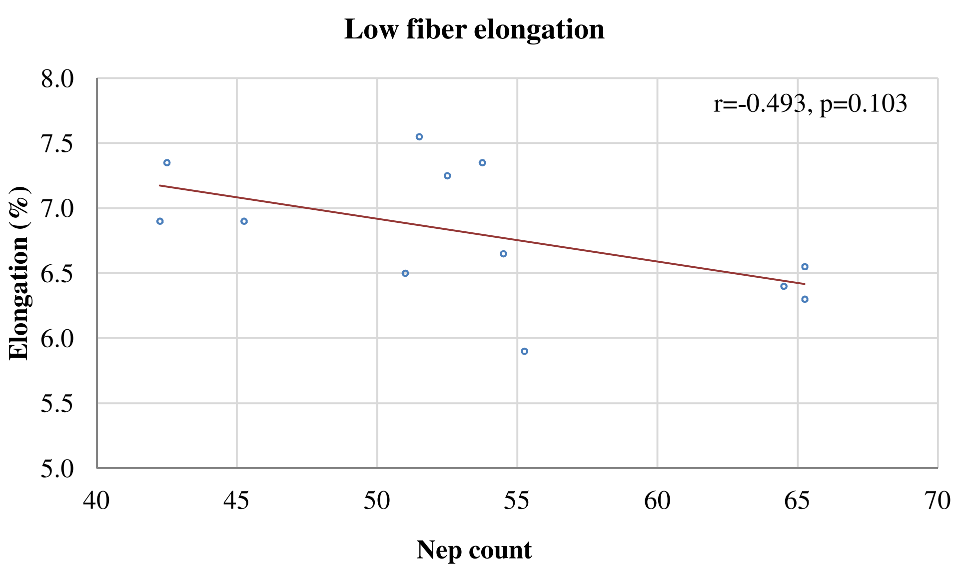


Figure 38. Correlation between high and low fiber elongation and yarn nep count.





4.5 Yield test

A yield test was planted to evaluate the productivity of the selected lines. The seed source came from the selection made in the F_4 in 2010. The test was 25 entries in total; five families selected for high and low elongation from the initial 15 families, four selections based on work-to-break and six selections based on high and low elongation from the entire population plus three checks. The test was a randomized complete block design with four replications planted initially in four locations in 2011; Halfway, Lamesa, Lubbock, TX, and the Texas Tech Quaker Avenue research farm. However, one location at Lamesa was not established, leaving the Halfway, Lubbock Texas AgriLife Research and the Texas Tech Quaker Avenue locations. A grab sample was collected from the burr cotton to calculate lint turnout and seed turnout. Lint turnout is the percentage of a seed cotton sample that is actually useable lint; and seed turn out is percent seed by weight of the stripper-harvested grab sample. These turnouts were later used to calculate plot lint weight and yield. Yield was determined as the amount of kilograms of lint harvested per hectare. The remaining lint was ginned and kept for spinning test.

Analysis of variance over locations indicate no interaction between entries and locations for yield (p-value=0.4875), lint turnout (p-value=0.1032) and seed turnout (p-value=0.2071). However, entries and locations were significantly different for yield, lint turnout and seed turnout. Means and mean separation for entries and locations are shown in table 39. Lines highlighted in blue are the lines selected for spinning tests. Table 40 shows the entries ranking for yield over locations. Because of the different levels of yield and gin turnouts observed in each location, analyses of variance were carried out in each location. Table 41, 42, and 43 show the means and mean separation for Halfway, Lubbock and the Texas Tech Quaker Avenue research farm respectively. In Halfway the low elongation selection from family 10b had the highest yield (885.99 kg/ha), while the selection for high elongation from the entire population had the lowest yield (623.45 kg/ha). In the Lubbock location, the check Deltapine DP491 (PVP200100159) had the highest yield (871.70 kg/ha) and a low elongation selection from family 6 from the entire population had the lowest yield (456.17 kg/ha). In the Texas Tech Quaker Avenue research farm, the check Deltapine DP491 had the highest yield (525.94kg/ha), and a high selection for elongation from family 3 has the lowest yield (309.9 kg/ha). Deltapine DP491 had the highest yield across locations. In Halfway, family 10b low selection had the highest yield. In addition, due to a severe drought in 2011, the Texas Tech Quaker Avenue research farm did not produce enough lint, and therefore yield was lower for all entries in comparison to the Halfway and Lubbock locations. Overall, the selections for high elongation had lower yield than the selections for low elongation and the checks. It is important to note that the low elongation parent, ‘ FM958’, is a high yielding cultivar on the high plains of Texas, and the negative association with high value of fiber elongation could be an artifact of this particular data set. On the other hand, a 50 boll sample was taken before harvest in order to obtain data on picked lint %, pulled lint %, boll size, lint index, and seed per boll (Table 44, 45 and 46). Notes on maturity, storm resistance, plant height and visual assessment are included.

Table 39. Analysis of variance for yield and gin turnouts over locations sorted by high to low yield.

Location/ entry	Family	Reason	Designation	Yield (kg/ha)		Lturn[a] (%)		Sdturn[b] (%)	
Halfway				759.02	a	26.29	a	46.02	b
Lubbock				623.02	b	26.21	a	47.38	a
Tech Farm				393.39	c	22.19	b	46.91	a
24		Check	DP 491	745.89	a	28.38	a	43.63	fg
10	10b	Low	09-2-1016-4	686.86	ab	26.89	ab	46.02	bcdefg
11	7	Low	09-2-1111-5	664.72	ab	25.78	bcde	47.95	abcd
14	11	HxH	09-2-1005-2	653.43	abc	25.30	bcdef	48.31	abc
15	13	HxL	09-2-409-1	648.66	abc	24.90	defg	47.38	abcde
16	15	LxH	09-2-816-2	647.73	abcd	24.71	defgh	46.48	abcdef
7	3	High	09-2-807-1	629.24	abcde	23.73	fghi	43.48	g
25		Check	FM 989	615.41	abcde	27.01	ab	44.50	efg
23		Check	FM 958	614.95	abcde	26.88	abc	45.14	defg
13	11	LxL	09-2-207-2	608.22	abcde	25.15	bcdef	43.78	fg
3	10a	Low	09-2-510-1	605.32	abcde	26.27	bcd	47.13	abcde
2	14	High	09-2-212-5	603.18	abcde	24.64	defghi	48.97	ab
9	10b	High	09-2-1015-5	596.08	bcde	25.53	bcdef	48.33	abc
6	9	High	09-2-708-4	582.73	bcde	23.03	ghi	47.34	abcde
1	14	Low	09-2-211-5	579.82	bcde	24.76	defgh	46.78	abcde
21	10	-E	09-2-804-1	575.44	bcde	22.98	hi	47.70	abcd
12	7	High	09-2-1112-1	566.37	bcde	25.00	cdef	46.46	abcdef
8	3	Low	09-2-808-5	552.18	bcde	26.41	bcd	48.83	ab
20	6	-E	09-2-612-2	545.64	bcde	25.52	bcdef	47.45	abcde
22	4	+E	09-2-912-1	542.84	bcde	24.02	efghi	46.33	abcdefg
17	7	-E	09-2-411-1	539.67	bcde	23.69	fghi	47.91	abcd
4	10a	High	09-2-511-3	507.53	cde	24.88	defg	49.34	a
18	8	+E	09-2-415-2	497.92	cde	22.98	hi	46.85	abcde
19	9	+E	09-2-708-1	493.15	e	21.18	j	45.32	cdefg
5	9	Low	09-2-707-6	492.22	e	22.79	i	47.88	abcd

*Means with the same letter indicate no significant difference at the 0.05 level
*Locations include Halfway, Lubbock and the Texas Tech Research Farm
[a]Lint Turnout
[b]Seed Turnout

Table 40. Entries ranking for yield over locations.

Entry	Family	Reason	Designation	Avg. yield (kg/ha)	Lubbock	Tech Farm	Halfway
24		Check	DP 491	746.45	1	1	5
10	10b	Low	09-2-1016-4	687.05	6	6	1
11	7	Low	09-2-1111-5	664.63	4	15	4
14	3	HxH	09-2-1005-2	653.43	11	3	3
15	13	HxL	09-2-409-1	648.94	2	11	16
16	15	LxH	09-2-816-2	647.82	5	4	17
7	3	High	09-2-807-1	629.89	3	25	10
25		Check	FM 989	615.32	13	8	7
23		Check	FM 958	615.32	10	9	11
13	11	LxL	09-2-207-2	608.59	18	2	9
3	10a	Low	09-2-510-1	605.23	16	18	2
2	14	High	09-2-212-5	602.99	7	16	15
9	10b	High	09-2-1015-5	596.27	15	17	6
6	9	High	09-2-708-4	582.82	14	13	13
1	14	Low	09-2-211-5	579.45	17	10	14
21	10	-E	09-2-804-1	576.09	8	24	18
12	7	High	09-2-1112-1	566.00	9	22	19
8	3	Low	09-2-808-5	552.55	24	12	8
20	6	-E	09-2-612-2	545.83	25	7	12
22	4	+E	09-2-912-1	542.47	22	5	20
17	7	-E	09-2-411-1	540.23	12	20	24
4	10a	High	09-2-511-3	507.72	19	23	21
18	8	+E	09-2-415-2	497.64	20	21	22
19	9	+E	09-2-708-1	493.15	21	14	25
5	9	Low	09-2-707-6	492.03	23	19	23

*Locations include Halfway, Lubbock and the Texas Tech Research Farm

Table 41. Analysis of variance for yield and gin turnouts in Halfway, TX, sorted by high to low yield.

Entry	Family	Reason	Designation	Yield (kg/ha)		Ltturn[a] (%)		Sdturn[b] (%)	
10	10b	Low	09-2-1016-4	885.99	a	28.40	ab	45.80	def
3	10a	Low	09-2-510-1	862.74	ab	28.00	abc	46.30	cdef
14	3	HxH	09-2-1005-2	855.17	abc	28.60	ab	46.30	cdef
11	7	Low	09-2-1111-5	848.17	abc	27.00	abcd	45.90	def
24		Check	DP 491	840.04	abcd	28.60	ab	42.50	g
9	10b	High	09-2-1015-5	818.46	abcde	27.10	abcd	47.10	cde
25		Check	FM 989	809.78	abcde	28.70	a	45.10	ef
8	3	Low	09-2-808-5	806.42	abcdef	28.70	a	48.40	abc
13	11	LxL	09-2-207-2	800.81	abcdef	26.60	bcdef	42.20	g
7	3	High	09-2-807-1	791.85	abcdef	26.90	abcde	46.50	cde
23		Check	FM 958	779.80	abcdefg	27.20	abcd	44.10	fg
20	6	-E	09-2-612-2	762.42	abcdefgh	26.90	abcde	45.90	def
6	9	High	09-2-708-4	757.38	abcdefghi	24.50	ghi	46.30	cdef
1	14	Low	09-2-211-5	754.58	abcdefghi	26.70	abcde	45.40	ef
2	14	High	09-2-212-5	739.17	bcdefghi	26.90	abcde	50.50	a
15	13	HxL	09-2-409-1	738.33	bcdefghu	24.90	efghi	45.20	ef
16	15	LxH	09-2-816-2	720.11	cdefghi	25.40	defgh	45.50	ef
21	10	-E	09-2-804-1	719.55	cdefghi	23.90	hi	46.30	cdef
12	7	High	09-2-1112-1	707.79	defghi	26.30	cdefg	44.90	ef
22	4	+E	09-2-912-1	707.51	defghi	24.60	fghi	45.10	ef
4	10a	High	09-2-511-3	688.17	efghi	25.30	defgh	50.00	ab
18	8	+E	09-2-415-2	671.64	fghi	26.50	defgh	46.10	def
5	9	Low	09-2-707-6	654.55	ghi	24.00	hi	47.80	bcd
17	7	-E	09-2-411-1	631.57	hi	24.00	hi	46.80	cde
19	9	+E	09-2-708-1	623.45	i	22.90	i	44.90	ef

*Means with the same letter indicate no significant difference at the 0.05 level
[a]Lint Turnout
[b]Seed Turnout

Table 42. Analysis of variance for yield and gin turnouts in Lubbock, TX, sorted by high to low yield.

Entry	Family	Reason	Designation	Yield (kg/ha)		Ltturn[a] (%)		Sdturn[b] (%)	
24		Check	DP 491	871.70	a	30.8	a	45	hij
15	13	HxL	09-2-409-1	812.86	ab	27.8	bcd	49.5	a
7	3	High	09-2-807-1	785.96	abc	27.3	bcde	47.9	abcd
11	7	Low	09-2-1111-5	768.59	abcd	27.4	bcde	48.8	abc
16	15	LxH	09-2-816-2	758.78	abcd	26.3	cdef	46.5	efghi
10	10b	Low	09-2-1016-4	740.29	abcd	28.0	bc	45.9	efghi
2	14	High	09-2-212-5	696.86	abcd	25.2	efgh	49.4	a
21	10	-E	09-2-804-1	690.97	abcd	25.0	fgh	49.6	a
12	7	High	09-2-1112-1	669.40	abcd	26.8	bcdef	47.1	bcdefg
23		Check	FM 958	652.87	abcd	28.8	ab	45.8	fghi
14	3	HxH	09-2-1005-2	641.66	abcd	25.2	efgh	48.7	abc
17	7	-E	09-2-411-1	635.77	abcd	25.6	defg	48.9	ab
25		Check	FM 989	618.96	abcd	28.2	bc	45.3	ghij
6	9	High	09-2-708-4	600.47	abcd	23.5	ghi	47	bcdef
9	10b	High	09-2-1015-5	598.23	abcd	27.7	bcd	48.7	abc
3	10a	Low	09-2-510-1	586.18	abcd	27.3	bcde	46.8	defgh
1	14	Low	09-2-211-5	580.85	abcd	25.7	defg	47	cdefg
13	11	LxL	09-2-207-2	547.79	bcd	26.2	cdef	43.8	j
4	10a	High	09-2-511-3	516.69	bcd	25.7	defg	49.2	a
18	8	+E	09-2-415-2	490.07	cd	23.0	hi	46.8	defgh
19	9	+E	09-2-708-1	467.09	cd	22.3	i	448	ij
22	4	+E	09-2-912-1	466.81	cd	24.8	fgh	46.7	defgh
5	9	Low	09-2-707-6	460.93	d	23.2	hi	48.5	abcd
8	3	Low	09-2-808-5	459.53	d	27.0	bcdef	49.2	a
20	6	-E	09-2-612-2	456.17	d	26.5	cdef	47.8	abcd

*Means with the same letter indicate no significant difference at the 0.05 level
[a]Lint Turnout
[b]Seed Turnout

Table 43. Analysis of variance for yield and gin turnouts in Texas Tech Quaker Avenue research farm, sorted by high to low yield.

Entry	Family	Reason	Designation	Yield (kg/ha)		Ltturn[a] (%)		Sdturn[b] (%)	
24		Check	DP 491	525.94	a	25.7	a	43.4	a
13	11	LxL	09-2-207-2	476.06	ab	22.7	abc	45.3	a
16	15	LxH	09-2-816-2	464.29	abc	22.5	abc	47.5	a
14	3	HxH	09-2-1005-2	463.45	abc	22.1	abc	50	a
22	4	+E	09-2-912-1	454.20	abcd	22.7	abc	47.2	a
10	10b	Low	09-2-1016-4	434.31	abcd	24.3	ab	46.4	a
20	6	-E	09-2-612-2	418.34	abcd	23.2	abc	48.7	a
25		Check	FM 989	417.50	abcd	24.2	ab	43.1	a
23		Check	FM 958	412.17	abcd	24.7	ab	45.6	a
1	14	Low	09-2-211-5	404.05	abcd	21.9	bcd	48	a
15	13	HxL	09-2-409-1	394.80	abcd	22	abcd	47.5	a
8	3	Low	09-2-808-5	390.60	abcd	23.6	abc	49	a
6	9	High	09-2-708-4	390.32	abcd	21.1	bcd	48.6	a
19	9	+E	09-2-708-1	388.92	abcd	18.3	de	46.3	a
11	7	Low	09-2-1111-5	377.43	bcd	22.9	abc	49.2	a
2	14	High	09-2-212-5	373.51	bcd	21.9	bcd	47.1	a
9	10b	High	09-2-1015-5	371.27	bcd	21.8	bcd	49.2	a
3	10a	Low	09-2-510-1	367.06	bcd	23.5	abc	48.3	a
5	9	Low	09-2-707-6	361.18	bcd	21.3	bcd	47.4	a
17	7	-E	09-2-411-1	351.65	bcd	21.5	bcd	48.1	a
18	8	+E	09-2-415-2	332.04	bcd	20.4	cde	47.7	a
12	7	High	09-2-1112-1	321.95	cd	22	abcd	47.4	a
4	10a	High	09-2-511-3	317.75	d	23.7	abc	48.8	a
21	10	-E	09-2-804-1	315.79	d	20.1	cde	47.2	a
7	3	High	09-2-807-1	309.90	d	17.1	e	36.1	b

*Means with the same letter indicate no significant difference at the 0.05 level
[a]Lint Turnout
[b]Seed Turnout

Table 44. Production data and field notes for Halfway, TX.

Entry	Family	Reason	Designation	Picked[a] (%)	Pulled[b] (%)	Blsz[c]	Maturity[d]	SR[e]	Height[f] (mm)	VA[g]
1	14	Low	09-2-211-5	37.3	26.5	5.1	50	6	685.8	6
2	14	High	09-2-212-5	33.7	26.2	4.5	40	6	787.4	5
3	10a	Low	09-2-510-1	37.9	28.5	4.8	53	6	685.8	6
4	10a	High	09-2-511-3	33.4	25.6	4.8	58	5	711.2	6
5	9	Low	09-2-707-6	33.2	24.3	5.3	43	6	762.0	6
6	9	High	09-2-708-4	35.8	26.0	4.5	45	5	762.0	6
7	3	High	09-2-807-1	36.9	26.9	4.7	64	5	736.6	7
8	3	Low	09-2-808-5	36.0	28.3	4.7	59	6	736.6	7
9	10b	High	09-2-1015-5	36.7	27.1	4.7	49	5	736.6	5
10	10b	Low	09-2-1016-4	36.4	25.9	4.3	40	5	762.0	5
11	7	Low	09-2-1111-5	37.0	27.9	4.9	40	5	736.6	6
12	7	High	09-2-1112-1	37.9	27.7	4.4	50	5	711.2	5
13	11	LxL	09-2-207-2	38.6	27.3	4.4	49	6	685.8	6
14	3	HxH	09-2-1005-2	35.1	26.9	4.4	68	6	711.2	7
15	13	HxL	09-2-409-1	35.2	26.6	4.7	44	5	812.8	4
16	15	LxH	09-2-816-2	36.5	26.9	4.0	53	5	736.6	6
17	7	-E	09-2-411-1	35.6	25.7	5.1	40	5	787.4	6
18	8	+E	09-2-415-2	37.0	27.2	4.5	41	4	736.6	5
19	9	+E	09-2-708-1	35.6	24.3	3.9	55	5	736.6	6
20	6	-E	09-2-612-2	38.1	29.7	4.8	50	6	736.6	6
21	10	-E	09-2-804-1	33.9	24.4	4.9	45	5	736.6	5
22	4	+E	09-2-912-1	36.8	26.8	4.4	40	5	685.8	4
23		Check	FM 958	37.7	28.5	5.1	49	5	711.2	6
24		Check	DP 491	38.1	28.6	4.5	40	5	762.0	4
25		Check	FM 989	37.6	27.0	4.6	36	4	762.0	4

[a]Pick Lint percent
[b]Pulled Lint percent
[c]Boll size
[d]Crop maturity
[e]Storm resistance, 1-very loose boll type to 9-very tight boll type
[f]Plant height
[g]Visual assessment, 1-non acceptable to 9-very attractive

Table 45. Production data and field notes for Lubbock, TX.

Entry	Family	Reason	Designation	Picked[a] (%)	Pulled[b] (%)	Blsz[c]	Maturity[d]	SR[e]	Height[f] (mm)	VA[g]
1	14	Low	09-2-211-5	32.5	22.1	5.1	74	6	24	6
2	14	High	09-2-212-5	32.3	24.4	5.1	71	5	26	4
3	10a	Low	09-2-510-1	34.4	25.5	5.1	78	5	25	7
4	10a	High	09-2-511-3	33.0	23.7	5.1	76	5	25	6
5	9	Low	09-2-707-6	31.3	21.8	5.2	66	5	28	6
6	9	High	09-2-708-4	32.9	23.8	5.0	70	5	27	5
7	3	High	09-2-807-1	34.0	24.8	5.4	79	6	25	6
8	3	Low	09-2-808-5	32.6	24.2	4.7	76	6	25	6
9	10b	High	09-2-1015-5	35.3	25.8	5.3	75	5	26	6
10	10b	Low	09-2-1016-4	34.1	24.7	5.3	71	5	27	6
11	7	Low	09-2-1111-5	35.4	25.6	5.4	79	5	26	6
12	7	High	09-2-1112-1	33.9	22.9	4.8	75	5	23	6
13	11	LxL	09-2-207-2	34.6	24.2	4.9	74	5	25	6
14	3	HxH	09-2-1005-2	31.1	24.6	4.5	78	5	26	5
15	13	HxL	09-2-409-1	31.7	23.4	4.7	70	5	29	4
16	15	LxH	09-2-816-2	31.7	21.4	4.8	73	6	26	6
17	7	-E	09-2-411-1	32.0	23.0	5.1	71	6	29	5
18	8	+E	09-2-415-2	35.2	23.7	4.5	73	5	27	6
19	9	+E	09-2-708-1	31.2	20.7	4.4	75	5	26	5
20	6	-E	09-2-612-2	34.2	24.9	5.1	74	5	25	5
21	10	-E	09-2-804-1	31.6	22.7	5.4	70	6	25	5
22		+E	09-2-912-1	35.2	25.5	4.9	70	5	25	5
23		Check	FM 958	35.9	26.8	5.2	79	6	25	7
24		Check	DP 491	36.3	25.0	5.4	54	5	26	4
25		Check	FM 989	36.0	23.8	5.5	71	5	26	5

[a]Pick Lint percent
[b]Pulled Lint percent
[c]Boll size
[d]Crop maturity
[e]Storm resistance, 1-very loose boll type to 9-very tight boll type
[f]Plant height
[g]Visual assessment, 1-non acceptable to 9-very attractive

Table 46. Production data and field notes for Texas Tech Research farm.

Entry	Family	Reason	Designation	Picked[a] (%)	Pulled[b] (%)	Blsz[c]	Maturity[d]	SR[e]	Height[f] (mm)	VA[g]
1	14	Low	09-2-211-5	31.7	22.3	4.4	65	6	18	5
2	14	High	09-2-212-5	26.6	19.3	3.5	51	5	22	5
3	10a	Low	09-2-510-1	31.8	23.3	3.8	71	6	18	6
4	10a	High	09-2-511-3	27.8	21.6	3.9	74	5	17	6
5	9	Low	09-2-707-6	26.2	18.2	3.8	63	5	23	5
6	9	High	09-2-708-4	31.0	22.6	4.1	53	5	22	5
7	3	High	09-2-807-1	31.6	22.6	3.6	75	5	19	6
8	3	Low	09-2-808-5	33.3	25.0	3.4	75	5	21	6
9	10b	High	09-2-1015-5	31.3	23.0	3.8	84	5	19	5
10	10b	Low	09-2-1016-4	31.8	22.4	3.8	73	6	21	6
11	7	Low	09-2-1111-5	30.6	23.5	4.1	78	5	20	6
12	7	High	09-2-1112-1	27.1	18.8	3.2	75	5	19	6
13	11	LxL	09-2-207-2	31.0	21.5	3.9	74	6	19	6
14	3	HxH	09-2-1005-2	28.0	20.9	3.7	76	4	19	6
15	13	HxL	09-2-409-1	31.4	22.8	3.5	71	5	23	5
16	15	LxH	09-2-816-2	32.5	22.4	3.1	81	6	20	6
17	7	-E	09-2-411-1	32.1	22.6	3.6	75	5	19	5
18	8	+E	09-2-415-2	30.6	20.1	3.4	73	5	19	5
19	9	+E	09-2-708-1	27.1	18.5	3.7	71	4	20	4
20	6	-E	09-2-612-2	29.4	21.1	3.8	68	5	20	6
21	10	-E	09-2-804-1	27.7	20.2	4.1	79	5	19	5
22	4	+E	09-2-912-1	29.9	21.0	3.7	74	6	20	5
23		Check	FM 958	31.2	22.5	3.7	70	5	19	6
24		Check	DP 491	31.1	23.2	3.8	78	4	21	5
25		Check	FM 989	31.9	23.6	3.9	58	5	21	6

[a]Pick Lint percent
[b]Pulled Lint percent
[c]Boll size
[d]Crop maturity
[e]Storm resistance, 1-very loose boll type to 9-very tight boll type
[f]Plant height
[g]Visual assessment, 1-non acceptable to 9-very attractive

Pearson correlations were carried out among HVI fiber properties, yield, lint turnout and seed turnout among entries in Lubbock and Halfway from the lines selected for spinning tests. The Texas Tech Quaker Avenue research farm was excluded because it did not produce enough fiber for spinning tests (Table 47). Fiber elongation was negatively correlated with yield (r=-0.193, p=0.105) (Figure 39) and lint turnout (r=-0.199, p=0.094) (Figure 40), and positively correlated with seed turnout (r=0.163, p=0.174) (Figure 41). In addition, strength was negatively correlated with yield (r=-0.285, p=0.015), lint turnout (r=-0.383, p=0.001) and positively correlated with seed turnout (r=0.233, p=0.049). Therefore, selecting for fiber tensile properties had a negative impact on yield in this study Nevertheless, according to Coyle and Smith, (1997); Green and Culp, (1990); and Schwartz and Smith, (2008), it could be possible to break this negative correlation by using complex crosses for the simultaneous improvement of fiber quality parameters and lint yield. Furthermore, the use of targeted selection could be used for the improvement of yield components in early generations that correlate with yield in later generations, along with fiber quality parameters. Nevertheless, the improvement of fiber elongation is the first step towards the improvement of cotton varieties able to withstand the stresses during fiber processing.

Table 47. Pearson correlation among HVI fiber properties, yield and yield components.

	Ltturn (%)	Sdturn (%)	Yield (lb/acre)	Mic	Length (mm)	Uniformity (%)	Strength (g/tex)	Elongation (%)
Ltturn (%)	1	0.090	0.473	0.332	-0.172	-0.102	-0.383	-0.199
		ns	<.0001	0.004	ns	ns	0.001	ns
Sdturn (%)	0.090	1	0.061	0.252	0.138	0.286	0.233	0.163
	ns		ns	0.033	ns	0.015	0.049	ns
Yield (lb/acre)	0.473	0.061	1	-0.185	0.013	-0.115	-0.285	-0.193
	<.0001	ns		ns	ns	ns	0.015	ns
Micronaire	0.332	0.252	-0.185	1	0.167	0.528	0.204	-0.048
	0.004	0.033	ns		ns	<.0001	ns	ns
Length (mm)	-0.172	0.138	0.013	0.167	1	0.554	0.498	-0.399
	ns	ns	ns	ns		<.0001	<.0001	0.001
Uniformity (%)	-0.102	0.286	-0.115	0.528	0.554	1	0.756	0.109
	ns	0.015	ns	<.0001	<.0001		<.0001	ns
Strength (g/tex)	-0.383	0.233	-0.285	0.204	0.498	0.756	1	0.319
	0.001	0.049	0.015	ns	<.0001	<.0001		0.006
Elongation (%)	-0.199	0.163	-0.193	-0.048	-0.399	0.109	0.319	1
	ns	ns	ns	ns	0.001	ns	0.006	

Figure 39. Correlation between fiber elongation and yield.

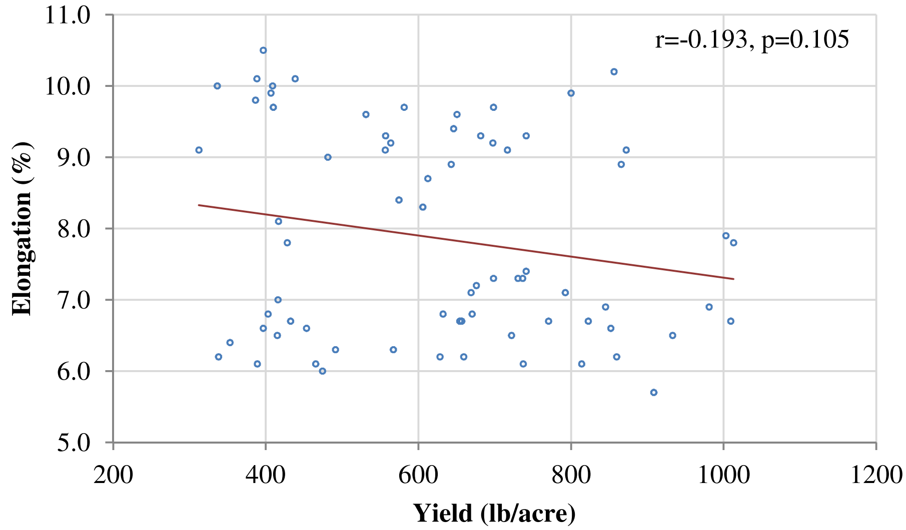


Figure 40. Correlation between fiber elongation and lint turnout.

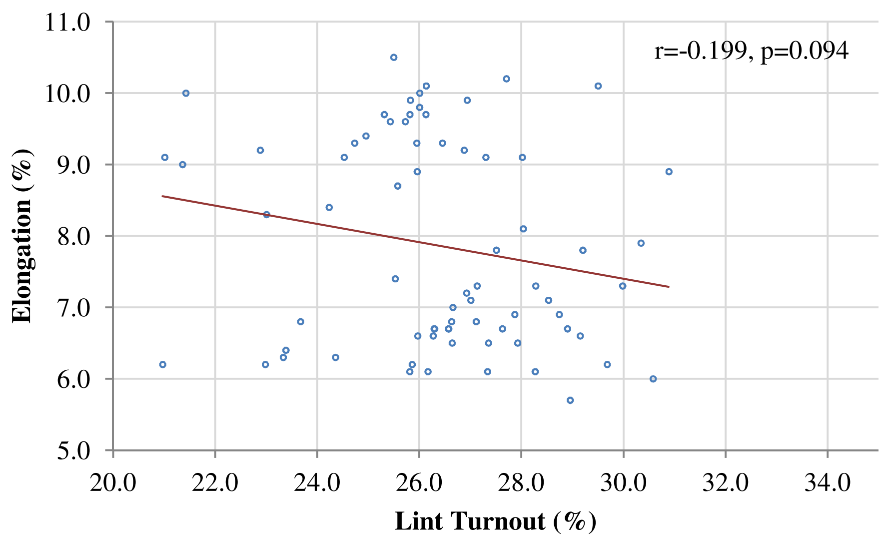
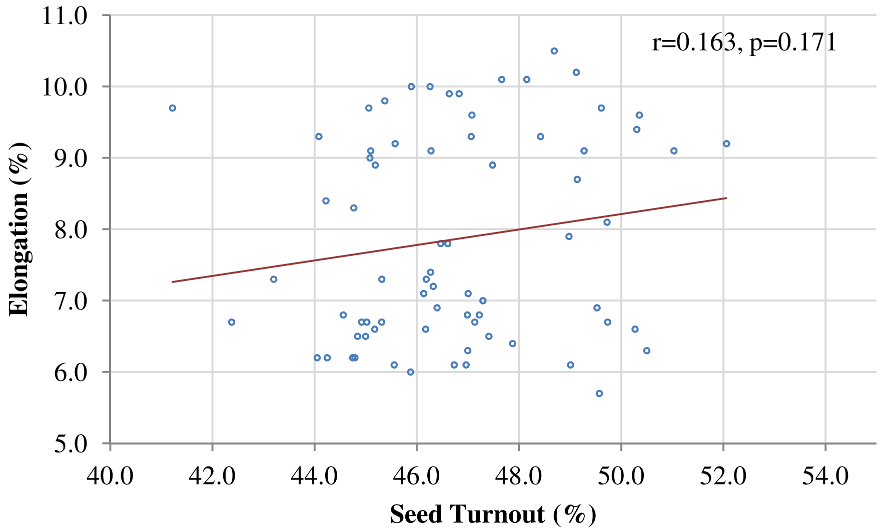


Figure 41. Correlation between fiber elongation and seed turnout.



4.6 Heritability

In addition to develop lines for fiber spinning tests with improved, or differentiated, fiber elongation, this project was amended to evaluate and determine the heritability of fiber elongation. Little is known about the genetics and the heritability of fiber elongation; because its improvement has been ignored due to its perceived negative correlation with fiber strength (Backe, 1996) and the measurement of the elongation trait had been unreliable. However, knowledge on the heritability of fiber elongation will help breeders understand the genetic action that controls this trait and if it would benefit from selection. Heritability estimates help breeders elucidate the best strategy for selection and to predict gains from selection (Holland et al., 2003; Nyquist, 1991). Also, since the phenotype is due the combined action of the genotypic and environmental effects, cotton breeders would be interested in determining in which proportion the trait is due to the genotype and in which proportion to the environment. Moreover, heritability gives a numeric estimate of the response from selection, which depends on the population under study, the environment, and the evaluation process.

Fifteen populations developed in 2007 by crossing high quality breeding lines with high elongation and good fiber characteristics to 'FM 958' (PVP 200100208), intended for the improvement of fiber elongation and spinning evaluation, were used to obtained estimates of heritability. Heritability was estimated using the variance component method and parent off-spring regression using F_3, F_4, and F_5 generation in 2011 and 2012 in three locations. To obtain unbiased estimates of heritability, samples were taken at random. Therefore, no selection pressure was applied to the populations under study. Bulked F_2 IPSs constituted the F_3 generation. The F_4 generation was constituted of F_3 boll samples, and the F_5 was obtained by increasing the F_4 generation in a winter nursery in Mexico. Additionally, realized heritability was estimated for the low and high divergent selections in the F_2, F_3 and F_4 for fiber elongation to obtained estimates of gain from selection.

4.6.1 Heritability by variance components

Broad sense heritability estimates were obtained by the components of variance method. Estimates were obtained in the F_3, F_4 and F_5 generation. The test was planted as an RCBD with three replications in three locations during two years (2011 and 2012); Halfway, Lubbock and Pecos, TX. Tables 48, 49 and 50 shows the means of the HVI fiber properties for Halfway, Lubbock and Pecos, TX, respectively during the two years, 2011 and 2012. Boll samples were harvested and ginned on a tabletop ten-saw gin (Dennis manufacturing, Athens, TX). The lint was tested on HVI with two micronaire and ten length/strength per sample. In addition, three cottons standards for elongation (produced by the Fiber and Biopolymer Research Institute, FBRI) were tested several times per day to ensure that there was no instrument drift or malfunction. Shapiro-Wilk and Kolmogorov-Smirnov tests suggested that the data had normal distribution. Following test for normality, Levene's test was carried out to test for homogeneity of variance across locations. The F-test for locations indicated homogeneity of variances for fiber elongation. Data were analyzed using PROC MIXED (SAS 9.2) for each location and for combined analysis over locations and years.

Heritability was estimated by entry mean basis over locations and years using equation 1 (Holland et al., 2003). No inbred was assumed because there was not family structure in the generations under study. Bulked F_2 IPSs constituted the F_3 generation. The F_4 generation was constituted of F_3 boll samples, and the F_5 was obtained by increasing the F_4 generation in a winter nursery in Mexico. Family 8 was missing in the F_5 generation; therefore it was excluded from the analysis in every generation.

Equation 1. Broad sense Heritability by entry mean basis over years and locations

$$H^2 = \frac{Vgenotype}{Vphenotype} = \frac{Vgenotype}{Vg + \frac{Vgl}{l} + \frac{Vgy}{y} + \frac{Vgyl}{ly} + \frac{Ve}{lyr}}$$

Where: Vp= progeny variance component
Vgl= genotype by location variance component
Vgy= genotype by year variance component
Vgyl= genotype by year by location variance component
Ve= environmental variance component
l= number of location
y= number of years
r= number of replications
e= number of locations or environments

Table 48. HVI fiber properties means for heritability study in Halfway, TX, 2011 and 2012.

Family	Generation	Micronaire	Length (mm)	Uniformity (%)	Strength (g/tex)	Elongation (%)
1	F_3	4.4	29.6	83.8	34.3	7.9
2	F_3	4.2	29.7	84.7	36.3	7.7
3	F_3	4.7	29.3	85.3	34.6	8.8
4	F_3	4.3	29.2	84.6	35.7	7.8
5	F_3	4.4	29.3	84.6	33.7	8.6
6	F_3	4.7	29.0	85.3	36.4	7.9
7	F_3	4.4	28.8	84.5	34.0	8.5
9	F_3	4.5	28.4	84.6	34.6	8.8
10	F_3	3.9	29.5	84.7	34.0	7.8
11	F_3	4.3	28.7	84.3	33.1	8.3
12	F_3	4.5	28.8	85.0	35.3	8.0
13	F_3	4.5	29.0	84.6	34.6	8.5
14	F_3	4.5	28.1	84.2	32.8	7.9
15	F_3	4.8	27.8	84.0	33.7	8.6
1	F_4	4.2	29.5	84.6	35.0	7.8
2	F_4	4.2	30.0	85.5	34.8	8.4
3	F_4	4.9	29.0	84.9	34.4	8.4
4	F_4	4.2	28.9	84.6	35.0	7.9
5	F_4	4.5	28.3	84.7	34.2	8.3
6	F_4	4.5	29.0	85.1	34.4	7.9
7	F_4	4.5	29.2	85.3	34.8	8.4
9	F_4	4.5	28.5	84.3	34.3	8.7
10	F_4	4.2	29.1	84.2	33.8	7.9
11	F_4	4.2	28.7	84.3	34.4	8.1
12	F_4	4.5	29.1	84.5	34.9	8.0
13	F_4	4.2	29.0	84.6	33.7	8.6
14	F_4	4.4	28.0	84.1	32.9	8.1
15	F_4	4.5	28.0	83.4	33.0	8.6
1	F_5	4.8	28.9	84.7	34.8	8.1
2	F_5	4.5	28.8	84.3	34.4	7.9
3	F_5	4.6	29.3	85.7	36.0	8.4
4	F_5	4.4	29.6	85.2	35.7	8.0
5	F_5	4.5	28.0	84.5	34.0	7.9
6	F_5	4.6	29.4	85.3	34.7	8.1
7	F_5	4.6	28.8	84.8	33.7	8.0
9	F_5	4.4	28.3	84.6	35.4	8.2
10	F_5	4.2	29.5	85.4	36.9	8.5
11	F_5	4.4	29.1	84.5	34.1	8.2
12	F_5	4.7	28.8	84.6	35.5	8.0
13	F_5	4.3	29.2	85.1	36.3	8.0
14	F_5	4.2	29.4	84.0	34.8	7.3
15	F_5	4.6	28.7	84.9	35.3	8.2

Table 49. HVI fiber properties mean for heritability study in Lubbock, TX, 2011 and 2012.

Family	Generation	Micronaire	Length (mm)	Uniformity (%)	Strength (g/tex)	Elongation (%)
1	F_3	4.5	29.9	85.2	35.6	8.3
2	F_3	4.5	30.7	85.2	35.9	8.6
3	F_3	5.0	28.3	83.9	33.2	9.2
4	F_3	4.4	29.9	85.1	37.0	8.7
5	F_3	4.6	28.5	84.7	34.5	9.1
6	F_3	4.8	29.3	85.3	36.1	8.3
7	F_3	4.7	29.5	85.0	34.5	9.1
9	F_3	4.6	28.8	85.1	34.7	8.4
10	F_3	4.6	29.4	84.6	35.7	9.0
11	F_3	4.3	29.9	85.1	35.5	8.6
12	F_3	4.7	29.8	85.3	36.4	8.3
13	F_3	4.7	29.4	84.9	35.8	9.2
14	F_3	4.8	28.2	83.7	31.8	8.5
15	F_3	5.0	27.9	84.3	33.9	8.8
1	F_4	4.6	29.5	84.4	36.0	8.2
2	F_4	4.5	30.0	84.5	34.4	8.4
3	F_4	4.9	29.2	85.0	35.4	8.9
4	F_4	4.7	29.0	84.5	35.1	8.5
5	F_4	4.8	29.0	84.8	34.1	9.0
6	F_4	4.7	29.5	85.6	36.4	8.3
7	F_4	4.9	29.3	84.8	34.7	9.4
9	F_4	4.6	28.3	84.3	35.5	8.5
10	F_4	4.5	28.7	84.4	35.6	8.9
11	F_4	4.1	28.9	83.9	35.8	9.1
12	F_4	4.8	28.9	83.4	34.2	8.5
13	F_4	4.7	28.9	84.4	35.3	8.8
14	F_4	4.7	28.5	83.8	32.3	8.6
15	F_4	4.8	28.1	83.7	32.8	8.8
1	F_5	4.5	29.9	85.0	36.9	8.0
2	F_5	4.8	28.8	84.9	33.9	9.2
3	F_5	4.6	30.1	85.6	36.3	8.9
4	F_5	4.5	29.5	84.9	35.0	9.1
5	F_5	4.9	28.4	84.7	34.3	8.8
6	F_5	4.8	29.7	85.5	36.3	8.1
7	F_5	5.0	29.6	85.5	35.0	8.9
9	F_5	4.6	28.9	85.0	35.8	8.8
10	F_5	4.5	29.9	85.8	38.7	8.5

Table 49. Continued.

Family	Generation	Micronaire	Length (mm)	Uniformity (%)	Strength (g/tex)	Elongation (%)
11	F_5	4.5	29.7	84.7	34.6	8.4
12	F_5	4.8	29.5	85.1	35.3	8.7
13	F_5	4.7	29.4	85.1	33.5	9.4
14	F_5	4.6	29.0	84.3	34.2	8.5
15	F_5	4.8	28.6	84.6	33.4	9.3

Table 50. HVI fiber properties means for heritability study in Pecos, TX, 2011 and 2012.

Family	Generation	Micronaire	Length (mm)	Uniformity (%)	Strength (g/tex)	Elongation (%)
1	F_3	5.0	29.3	84.6	34.7	6.4
2	F_3	4.7	29.7	83.7	34.8	6.6
3	F_3	5.1	28.7	84.4	33.8	7.3
4	F_3	4.9	29.2	84.4	34.1	6.6
5	F_3	4.9	29.0	84.9	34.1	7.5
6	F_3	5.1	29.0	84.8	35.0	7.1
7	F_3	5.0	29.2	84.5	33.3	8.2
9	F_3	5.0	28.2	84.1	33.4	7.7
10	F_3	4.9	29.4	84.3	36.2	6.9
11	F_3	4.8	29.1	84.4	34.0	7.2
12	F_3	5.0	28.8	84.3	34.6	6.8
13	F_3	5.0	28.5	83.9	34.8	7.3
14	F_3	5.1	28.3	83.9	32.0	6.8
15	F_3	4.8	28.4	84.0	33.3	7.6
1	F_4	4.8	29.2	84.4	35.8	7.1
2	F_4	4.8	29.4	84.4	34.5	6.9
3	F_4	5.2	28.9	84.5	34.9	7.2
4	F_4	5.1	28.8	84.4	34.1	6.6
5	F_4	4.9	29.0	84.7	34.7	7.1
6	F_4	5.1	29.4	84.9	35.5	7.0
7	F_4	5.0	28.8	84.1	34.2	7.2
9	F_4	4.9	28.1	83.6	33.9	7.6
10	F_4	4.9	29.5	84.4	35.8	6.8
11	F_4	4.9	28.7	83.9	34.2	7.1
12	F_4	5.1	29.3	84.5	35.1	6.6
13	F_4	5.0	28.9	84.2	33.8	7.2
14	F_4	4.9	27.9	83.8	32.7	7.0
15	F_4	5.1	28.4	83.8	32.8	7.1
1	F_5	5.0	28.3	83.6	32.3	6.9
2	F_5	4.8	28.5	84.1	33.5	7.4
3	F_5	5.0	29.3	85.1	34.5	7.2
4	F_5	5.0	28.6	84.5	34.1	7.0
5	F_5	5.1	28.4	84.2	33.5	7.1
6	F_5	5.3	28.1	84.5	32.5	7.2
7	F_5	4.9	29.1	84.1	34.7	7.1
9	F_5	5.0	28.0	84.6	34.6	7.5
10	F_5	4.7	28.9	84.2	34.2	7.2

Table 50. Continued.

Family	Generation	Micronaire	Length (mm)	Uniformity (%)	Strength (g/tex)	Elongation (%)
11	F_5	4.7	29.4	84.4	34.2	7.1
12	F_5	5.0	29.6	84.6	35.1	6.9
13	F_5	5.0	29.2	84.0	34.2	6.8
14	F_5	4.7	28.4	83.3	31.1	6.4
15	F_5	5.2	28.2	84.1	34.3	7.2

Table 51 summarizes the estimates of heritability for fiber elongation, strength, micronaire, length and uniformity during the two years of the study. Heritability for fiber elongation varied between 47.9% to 69.5%; moderate values. This indicates that around 40 to 50% of the observable variance was due to non-genetic effects. Similar results were obtained for fiber strength, with estimates from 43.3 to 73.3%, and for fiber length from 73.9 to 83.2%.

Genetic variation estimated by broad sense heritability cannot be partitioned into its components (additive and dominant), and therefore, information on the type of variation cannot be obtained. Nevertheless, broad sense heritability provides information needed to determine the amount of genetic variability in the population; although it does not provide information on the type of variation itself. Broad sense heritability denotes the importance of nature versus nurture, and estimates drop as the population moves towards inbreeding (Bernardo, 2002; Fehr, 1991; Hallauer and Miranda, 1981; Hanson, 1963; Holland et al., 2003; Nyquist, 1991). Such estimates drop, because genetic variation is reduced within the population with cycles of inbreeding (Fehr, 1991; Hanson, 1963).

Table 51. Estimate of broad sense heritability in the F_2, F_3, and F_4 generations over locations and years, 2011 and 2012.

	H^2 (%) F_3	H^2 (%) F_4	H^2 (%) F_5
Elongation (%)	**69.5**	**56.7**	**47.9**
Strength (g/tex)	73.3	78.0	43.3
Micronaire	77.8	76.5	68.5
Length (mm)	83.2	73.9	74.6
Uniformity (%)	37.7	80.6	72.1

*Locations include Lubbock, Halfway and Pecos Texas in 2011.

4.6.2 Heritability by parent off-spring regression

Heritability was estimated by the parent off-spring regression method to determine the degree of resemblance between parents and progenies. Linear correlation coefficients were calculated by regressing F_5 progeny means on F_4 parental lines, and F_4 progeny means on F_3 parental lines. F_3, F_4, and F_5 generations were grown in a RCBD in three locations, Lubbock, Halfway and Pecos, TX, in 2011and 2012. Table 48, 49 and 50 shows the means of the HVI fiber properties per location in both years. Boll samples were harvested and ginned in a tabletop ten-saw gin (Dennis manufacturing, Athens, TX). The lint was tested on HVI with two micronaire and ten length/strength per sample. In addition, three cottons standards for elongation (produced by the Fiber and Biopolymer Research Institute, FBRI) were tested several times per day to ensure that there was no instrument drift or malfunction. Shapiro-Wilk and Kolmogorov-Smirnov tests suggested that the data had normal distribution. Following test for normality, Levene's test was carried out to test for homogeneity of variance across locations. The F-test for locations indicated homogeneity of variances for fiber elongation. To estimate the value of heritability by parent off-spring regression, the data are obtained in the form of measurements of parents (or the mean of parents), and measurements from the off-spring. Then a simple linear regression is calculated. Heritability (h^2) is estimated from the linear regression coefficient (b). Linear regression coefficient was obtained using PROC REG (SAS 9.2). Table 52 shows the estimates of heritability by parent off-spring regression in the F_3 to F_4 generation, and the F_4 to F_5 generation for fiber elongation, strength, micronaire, length and uniformity. Estimates indicate that heritability was moderate to high for fiber elongation, strength, length, uniformity and micronaire. A moderate to strong relationship between generations (F_3 and F_4; F_4 and F_5) was observed and therefore resemblance transmitted from parents to off-spring. Parent off-spring regression method for estimating heritability is closely related to narrow sense heritability, where genetic effects are transmitted from one generation to the next. On the other hand, estimates were low for fiber length and uniformity, indicating a low relationship from generation to generation for these traits in this data set.

Table 52. Estimates of heritability by parent off-spring regression across locations, 2011 and 2012.

	H^2 (%) F_3-F_4	H^2 (%) F_4-F_5
Elongation (%)	66.1	62.8
p-value	<.0001	<.0001
Strength (g/tex)	56.1	59.5
p-value	<.0001	<.0001
Micronaire	56.9	52.3
p-value	<.0001	0.0003
Length (mm)	54.0	51.9
p-value	<.0001	<.0001
Uniformity (%)	73.6	82.5
p-value	<.0001	<.0001

*Locations include Lubbock, Halfway and Pecos Texas in 2011.
*Significance at 0.05 level.

4.6.3 Realized heritability

Realized heritability was estimated for low and high fiber elongation selections using equation 2 (Fehr, 1991), expressed as the difference in mean performance of high and low progeny divided by the mean of the parents in the F_2, F_3 and F_4 generations. Realized heritability is a useful indicator of the progress realized from selection, but it does not provide a valid estimate of the true heritability. Estimates were intermediate (0.44–0.55) (Table 53), indicating moderately good progress from selection. These results indicate that targeted selection was a successful method for the improvement of fiber elongation in early generations while keeping other fiber characteristics constant. Low and high selections for the F_2-F_3 are presented in table 54. Low and high selections for the F_3-F_4 are presented in table 55.

Equation 2. Realized heritability for low and high selections in the F_2 and F_3 generations.

$$H^2 = \frac{\bar{x}_{high,F3} - \bar{x}_{low,F3}}{\bar{x}_{high,F2} - \bar{x}_{low,F2}}$$

where, $\bar{x}_{high,F3}$= mean performance of F_3 progeny of F_2 plants selected in high group

$\bar{x}_{low,F3}$ = mean performance of F_3 progeny of F_2 plants in low group

$\bar{x}_{high,F2}$ = mean performance of F_2 plant in high group

$\bar{x}_{low,F2}$ = mean performance of F_2 plants in low group

Table 53. Estimates of heritability for low and high selections of fiber elongation by realized heritability.

Generation	H^2_R (fiber elongation)
$F_2 - F_3$	0.44
$F_3 - F_4$	0.55

Table 54.Low and high fiber elongation selections and lines in the F_2 and F_3.

	F_2 selections				F_3 lines			
Fam. Entry	Select. reason	Elong (%)	Select. reason	Elong (%)	Select. reason	Elong (%)	Select. reason	Elong (%)
1	H	11.8	L	8.2	H	7.5	L	5.1
1	H	10.1	L	8.9	H	6.0	L	5.4
1	H	10.1	L	8.3	H	6.9	L	6.6
1	H	9.9	L	7.7	H	6.9	L	5.7
1	H	9.6	L	8.0	H	6.5	L	5.9
2	H	10.0	L	8.3	H	6.2	L	5.7
2	H	10.4	L	8.9	H	5.9	L	5.8
2	H	10.2	L	8.2	H	6.3	L	5.3
2	H	10.2	L	8.8	H	5.9	L	6.0
2	H	9.9	L	8.4	H	7.2	L	6.6
3	H	10.0	L	8.8	H	7.3	L	6.4
3	H	10.4	L	8.2	H	6.2	L	5.0
3	H	10.5	L	8.2	H	8.1	L	5.5
3	H	10.0	L	8.4	H	7.2	L	6.4
4	H	9.3	L	7.7	H	5.5	L	5.0
4	H	10.6	L	8.1	H	5.2	L	5.3
4	H	9.6	L	8.2	H	5.8	L	5.7
4	H	9.4	L	7.8	H	5.6	L	5.0
4	H	9.4	L	8.7	H	6.6	L	6.4
4	H	9.3	L	8.8	H	6.5	L	6.3
5	H	10.2	L	8.4	H	6.5	L	5.3
5	H	10.1	L	8.4	H	6.4	L	5.7
5	H	12.8	L	8.4	H	7.6	L	5.5
5	H	10.2	L	8.1	H	6.8	L	5.5
5	H	9.5	L	8.0	H	6.7	L	5.7
6	H	11.0	L	8.0	H	6.9	L	5.7
6	H	9.8	L	8.3	H	6.2	L	5.5
6	H	9.6	L	8.3	H	5.7	L	5.5
6	H	9.8	L	7.5	H	6.2	L	5.9
7	H	10.5	L	8.2	H	6.8	L	5.7
7	H	9.0	L	7.9	H	6.2	L	6.0
7	H	11.6	L	9.0	H	7.3	L	5.9
7	H	12.2	L	8.3	H	9.2	L	6.4
8	H	10.2	L	8.1	H	6.3	L	5.3
8	H	10.0	L	8.3	H	6.9	L	5.6
8	H	11.1	L	8.2	H	6.4	L	5.3
8	H	11.0	L	8.9	H	6.4	L	5.8
8	H	12.0	L	9.1	H	7.8	L	6.9
8	H	9.6	L	8.2	H	6.3	L	6.0
9	H	10.4	L	8.6	H	6.9	L	6.0
9	H	10.5	L	8.6	H	6.2	L	5.5

Table 54. Continued.

	F2				F3			
Fam. Entry	Select. reason	Elong (%)	Select. reason	Elong (%)	Select. reason	Elong (%)	Select. reason	Elong (%)
9	H	11.1	L	9.1	H	7.0	L	5.9
9	H	9.5	L	8.2	H	6.5	L	6.9
10	H	10.6	L	8.2	H	6.8	L	5.1
10	H	10.5	L	7.7	H	6.2	L	5.2
10	H	11.0	L	8.3	H	7.0	L	5.2
10	H	10.6	L	8.5	H	5.8	L	4.8
10	H	10.4	L	8.2	H	6.5	L	5.0
10	H	10.7	L	8.1	H	8.2	L	6.4
11	H	9.2	L	7.5	H	5.7	L	4.6
11	H	11.4	L	7.8	H	6.7	L	4.9
11	H	10.1	L	7.4	H	6.5	L	5.5
11	H	11.8	L	9.0	H	7.3	L	6.5
11	H	10.0	L	8.2	H	7.3	L	5.9
11	H	10.0	L	8.7	H	7.0	L	6.4
12	H	10.1	L	8.3	H	6.2	L	4.8
12	H	8.4	L	9.4	H	5.5	L	5.6
12	H	10.1	L	8.0	H	5.8	L	5.1
12	H	9.7	L	8.7	H	6.8	L	6.3
12	H	10.1	L	8.3	H	6.0	L	7.6
13	H	10.0	L	7.2	H	6.8	L	5.5
13	H	10.5	L	8.7	H	6.8	L	6.1
13	H	9.4	L	7.6	H	5.6	L	4.8
13	H	10.1	L	8.1	H	7.3	L	6.1
13	H	10.3	L	9.0	H	6.9	L	7.3
14	H	9.8	L	7.0	H	6.2	L	4.0
14	H	10.5	L	9.1	H	5.8	L	5.7
14	H	10.2	L	7.4	H	6.3	L	5.4
14	H	9.6	L	7.3	H	6.4	L	5.5
14	H	10.1	L	8.5	H	7.0	L	6.6
15	H	10.8	L	9.1	H	6.9	L	6.1
15	H	10.6	L	8.8	H	6.6	L	5.9
15	H	9.8	L	8.6	H	7.1	L	6.0
15	H	9.5	L	7.9	H	7.1	L	5.5
16	H	8.5	L	7.3	H	5.6	L	5.1
16	H	9.1	L	7.3	H	5.5	L	4.9
16	H	8.4	L	7.4	H	5.6	L	4.8
16	H	8.8	L	7.6	H	6.2	L	5.2

Table 55. Low and high fiber elongation selections and lines in the F_3 and F_4.

	F2				F3			
Fam. Entry	**Select reason**	**Elong (%)**	**Select reason**	**Elong (%)**	**Select reason**	**Elong (%)**	**Select reason**	**Elong (%)**
3	H	13.00	L	10.80	H	9.2	L	7.4
7	H	16.00	L	10.50	H	9.5	L	7.3
9	H	13.00	L	9.30	H	8.7	L	6.9
10a	H	13.00	L	10.30	H	10.2	L	8.0
10b	H	12.60	L	8.40	H	9.2	L	7.0
14	H	11.80	L	7.30	H	8.4	L	6.2

5. **CONCLUSIONS**

This project was intended to demonstrate that work-to-break characteristics of cotton fibers and yarns can be improved through breeding, specifically selecting for elongation. Cotton fiber is an important natural resource used for multiple purposes; widely used in industry for textile processing. With the advancement and acceleration in spinning speed and processing, the requirement of improved cotton fiber quality is of great importance to the textile industry because it directly relates to processing performance, productivity and yarn quality.

Fiber elongation , is a property of the fibers measured during the determination of bundle strength (May, 1999a). Elongation refers to the amount of elasticity of the bundle sample before breaking, tested on tensile strength instrument like the stelometer, or the HVI (High Volume Instrument). Backe (1996) studied the effects of fiber elongation on yarn and textile manufacturing. He determined that fiber bundle elongation is important for producing better yarn's quality and resistance to stresses in weaving. However, fiber elongation has never been a selection criterion during line or cultivar development, mainly because of the lack of calibration of HVI instruments and a weak negative correlation with fiber strength (Benzina et al., 2007). Nevertheless, as spinning technologies evolve and speeds in processing increases, fiber elongation might become a more important property (May, 1999a).

The primary walls of cotton fibers are formed during the fiber trichomes elongation phase, and contain less than 30 percent of cellulose, noncellulosic polymers, neutral sugars, and various proteins (Hsieh, 1999). Spirals and angles are formed during elongation of fibers before boll opens, or primary cell wall deposition, which is known to affect secondary cell wall deposition and later, fiber strength. The same mechanisms of spirals and angles might affect the degree of stretching of post-harvest fibers. However, there is a lack of understanding regarding the relationship between primary cell wall formation and fiber structure and properties (Hsieh, 1999). According to Hsieh

(1999), primary cell wall development appears to contribute two-thirds or more of the fiber strength. However, no data is reported on fiber elongation. Nonetheless, he reports that elongation is affected by the development of the fibers before boll opening. Yet, secondary cell formation (cellulose deposition and crystallization) is more directly related to tensile properties than primary cell formation (Hsieh, 1999). Nevertheless, fiber development is highly influenced by genetics and the environment, which at the same time affect fiber properties important for fiber and yarn processing. As pre-harvested fiber elongation determines the length of the fibers, likewise it is probable to have a direct impact on post-harvested fiber elongation. However, since cotton fiber elongation (post-harvest) has never been a selection criterion, studies of the relationship between fiber development and cell wall deposition to post-harvest fiber elongation has not been extensively studied. Therefore, to better understand fiber quality and the effect of fiber elongation on yarn processing and weaving, the linkages between fiber development and fiber elongation (post-harvest) should be more extensively studied.

To determine the effect of fiber elongation (post-harvest) on yarn properties, Benzina et al. (2007), produced 3 standard cottons with known values of tenacity and elongation (measured with the instron). Reference material was created that could be used to calibrate the HVI instrument. This allowed elongation levels to be held constant over an extended period of time, which is indispensable for a breeding program selecting for the measured character. The CV% for elongation were below the target value of 5% (5% is the maximum CV% allowable for the fiber testing), and no instrument drift or malfunction was observed during the testing period. Therefore, reliable fiber elongation measurements were obtained.

In addition, the elongation property of fibers has not been emphasized in breeding programs because it has shown to have inconsistent genetic contribution to fiber and yarn tenacity. Additionally there is a perceived negative correlation between fiber elongation and strength, which make breeders more skeptical to focus on this particular trait. Nevertheless, the negative correlation is weak and it does not preclude a simultaneous improvement of fiber strength and fiber elongation. The work of rupture, or combination of breaking strength and fiber elongation, is very important to spinning quality and the best way to improve it is to work on genetically improving both tenacity and elongation. By genetically improving fiber properties, breeders are contributing to productivity gains in the textile industry. The project included development of similar lines with different levels of elongation through divergent selection in a typical pedigree breeding scheme to use for spinning studies; and heritability studies to help determine if elongation can be impacted through breeding using improved measurement technology.

The results from this project demonstrate that it is possible to improve fiber elongation and to break the negative correlation between elongation and strength. Furthermore, it was demonstrated that improving fiber elongation results in the increase of uniformity index and decrease of short fiber content. Additionally, directed divergent selection was a successful methodology for the improvement of fiber elongation, and it was useful to demonstrate that higher fiber elongation has a positive effect on yarn tensile properties and processing. Preliminary results showed that in the F_2 generation there was a wide range of variation for fiber elongation; with a maximum value of 12% and minimum value of 6%. This variability in fiber elongation made possible the use of divergent selection. In the F_3 generation, an excellent diversity in fiber elongation was maintained; with a wide range of maximum values of 9% and minimum values of 4%. Therefore, it was possible to keep divergent selections. In the following generation, the F_4, it was observed that high and low levels of elongation were kept through generations of selection, still maintaining a high range of variation for fiber elongation. All selections for high fiber elongation were higher than the check cultivar.

A weak negative correlation was observed between fiber elongation and strength in early generations; -0.32 in the F_2, -0.36 in the F_3 and -0.0889 in the F_4. However, with constant targeted selection this relationship changed towards a positive relationship (0.424) for the lines selected for spinning tests. In the early generations, selection pressure was applied only to elongation attempting to keep other fiber properties constant, for the purpose of developing lines for spinning that isolate the influence of elongation specifically. However, in the final round of selections, other fiber properties were considered. Therefore, the positive correlation between fiber strength and elongation at the end, compared to negative correlation in the early generations, indicated that the two properties that constitute the work-to-break can be improved simultaneously. In addition, it was demonstrated that improving fiber elongation increases uniformity index. A positive correlation was observed between them in every generation; 0.319 in the F_2, 0.0042 in the F_3 and 0.162 in the F_4. In the selected lines for spinning test the positive correlation remained constant (0.182). Data from HVI shows a steady improvement of fiber length and strength, however, length uniformity had remained stagnant. Nevertheless, this research shows that the ability to select for improved fiber elongation has the potential to impact length uniformity indirectly. Fiber elongation was also negatively correlated with short fiber content by weight and by number. However, AFIS data was only obtained in later generation and for the lines selected for spinning. Nevertheless, the results indicated that improving fiber elongation reduces short fiber content; -0.080 in the F_4 (short fiber content by weight) and -0.111 (short fiber content by number) in the lines selected for fiber spinning.

Spinning performance and yarn quality on the selected F_4 lines suggest that improving fiber elongation improves yarn tensile properties and evenness. Lines selected for high and low elongation had better tensile properties than the check cultivar 'FM958'. For instance, fiber elongation was positively correlated to yarn tenacity (0.383), breaking elongation (0.594) and work-to-break (0.596). On the other hand, fiber elongation was negatively correlated with thin places (-0.272), thick places (-0.494), nep count (-0.493), hairiness (-0.635) and total number of imperfections (-0.563). All selections for high elongation were superior for all tensile properties compare to the low selections and the check in the analysis over locations and in each location. Furthermore, selections for high elongation were significantly different from the selections for low elongation and the check. Additionally, fiber strength was kept constant in the selection process, and the final lines used for spinning test had high levels of strength that positively correlated with fiber elongation. Therefore, fiber elongation and fiber strength can be simultaneously improved. Results from this project will lay the foundations for future efforts to breed new varieties with improved work-to-break. Including breeding lines with improved elongation and selection pressure for work-to-break characteristics in new variety development programs is important and will reduce the amount of short fiber content and increase uniformity index. The development of new varieties with improved fiber elongation will improve the quality and reputation of U. S.-grown cotton. The ultimate result will be better yarn quality and improved weaving efficiency, and particularly address current weaknesses in U. S. –grown cotton varieties, especially from the High Plains of Texas, of more short fiber content, lower uniformity ratios, and weaker yarn strength.

On the other hand, yield tests were planted to determine the productivity of the selected lines. The test was initially planted in four locations; however, one location at Lamesa was not established, and the location at the Texas Tech Research Farm did not produce enough lint due a severe drought during 2011. Nevertheless, lint was harvested in this location and yield data was analyzed along with yield data from the other two locations, Halfway and Lubbock, TX. The results from the yield test showed negative correlations between lint yield and fiber elongation (-0.193) and lint yield and fiber strength (-0.285). The analysis of variance over locations indicated that there was no interaction between entries and locations, and the check cultivar Deltapine DP491 had the highest yield (745.89 kg/ha), followed by the selection for low elongation from family 10b (686.86 kg/ha), and the selection for low elongation from family 7 (664.72 kg/ha). The selections for high elongation were in the middle to the lower range of yield. Furthermore, locations were significantly different with the Texas Tech Research Farm having the lowest value. In the analysis in each location, Halfway had the highest yield among all locations. The low selection from family 10b with a yield of 885.99kg/ha and the low selection from family 10a with 862.74kg/ha were the highest yielding in this location. In Lubbock and the Texas Tech Research Farm, the commercial check Deltapine 491 was the highest yielder with 871 kg/ha and 525.94 kg/ha in Lubbock and the Tech Farm respectively. The yield from the Texas Tech Research Farm was considerably lower due to a severe drought during 2011, and inadequate irrigation.

The negative correlations between lint yield and fiber elongation contrasted with the results from Tang et al. (1996). The authors reported positive correlations (0.26) between lint yield and elongation. However, it has been demonstrated that yield components are negatively correlated with fiber quality (Desalegn et al., 2009; Green and Culp, 1990; Smith and Coyle, 1997) in accordance with the results from this project. The low elongation parent used in all of the crosses, 'FM 958', is a high yielding cultivar on the High Plains, and the negative yield association with elongation could be an artifact of this particular data set in the Texas High Plains environment. Nevertheless, the use of more complex crosses, such three way crosses, modified backcrosses, inter-mating or recurrent selection could be used in future experiments to improve fiber quality characteristics and yield at the same time (Coyle and Smith, 1997; Green and Culp, 1990; Schwartz and Smith, 2008). Additionally, since fiber elongation has not been emphasized in breeding programs, future efforts should include the simultaneous improvement of tensile properties, fiber strength and elongation, along with improvement of yield and yield components. Lines developed in this project are being used in molecular marker studies and tools could be forthcoming that assist in introgressing improved fiber elongation in higher yielding breeding lines.

In addition to using divergent selection for fiber elongation to test the hypothesis that fiber elongation is important for spinning, this project was intended to evaluate and determine the heritability of fiber elongation. Little is known about the genetics and the heritability of fiber elongation; because its improvement has been ignored due to its perceived negative correlation with fiber strength (Backe, 1996). However, knowledge on the heritability of fiber elongation will help breeders understand the genetic action that controls this trait and if it would benefit from selection. Additionally, heritability estimates help breeders elucidate the best strategy for selection and to predict gains from selection (Holland et al., 2003; Nyquist, 1991).

Three different methodologies were used to obtain estimates of heritability; variance components, parent off-spring regression and realized heritability. Broad sense heritability was estimated from the variance component method. Genetic variation estimated by broad sense heritability cannot be partitioned into its components (additive and dominant), and therefore, information on the type of variation cannot be obtained. Nevertheless, broad sense heritability provides information needed to determine the amount of genetic variability in the population. Heritability was estimated in each generation because no family relationships could be determined. The results indicated that about 40 to 50% of the variation was due to non-genetic effects. Estimates of heritability from parent off-spring regression indicated that there is a 50 – 60% resemblance from parents to off-spring for fiber elongation. Parent off-spring regression method for estimating heritability is closely related to narrow sense heritability. Therefore, fiber elongation has a high possibility to be improved in early generations. In addition estimates of realized heritability were obtained to determine the progress realized from selection for the low and high selection for fiber elongation. Estimates were intermediate (0.44–0.55), indicating moderately good progress from selection. These results indicate that targeted selection was a successful method for the improvement of fiber elongation in early generations while keeping other fiber characteristics constant.

The results demonstrated that divergent selection for fiber elongation was successful in indicating that elongation is important for spinning. Additionally, it was verified that elongation responded to selection while keeping other fiber properties constant. Hence elongation can be improved through classical breeding techniques. Likewise fiber strength and elongation can be simultaneously improved using targeted selection. Additionally, the improvement of fiber elongation has a positive effect on yarn tensile properties. Higher fiber elongation resulted in higher yarn tenacity, work-to-break and breaking elongation, improving spinning performance and yarn quality. Therefore, improving elongation in combination with breaking strength significantly improves spinning quality of cotton compared to the check cultivars. Furthermore, it was demonstrated that improved elongation resulted in higher uniformity index and reduce short fiber content. Finally, estimates of heritability demonstrated that fiber elongation would benefit from selection.

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APPENDIX

Table A-1. HVI fiber properties for the 156 F_2 plants selected in 2008 sorted by increasing elongation.

Fiber Sample ID	Micronaire	Length (mm)	Uniformity (%)	Strength (g/tex)	Elongation (%)
JO-69	4.17	31.75	85.4	34.3	7.0
JO-216	3.91	32.25	83.0	30.2	7.2
JO-156	4.31	29.97	83.4	30.5	7.3
JO-489	4.73	29.97	83.7	31.0	7.3
JO-885	4.35	30.98	82.5	29.4	7.3
JO-261	4.73	29.46	84.2	30.3	7.4
JO-536	4.68	30.98	82.7	29.9	7.4
JO-729	4.21	30.98	82.7	29.9	7.4
JO-38	4.05	32.76	83.0	30.6	7.5
JO-946	4.93	29.97	84.8	30.6	7.5
JO-572	4.05	30.98	82.7	30.2	7.6
JO-978	4.83	30.48	83.5	30.0	7.6
JO-22	4.38	30.98	84.6	31.8	7.7
JO-389	4.24	30.73	85.5	32.1	7.7
JO-793	4.62	30.98	84.8	30.7	7.7
JO-43	4.36	29.71	83.7	30.4	7.8
JO-591	4.75	31.24	84.9	29.8	7.8
JO-294	4.05	32.51	85.9	30.9	7.9
JO-976	4.95	28.95	84.7	30.4	7.9
JO-167	4.35	31.49	84.9	30.9	8.0
JO-555	4.36	31.75	83.1	29.7	8.0
JO-796	4.32	31.75	85.2	30.3	8.0
JO-855	4.44	30.98	84.4	30.3	8.0
JO-103	4.31	29.71	84.9	31.0	8.1
JO-378	4.46	30.98	84.3	31.3	8.1
JO-625	4.18	31.49	85.5	31.0	8.1
JO-935	4.43	31.49	85.2	31.9	8.1
JO-995	3.23	30.22	83.5	30.2	8.1
JO-7	3.54	32.76	85.5	32.4	8.2
JO-202	3.65	29.97	82.5	29.2	8.2
JO-247	4.26	30.73	84.8	30.6	8.2
JO-305	4.53	29.46	84.4	33.5	8.2
JO-353	3.79	30.48	83.5	30.8	8.2
JO-478	4.07	30.98	83.3	29.8	8.2
JO-586	4.41	30.48	82.7	30.4	8.2
JO-672	4.01	34.29	85.0	32.6	8.2
JO-704	4.72	30.48	85.2	28.6	8.2
JO-818	3.63	31.75	81.2	28.5	8.2
JO-840	4.92	29.97	85.2	32.5	8.2
JO-899	4.88	29.97	84.3	31.1	8.2
JO-93	4.20	31.24	85.1	31.8	8.3
JO-105	4.35	30.73	83.8	30.7	8.3
JO-117	4.29	30.98	83.9	28.5	8.3
JO-396	3.96	30.22	83.5	30.2	8.3
JO-443	4.24	31.24	84.1	29.3	8.3

Table A-1. Continued.

Fiber Sample ID	Micronaire	Length (mm)	Uniformity (%)	Strength (g/tex)	Elongation (%)
JO-517	4.31	30.73	83.9	30.4	8.3
JO-749	4.26	29.71	84.3	32.6	8.3
JO-770	4.52	32.00	82.7	30.6	8.3
JO-1020	4.74	31.49	84.6	30.2	8.3
JO-57	4.18	30.98	85.3	29.2	8.4
JO-458	4.37	30.73	83.5	31.1	8.4
JO-501	4.03	29.97	82.5	28.9	8.4
JO-531	4.51	31.49	84.9	30.1	8.4
JO-634	4.72	29.21	84.5	31.1	8.4
JO-876	4.22	31.24	85.5	29.8	8.4
JO-922	4.26	29.71	83.8	30.7	8.4
JO-145	4.78	30.48	85.7	30.5	8.5
JO-671	4.58	29.71	83.8	29.6	8.5
JO-886	4.38	29.71	81.6	25.6	8.5
JO-192	4.57	30.48	86.0	32.1	8.6
JO-428	3.61	30.98	83.1	30.1	8.6
JO-753	4.09	28.70	83.3	30.1	8.6
JO-284	4.55	30.48	84.1	28.8	8.7
JO-772	4.82	30.73	84.8	30.8	8.7
JO-816	4.79	29.71	84.6	29.3	8.7
JO-817	3.65	31.49	83.3	30.3	8.7
JO-229	4.46	31.75	84.4	28.9	8.8
JO-321	4.33	30.73	84.9	29.9	8.8
JO-643	4.12	31.24	84.7	31.1	8.8
JO-809	4.36	31.49	85.8	32.3	8.8
JO-989	4.68	29.97	85.5	30.9	8.8
JO-121	4.75	29.21	84.2	28.4	8.9
JO-318	4.58	30.98	85.2	32.5	8.9
JO-401	4.70	28.95	85.5	29.2	8.9
JO-303	4.69	31.49	84.4	29.9	9.0
JO-609	4.54	29.46	83.6	29.1	9.0
JO-719	3.86	31.75	83.9	30.1	9.0
JO-1008	4.58	30.22	84.0	29.8	9.0
JO-137	4.51	30.98	85.2	31.2	9.1
JO-348	4.09	30.48	83.6	29.2	9.1
JO-481	4.11	29.97	83.6	29.5	9.1
JO-599	4.58	29.97	85.7	31.1	9.1
JO-678	4.75	30.73	86.2	31.4	9.1
JO-44	3.96	32.00	85.2	31.1	9.2
JO-26	4.36	32.51	85.5	31.4	9.3
JO-802	4.38	31.49	84.2	30.2	9.3
JO-449	4.40	30.48	83.4	30.3	9.4
JO-569	4.34	30.98	85.2	32.1	9.4
JO-577	4.40	31.49	85.8	29.9	9.4

Table A-1. Continued.

Fiber Sample ID	Micronaire	Length (mm)	Uniformity (%)	Strength (g/tex)	Elongation (%)
JO-803	4.44	29.46	84.8	28.6	9.4
JO-851	4.14	29.71	84.4	30.4	9.5
JO-910	4.50	29.97	84.3	29.6	9.5
JO-968	4.96	29.71	84.0	29.3	9.5
JO-527	4.26	30.98	84.0	30.9	9.6
JO-582	4.42	30.22	83.9	29.6	9.6
JO-800	4.32	31.49	85.1	29.0	9.6
JO-834	4.80	30.48	85.3	33.2	9.6
JO-883	4.17	30.98	82.9	27.6	9.6
JO-776	4.28	30.73	86.1	32.2	9.7
JO-79	4.25	30.73	82.9	28.8	9.8
JO-444	4.55	30.98	84.8	28.6	9.8
JO-763	4.87	29.21	84.7	30.7	9.8
JO-958	4.60	29.71	85.1	27.9	9.8
JO-788	4.96	30.48	84.3	30.0	9.9
JO-926	4.12	29.71	82.7	28.5	9.9
JO-110	3.91	30.73	83.7	30.0	10.0
JO-115	4.14	31.75	85.8	26.6	10.0
JO-218	3.98	30.98	85.5	31.6	10.0
JO-232	3.61	32.00	84.7	31.7	10.0
JO-828	3.89	30.98	82.8	28.9	10.0
JO-821	3.53	32.25	83.6	30.3	10.0
JO-868	4.33	29.97	84.6	30.9	10.0
JO-94	3.94	30.98	84.1	28.5	10.1
JO-269	4.58	28.70	83.8	30.1	10.1
JO-412	4.37	30.22	84.3	29.7	10.1
JO-506	4.32	30.98	85.2	27.6	10.1
JO-547	4.53	30.48	84.7	30.8	10.1
JO-741	5.09	29.21	83.8	29.4	10.1
JO-784	3.59	30.98	84.5	31.8	10.1
JO-895	3.79	29.97	83.4	27.3	10.1
JO-1005	3.99	29.71	84.1	29.0	10.1
JO-63	4.44	29.97	84.6	28.3	10.2
JO-100	4.45	29.97	83.9	30.1	10.2
JO-359	4.26	30.98	85.9	29.2	10.2
JO-630	4.17	30.98	84.2	28.3	10.2
JO-646	4.54	30.98	85.2	31.2	10.2
JO-728	4.28	29.71	85.1	28.9	10.2
JO-997	4.47	30.22	85.2	29.7	10.3
JO-124	4.26	29.46	85.0	28.9	10.4
JO-182	4.31	29.71	85.5	30.7	10.4
JO-472	4.49	30.73	85.4	28.8	10.4
JO-669	3.74	32.00	86.0	31.1	10.4
JO-15	4.50	30.48	86.3	28.0	10.5
JO-274	4.52	30.48	85.0	31.0	10.5

Table A-1. Continued..

Fiber Sample ID	Micronaire	Length (mm)	Uniformity (%)	Strength (g/tex)	Elongation (%)
JO-337	4.68	29.71	85.1	29.4	10.5
JO-387	3.83	31.49	85.2	31.2	10.5
JO-424	4.05	30.73	86.1	28.5	10.5
JO-695	4.59	29.97	84.8	27.6	10.5
JO-244	4.06	29.71	85.3	29.7	10.6
JO-324	3.94	30.22	84.0	30.8	10.6
JO-375	4.03	30.48	85.4	29.7	10.6
JO-663	4.31	30.48	85.3	33.0	10.6
JO-930	4.35	31.49	85.9	31.9	10.7
JO-129	4.45	30.22	84.6	29.0	10.8
JO-163	4.37	30.73	85.0	28.4	11.0
JO-314	4.14	32.25	86.0	30.8	11.0
JO-395	4.45	28.95	85.3	30.2	11.0
JO-315	4.75	29.21	85.7	31.9	11.1
JO-600	4.51	29.97	85.2	29.1	11.1
JO-45	4.04	29.97	86.0	28.0	11.4
JO-613	4.34	30.22	83.5	29.4	11.6
JO-194	3.64	29.71	83.5	26.5	11.8
JO-706	4.01	31.49	85.1	28.4	11.8
JO-676	4.48	31.24	85.7	31.3	12.0
JO-1022	4.28	30.98	84.0	29.2	12.2
JO-640	4.02	28.19	85.1	27.1	12.8

Table A-2. HVI fiber properties for the 156 boll samples sorted by low and high selections for fiber elongation in the F_3 generation, 2009.

Fiber Sample ID	Family	Selection	Micronaire	Length (mm)	Uniformity (%)	Strength (g/tex)	Elongation (%)
JO-11	14	L	4.44	32.77	86.9	39.0	4.0
JO-5	11	L	4.11	34.54	87.0	36.7	4.6
JO-13	12	L	4.11	32.26	84.7	37.2	4.8
JO-78	16	L	4.37	32.26	84.8	38.5	4.8
JO-82	13	L	4.11	32.00	84.3	36.3	4.8
JO-98	10	L	4.08	30.99	85.9	37.1	4.8
JO-7	11	L	4.12	30.23	84.7	38.0	4.9
JO-72	16	L	4.46	31.75	85.2	35.3	4.9
JO-4	4	L	3.80	31.50	85.6	36.9	5.0
JO-70	3	L	4.18	32.77	86.3	37.7	5.0
JO-86	4	L	3.98	31.75	85.4	37.3	5.0
JO-100	10	L	3.84	34.04	87.1	37.5	5.0
JO-26	16	L	4.38	32.51	86.6	35.4	5.1
JO-32	1	L	4.45	32.51	84.9	32.3	5.1
JO-38	10	L	4.51	33.02	86.6	35.8	5.1
JO-80	12	L	4.45	34.29	86.1	34.4	5.1
JO-58	10	L	4.47	30.99	85.1	38.3	5.2
JO-60	10	L	4.52	32.00	86.4	39.6	5.2
JO-149	16	L	4.25	30.73	84.4	35.4	5.2
JO-9	5	L	4.45	31.75	87.2	34.7	5.3
JO-16	8	L	4.36	30.99	85.5	35.2	5.3
JO-45	8	L	4.79	31.50	86.3	37.2	5.3
JO-53	2	L	3.97	33.78	85.5	38.3	5.3
JO-56	4	L	4.49	32.77	85.4	36.0	5.3
JO-61	1	L	4.68	30.99	84.5	33.1	5.4
JO-108	14	L	4.16	32.51	86.4	36.3	5.4
JO-33	13	L	4.25	32.51	86.9	33.8	5.5
JO-39	11	L	4.29	30.99	86.3	34.3	5.5
JO-64	9	L	3.53	34.54	86.0	35.4	5.5
JO-65	6	L	4.34	32.51	85.3	35.2	5.5
JO-75	6	L	4.34	32.51	84.6	33.8	5.5
JO-91	5	L	4.61	30.99	86.4	35.6	5.5
JO-93	5	L	4.28	32.26	86.7	32.8	5.5
JO-104	3	L	4.60	32.00	87.2	33.6	5.5
JO-136	14	L	3.98	32.00	86.0	35.8	5.5
JO-148	15	L	4.50	29.46	84.7	34.3	5.5
JO-17	8	L	4.67	31.50	85.3	34.9	5.6
JO-67	12	L	4.52	31.75	86.1	34.9	5.6
JO-1	7	L	4.26	33.02	87.3	38.0	5.7
JO-20	2	L	4.48	32.00	86.7	35.1	5.7
JO-28	6	L	4.27	32.51	85.3	35.2	5.7
JO-52	14	L	4.18	32.51	87.0	36.0	5.7
JO-73	5	L	3.77	31.24	85.2	34.4	5.7
JO-84	4	L	4.43	32.00	85.9	35.4	5.7

Table A-2. Continued.

Fiber Sample ID	Family	Selection	Micronaire	Length (mm)	Uniformity (%)	Strength (g/tex)	Elongation (%)
JO-118	1	L	4.63	31.75	85.8	36.7	5.7
JO-132	5	L	4.47	32.00	85.3	35.5	5.7
JO-21	2	L	4.40	30.99	83.9	34.6	5.8
JO-48	8	L	4.65	32.77	85.8	38.5	5.8
JO-49	15	L	4.29	31.24	86.4	36.1	5.9
JO-87	9	L	4.30	30.73	86.9	35.1	5.9
JO-89	7	L	4.62	32.00	86.3	32.9	5.9
JO-119	1	L	4.49	32.26	86.0	34.6	5.9
JO-125	11	L	3.71	33.78	84.5	33.8	5.9
JO-145	6	L	4.74	30.99	85.6	35.5	5.9
JO-30	9	L	4.25	30.99	87.9	36.7	6.0
JO-43	7	L	4.47	32.77	85.8	33.7	6.0
JO-95	2	L	4.42	32.51	84.8	33.7	6.0
JO-111	15	L	4.46	31.24	86.0	36.5	6.0
JO-130	8	L	4.49	30.73	85.9	36.8	6.0
JO-24	15	L	4.43	31.75	86.6	37.5	6.1
JO-42	13	L	4.58	31.24	85.7	32.8	6.1
JO-151	13	L	4.07	32.00	86.0	33.9	6.1
JO-113	12	L	4.65	31.24	85.9	33.2	6.3
JO-124	4	L	4.31	33.27	88.5	37.1	6.3
JO-35	3	L	4.20	32.51	86.5	34.0	6.4
JO-122	4	L	4.06	31.50	85.0	35.4	6.4
JO-127	11	L	4.31	31.50	84.9	30.9	6.4
JO-134	3	L	4.20	33.02	86.9	31.5	6.4
JO-144	10	L	4.31	31.50	85.8	35.2	6.4
JO-155	7	L	4.52	32.00	86.0	33.6	6.4
JO-106	11	L	4.43	32.51	86.6	34.6	6.5
JO-110	1	L	4.25	31.24	85.6	35.3	6.6
JO-137	14	L	4.13	32.00	85.3	32.9	6.6
JO-141	2	L	4.12	32.51	86.4	35.5	6.6
JO-102	8	L	4.75	31.75	85.9	38.2	6.9
JO-139	9	L	4.41	30.48	85.6	34.6	6.9
JO-154	13	L	4.14	30.23	84.2	35.0	7.3
JO-115	12	L	4.08	31.24	85.9	35.5	7.6
JO-55	4	H	4.05	33.27	87.1	36.5	5.2
JO-3	4	H	4.35	33.02	87.3	37.1	5.5
JO-68	12	H	4.60	32.00	86.0	35.0	5.5
JO-71	16	H	4.20	30.99	85.8	36.4	5.5
JO-25	16	H	4.52	31.50	86.3	36.6	5.6
JO-77	16	H	4.24	33.27	86.7	37.7	5.6
JO-81	13	H	4.54	31.75	87.0	37.7	5.6
JO-85	4	H	4.09	31.75	86.3	36.8	5.6
JO-6	11	H	3.60	32.77	84.4	36.6	5.7
JO-76	6	H	4.31	33.02	87.3	36.2	5.7

Table A-2. Continued.

Fiber Sample ID	Family	Selection	Micronaire	Length (mm)	Uniformity (%)	Strength (g/tex)	Elongation (%)
JO-51	14	H	4.26	30.99	85.6	36.4	5.8
JO-79	12	H	4.66	31.50	86.6	37.6	5.8
JO-83	4	H	4.34	32.77	85.3	35.7	5.8
JO-97	10	H	4.55	31.24	85.9	36.7	5.8
JO-22	2	H	3.88	31.75	86.2	38.8	5.9
JO-96	2	H	4.08	32.26	86.2	37.8	5.9
JO-62	1	H	4.26	32.00	86.2	33.7	6.0
JO-116	12	H	4.56	32.77	85.3	37.1	6.0
JO-12	14	H	4.23	31.75	85.1	33.5	6.2
JO-14	12	H	4.53	31.24	85.5	33.1	6.2
JO-19	2	H	3.93	33.27	84.6	33.3	6.2
JO-44	7	H	4.94	33.27	86.7	33.9	6.2
JO-57	10	H	4.13	33.53	87.0	35.6	6.2
JO-63	9	H	3.65	32.26	87.0	32.1	6.2
JO-66	6	H	4.58	31.75	85.2	33.8	6.2
JO-69	3	H	4.24	32.26	86.8	34.2	6.2
JO-146	6	H	5.37	31.50	85.9	35.1	6.2
JO-150	16	H	4.59	30.23	85.3	34.7	6.2
JO-15	8	H	4.34	31.24	84.7	36.9	6.3
JO-54	2	H	4.34	32.26	87.1	33.0	6.3
JO-107	14	H	4.52	30.48	84.9	33.6	6.3
JO-129	8	H	4.74	32.00	86.8	38.2	6.3
JO-46	8	H	5.09	30.73	86.0	34.4	6.4
JO-47	8	H	4.16	33.27	85.8	40.6	6.4
JO-74	5	H	4.21	32.77	86.1	34.6	6.4
JO-135	14	H	4.69	29.72	83.6	33.3	6.4
JO-10	5	H	4.49	31.24	86.3	35.6	6.5
JO-40	11	H	4.19	31.24	86.0	33.5	6.5
JO-99	10	H	4.27	31.24	85.7	35.9	6.5
JO-120	1	H	4.55	32.26	87.0	34.6	6.5
JO-123	4	H	4.52	32.77	86.4	36.4	6.5
JO-140	9	H	4.53	31.24	85.8	34.6	6.5
JO-50	15	H	4.42	33.02	86.6	33.1	6.6
JO-121	4	H	4.95	30.48	85.3	32.2	6.6
JO-8	11	H	4.24	32.77	87.5	33.1	6.7
JO-131	5	H	4.02	30.99	86.5	35.3	6.7
JO-2	7	H	4.62	30.48	84.7	34.5	6.8
JO-34	13	H	3.94	30.23	85.6	35.5	6.8
JO-37	10	H	4.25	31.24	87.4	38.9	6.8
JO-41	13	H	4.22	32.77	86.4	33.9	6.8
JO-94	5	H	4.01	31.50	85.6	33.0	6.8
JO-114	12	H	4.09	29.46	86.3	34.7	6.8
JO-18	8	H	4.49	33.27	86.9	33.9	6.9

Table A-2. Continued.

Fiber Sample ID	Family	Selection	Micronaire	Length (mm)	Uniformity (%)	Strength (g/tex)	Elongation (%)
JO-23	15	H	4.44	31.24	86.8	33.5	6.9
JO-27	6	H	4.55	32.51	87.5	32.4	6.9
JO-29	9	H	4.09	31.75	86.2	35.1	6.9
JO-109	1	H	4.94	29.72	84.0	30.7	6.9
JO-117	1	H	5.23	30.48	84.2	37.0	6.9
JO-153	13	H	4.49	32.00	87.2	32.1	6.9
JO-59	10	H	4.61	29.72	86.2	34.2	7.0
JO-88	9	H	4.43	30.23	85.0	34.9	7.0
JO-128	11	H	3.96	32.51	84.6	34.7	7.0
JO-138	14	H	4.10	31.24	84.8	32.9	7.0
JO-112	15	H	4.63	30.73	86.1	37.0	7.1
JO-147	15	H	4.62	30.48	86.1	33.6	7.1
JO-133	3	H	4.63	30.99	85.8	34.5	7.2
JO-142	2	H	4.26	32.00	83.0	34.7	7.2
JO-36	3	H	4.13	32.77	86.1	37.1	7.3
JO-90	7	H	4.24	31.75	87.5	37.0	7.3
JO-105	11	H	4.17	32.77	86.5	31.9	7.3
JO-126	11	H	4.35	30.99	84.0	31.5	7.3
JO-152	13	H	4.22	32.00	86.9	35.3	7.3
JO-31	1	H	3.80	33.02	86.4	32.7	7.5
JO-92	5	H	4.43	29.46	85.7	31.3	7.6
JO-101	8	H	4.35	32.00	84.5	34.1	7.8
JO-103	3	H	4.68	31.75	87.1	33.0	8.1
JO-143	10	H	4.30	31.24	85.4	38.8	8.2
JO-156	7	H	4.20	30.48	87.0	33.8	9.2