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Relationships of cotton fiber properties to ring-spun yarn quality on selected High Plains cottons

William Brock Faulkner[1], Eric F Hequet[2], John Wanjura[3] and Randal Boman[4]

Abstract

Cotton fiber properties play an important role in determining spinning performance but explain only a portion of the variability in final yarn quality parameters. This research investigates relationships between ring-spun yarn quality and fiber properties (measured using the High Volume Instrument (HVI) and Advanced Fiber Information System (AFIS)) given additional information on harvest method and cultivar. Seventy-six samples of commercially grown cotton representing five cultivars from six locations across the Texas High Plains were collected over three years. Carded 14.5 tex (40 Ne) ring-spun yarns were produced and tested for various yarn quality characteristics. Principal component analysis and partial least squares regression were used to determine relationships between fiber and yarn properties. Neither harvest method nor cultivar explained a significant portion of yarn quality variability beyond that captured by HVI and AFIS results. Yarn work-to-break was highly correlated to fiber bundle elongation, which is not currently reported in official cotton classing reports.

Keywords

Advanced Fiber Information System, cultivar, harvest, High Volume Instrument, partial least squares, principal component analysis

Production and use of US cotton has changed dramatically in recent years, with exports surpassing domestic use annually since 2001 (Figure 1[1]).

The shift to foreign markets has coincided with a shift in the primary end use of US cotton from domestic open-end mills to foreign ring-spinning mills (Figure 2;[2–4] Table 1[4,5]).

As the end use of US cotton has changed, so has the regional distribution of upland cotton production (Figure 3[6]). Changes in water availability and commodity prices have reduced production acres in California, which dropped from the second largest producing state in 2000 (15% of the US crop) to fifth in 2009 (5% of the US crop). Commensurately, recent improvements in irrigation technologies and cotton cultivars have increased yields on the High Plains of Texas, increasing the portion of the US crop produced in this region.

Improved yields on the High Plains have been accompanied by improved fiber quality (Figure 4[7]). Since 2000, the length of fibers produced in Texas has improved to match that of cottons produced in California 10 years ago, and fiber strength has also markedly improved. However, thus far there has still been difficulty producing fine yarns of comparable quality to those produced from Acala cottons using cottons from West Texas.[8]

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[1]Department of Biological and Agricultural Engineering, Texas A&M University, College Station, USA.
[2]Fiber and Biopolymer Research Institute and Department of Plant and Soil Science, Texas Tech University, Lubbock, Texas, USA.
[3]USDA-ARS Cotton Production and Processing Research Unit, Lubbock, Texas, USA.
[4]Southwest Research and Extension Center, Oklahoma State University, Altus, Oklahoma, USA.

Corresponding author:
William Brock Faulkner, Department of Biological and Agricultural Engineering, Texas A&M University, 2117 TAMU, College Station, TX 77843-2117, USA
Email: faulkner@tamu.edu

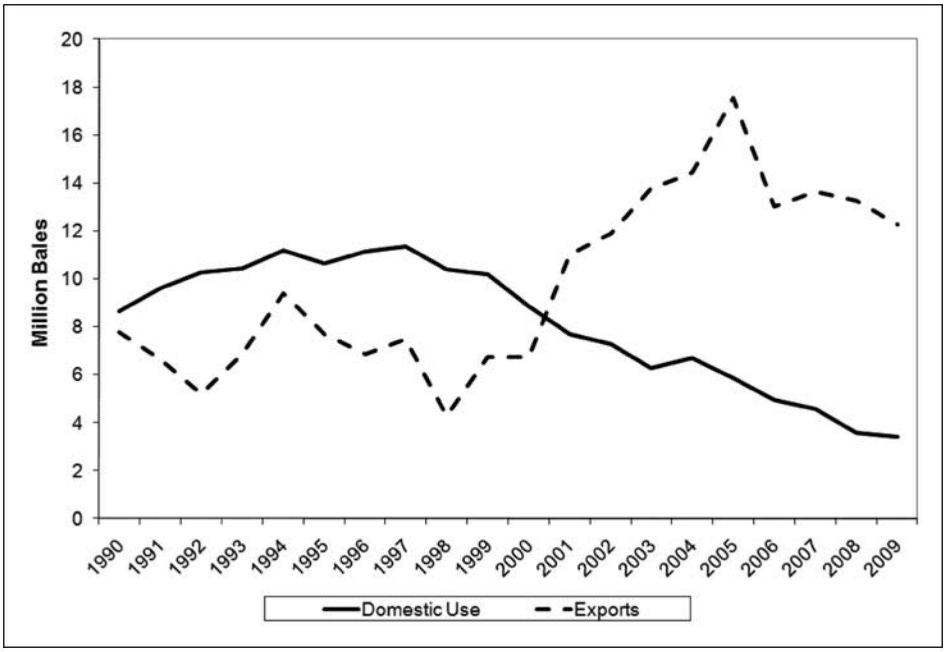

Figure 1. Domestic mill use and US cotton exports.[1]

Table 1. Regional share of yarn rotor and ring-spun[4] and 2008/2009 US cotton exports.[5]

	Share of yarn spun (%)		
Region	Rotor-spun	Ring-spun	US cotton exports (%)
Africa	20	80	0.6
North America	44	56	10.2
South America	30	70	3.6
Asia and Oceania	16	84	76.6
Mainland China	17	83	28.6
Turkey	38	62	13.8
Western Europe	37	63	0.5
Eastern Europe	76	24	0.01
Global	**20**	**80**	

Fiber properties and spinning performance

Fiber properties determine performance during processing and spinning. To produce high-quality ring-spun textiles, fibers must be fine and have sufficient strength to endure processing (spinning preparation, spinning, and weaving or knitting). Fiber length and fineness affect the forces between fibers that dictate the 'count,' or fineness, of the final yarn. Fiber maturity and strength affect a fiber's ability to withstand the forces placed upon it during opening and blending, carding, drafting and spinning. The spinning limit (i.e. the finest yarn number that can be spun satisfactorily from a specified lot of fiber under specified conditions) of a cotton is dependent on fiber properties and spinning method.[9] Longer, stronger fibers are better able to withstand the large forces placed on them during spinning and have more contact between fibers, thus increasing inter-fiber friction. These fibers are therefore able to be spun into finer yarns.

While fiber length, strength and fineness are most frequently correlated to yarn properties,[10] the trash content of cotton can also affect the maximum achievable yarn count. Due to the high angular speeds encountered by fibers during spinning, trash particles can cause fiber breaks by exerting centrifugal force on the forming yarn. Foreign matter and neps increase yarn unevenness and ends down (i.e. breaks) in spinning, which decrease production efficiency and increase imperfections in fabrics. For ring spinning, finer yarns are particularly susceptible to end breaks due to the presence of trash in the roving.

The fiber properties and foreign matter content of US cotton bales are assessed at Cotton Classing Offices maintained by the United States Department of Agriculture (USDA) Agricultural Marketing Service (AMS). Each bale receives a grade that is available to merchants or buyers based on micronaire, fiber length (reported as upper half mean length (UHML)), length uniformity, strength, color and quantity of leaf trash or extraneous matter. Not included in the data are harvest method and cultivar, both of which may affect spinning performance in ways not captured by currently available classing grades.

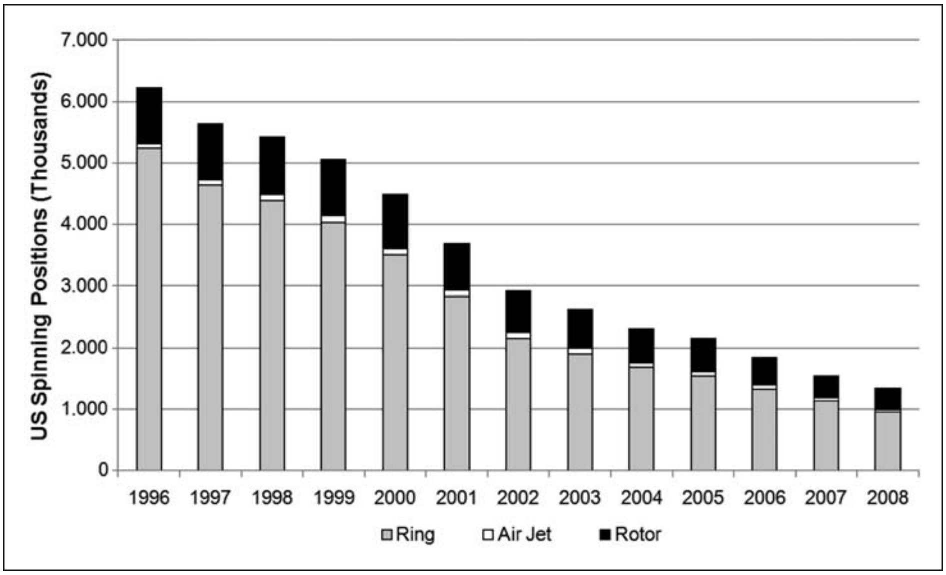

Figure 2. US spinning positions.[2,3] Note: rotor positions in the US are able to produce approximately nine times the output (by mass) of ring positions.[4] Therefore, even with fewer rotor positions, the US had the capacity to produce approximately three times more rotor-spun yarn than ring-spun yarn in 2008.

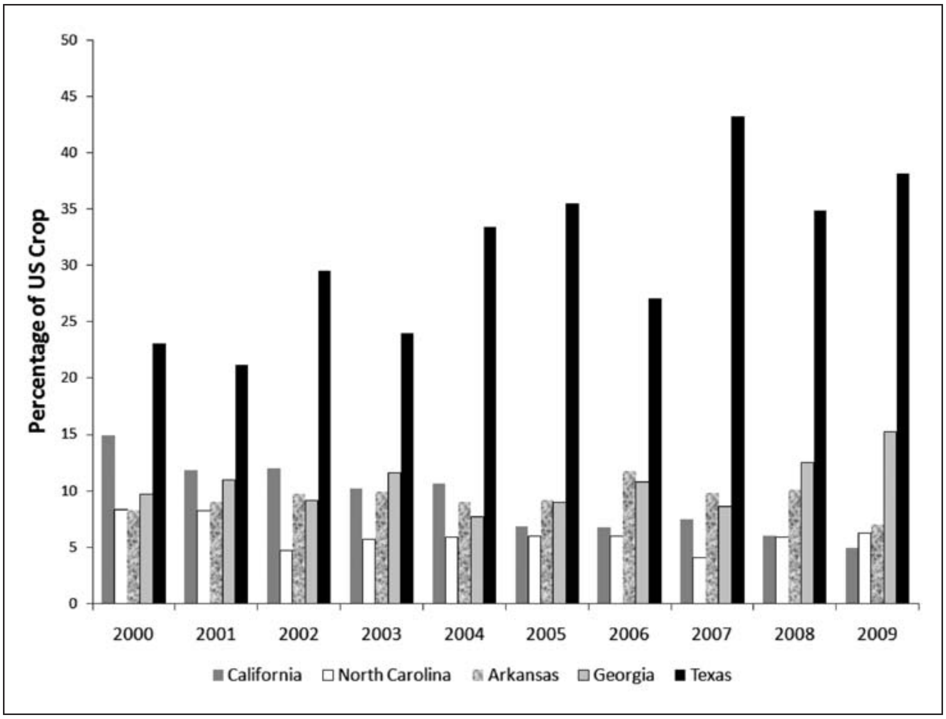

Figure 3. Percentage of US upland crop produced by state in the top five producing states.[6]

High Plains cotton production

Production practices in the High Plains are different than those of other US regions. Harsh weather conditions have historically led to the use of more storm-proof cultivars, and the combination of these tight-locked cultivars and short plant heights have led to the use of stripper harvesters rather than the mechanical picker harvesters used throughout most of the US. However, new germplasm, increased yields and improved irrigation practices have led to the use of picker harvesters on some irrigated cotton on the

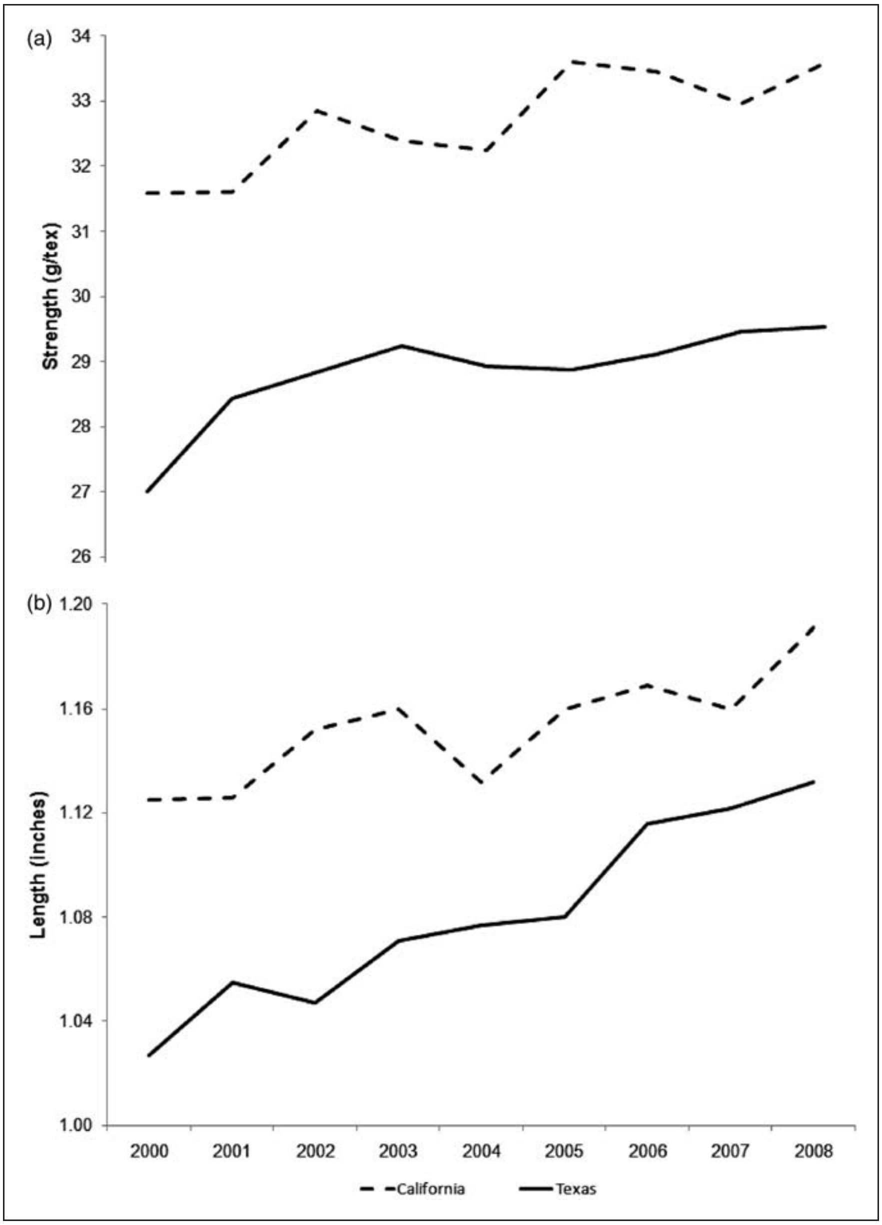

Figure 4. Average strength (upper) and length (lower) of upland cottons produced in Texas and California from 2000 to 2008.[7]

High Plains. This moderate shift in harvest method and the substantial improvement in fiber quality have led to questions regarding the impact of these changes on the value of cottons produced on the High Plains. Expecting differences in mill performance beyond those that would be predicted by High Volume Instrument (HVI) classing data, several cotton marketing pools have offered price premiums for picked cottons with similar classing grades to stripped cottons.

With the geographic shifts in US cotton production and the introduction of new cultivars to the High Plains, there is a question as to whether High Plains cottons might be able to fill the demand for fibers suitable for making high-quality, fine, ring-spun yarns. In preliminary research, Krifa and Ethridge[11] reported that cottons produced on the High Plains with relatively high micronaire (>4.1) performed similarly to California Acala cottons with similar HVI properties in textile production. However, unlike most of California, the High Plains is characterized by variable weather conditions that often lead to termination of cotton plants before fibers reach full maturity. Experimental work is currently ongoing to characterize the processing characterisitics related to lower micronaire values.[12]

Unlike the HVI, which estimates fiber properties from a bundle of fibers, the Advanced Fiber Information System (AFIS) measures properties of individual fibers. For each replication, a 0.5 g sample

Table 2. Sampling site cultivar summary.[13]

	2006	2007	2008
Site 1	ST 4554 B2RF[a]		
Site 3		ST4554 B2RF[a], FM 9058 F[b], FM9063 B2F[c], PHY 485 WRF[d]	
Site 4		ST4554 B2RF[a], FM 9058 F[b], FM9063 B2F[c], PHY 485 WRF[d]	
Site 5			FM 9180 B2F[e]
Site 7			FM 9180 B2F[e]

[a] ST 4554 B2RF = Stoneville 4554 Bollgard II® Roundup Ready Flex® (Bayer CropScience; Research Triangle Park, NC).
[b] FM 9058 F = FiberMax 9058 Flex® (Bayer CropScience; Research Triangle Park, NC).
[c] FM 9063 B2F = FiberMax 9063 Bollgard II® Roundup Ready Flex® (Bayer CropScience; Research Triangle Park, NC).
[d] PHY 485 WRF = PhytoGenTM 485 WidestrikeTM Roundup Ready Flex® (Dow AgroSciences; Indianapolis, IN).
[e] FM 9180 B2F = FiberMax 9180 Bollgard II® Roundup Ready Flex© (Bayer CropScience; Research Triangle Park, NC).

is formed into a 30 cm long sliver and placed in the sampling tube of the AFIS. A pinned cylinder and fiber individualizer align and separate individual fibers, which then pass through one of two optical sensors: one for trash and dust and the other for length, maturity and neps.

The objective of this research was to investigate the influence of fiber properties, harvest method and cultivar on properties of ring-spun yarn produced from High Plains cottons. Fiber properties measured using the HVI (i.e. those available to merchants and buyers plus fiber elongation) and the AFIS, along with harvest method and cultivar/harvest location/year interaction, were analyzed to determine their relative influence on the properties of ring-spun yarns.

Methods

Irrigated cotton was harvested using picker and stripper harvesters from six commercial farms on the High Plains of Texas and ginned at the USDA-ARS Cotton Production and Processing Research Unit in 2006, 2007 and 2008. Sample sites and methods are described in detail by Faulkner et al. (Table 2).[13] (Data from Site 6 were excluded due to extremely low maturity – average micronaire of 2.5 for this site – and non-field-cleaned samples were excluded due to the small number of samples. No fiber quality data was collected at Site 2.) In summary, 140 kg samples of seed cotton were collected from six commercial farms (sites) in which samples were harvested using a picker (John Deere 9996) or stripper (John Deere 7460) harvester from adjacent plots in the same field.

Fiber quality analyses are described in detail by Faulkner et al.[14] Summary fiber quality data from each site is shown in Tables 3–5.

Twenty three kilogram (50 lbs) samples of lint were processed to produce carded ring-spun yarns at the Fiber and Biopolymer Research Institute. While a

Table 3. Fiber quality properties for all samples from 2006 (Site 1, $n = 8$).[14]

	Minimum	Average	Maximum
HVI			
Micronaire	2.9	3.3	3.6
Length (cm)	2.77	2.79	2.84
Uniformity (%)	78.8	79.7	81.3
Strength (g/tex)	24.8	26.6	28.6
Elongation (%)	8.1	8.5	9.2
Reflectance	80.4	81.2	81.8
Yellowness	7.9	8.4	8.9
Leaf grade	2	2.3	3
AFIS			
Nep size (μm)	707	726	748
Neps (cnt/g)	460	640	780
Length by no. (cm)	1.52	1.60	1.73
No. length CV (%)	56.9	62.1	65.1
UQL[a](cm)	2.79	2.85	2.92
SFC$_w$[b](%)	13.7	17.0	18.8
Total count[c](cnt/g)	252	367	526
Trash size (μm)	286	304	322
Dust (cnt/g)	216	321	458
Trash (cnt/g)	34	46	68
VFM[d] (%)	0.83	1.13	1.44
SCN Size[d](μm)	995	1091	1202
SCN[e](cnt/g)	13	19	26
IFC[f](%)	11.1	13.4	15.0
Maturity ratio	0.75	0.77	0.81
Standard fineness	195	197	201

[a] UQL = upper quartile length.
[b] SFC$_w$ = short fiber content by weight.
[c] Total count = Dust + Trash count per gram.
[d] VFM = visible foreign matter.
[e] SCN = seed coat nep.
[f] IFC = immature fiber content.
HVI: High Volume Instrument, AFIS: Advanced Fiber Information System, CV: coefficient of variation.

Table 4. Fiber quality properties for all samples from 2007.[14]

	Site 3 ($n = 24$)			Site 4 ($n = 24$)		
	Minimum	Average	Maximum	Minimum	Average	Maximum
HVI						
Micronaire	3.6	4.1	4.8	3.7	4.1	4.5
Length (cm)	2.69	2.92	3.05	2.82	2.98	3.15
Uniformity (%)	79.0	81.5	83.7	81.3	82.6	84.1
Strength (g/tex)	28.2	29.9	31.8	27.0	29.0	31.3
Elongation (%)	7.1	8.6	10.3	7.3	8.8	10.2
Reflectance	76.2	80.9	84.2	75.4	79.8	83.9
Yellowness	7.2	8.3	9.7	7.5	8.7	10.4
Leaf grade	1	1.6	3	1	1.4	3
AFIS						
Nep Size (μm)	651	695	720	670	689	725
Neps (cnt/g)	240	354	506	226	326	426
Length by no. (cm)	1.75	1.87	2.01	1.83	1.95	2.11
No. length CV (%)	50.4	54.9	58.7	50.0	53.3	58.1
UQL[a](cm)	2.79	3.03	3.18	2.95	3.09	3.25
SFC_w[b](%)	9.0	11.1	13.2	7.9	10.0	12.3
Total count[c](cnt/g)	294	771	1758	307	945	2849
Trash size (μm)	253	278	294	243	261	298
Dust (cnt/g)	256	682	1528	284	858	2615
Trash (cnt/g)	38	89	230	23	86	234
VFM[d](%)	0.66	1.82	3.71	0.65	1.87	4.67
SCN size[d](μm)	696	811	923	761	848	955
SCN[e](cnt/g)	6	17	30	6	16	28
IFC[f](%)	7.5	9.4	11.7	6.8	8.7	10.0
Maturity ratio	0.81	0.84	0.89	0.82	0.85	0.88
Standard fineness	184	194	202	185	194	204

[a] UQL = upper quartile length.
[b] SFC_w = short fiber content by weight.
[c] Total count = Dust + Trash count per gram.
[d] VFM = visible foreign matter.
[e] SCN = seed coat nep.
[f] IFC = immature fiber content.
HVI: High Volume Instrument, AFIS: Advanced Fiber Information System, CV: coefficient of variation.

brief description of the spinning process is given here, a more detailed description of the spinning process and yarn quality results is given by Faulkner et al.[15] Samples were opened using a Rieter Monocylinder B4/1 and a Reiter ERM B5/5 (Winterthur, Switzerland). Cotton was carded (Model DK-903; Trützschler; Mönchengladbach, Germany) at a production rate of 32 kg/h to produce carded slivers with a linear density of 4600 tex. Card slivers were blended and drawn to a linear density of 3900 tex using an HSR 1000 draw frame (Trützschler; Mönchengladbach, Germany). A Reiter RSB 851 draw frame (Reiter, Winterthur, Switzerland) was then used to draw the samples to a final linear density of 4250 tex. On the roving frame, samples were drawn to a linear density of 490 tex, and a slight twist (0.51–0.63 turn/cm) was added. Half of the slivers were spun into 14.5 tex (40 Ne) yarns with a twist multiplier of 4.2 (weaving twist) on a Seussen Fiomax ring-spinning frame. Ten bobbins of yarn were made from each sample using a traveler speed of 32 m/s, a back to middle gauge of 64 mm, a middle to front gauge of 46 mm and a spindle speed of 13,500 rpm.

Yarn count and skein break tests were performed with a Scott Tester (Model J-2; Henry L. Scott, Providence, RI) (10 bobbins per sample); yarn elongation, tenacity and work to break were measured with an Uster Tensorapid (Model 3, Uster Technologies, Knoxville, TN) (10 bobbins per sample and ten breaks per bobbin); yarn evenness was tested with an Uster Tester (Model 3, Uster Technologies, Knoxville,

Table 5. Fiber quality properties for all samples from 2008.[14]

	Site 5 ($n = 8$)			Site 7 ($n = 8$)		
	Minimum	Average	Maximum	Minimum	Average	Maximum
HVI						
Micronaire	3.4	3.6	3.7	3.0	3.2	3.6
Length (cm)	3.00	3.03	3.07	2.95	3.00	3.05
Uniformity (%)	82.4	82.9	83.6	81.9	82.5	83.3
Strength (g/tex)	28.5	29.2	29.7	28.1	29.3	29.9
Elongation (%)	9.9	10.0	10.2	9.2	9.5	9.7
Reflectance	81.0	82.4	83.1	82.0	82.6	83.7
Yellowness	6.9	7.2	7.5	7.4	7.8	8.1
Leaf grade	1	1.25	2	1	1	1
AFIS						
Nep size (μm)	690	699	706	700	708	718
Neps (cnt/g)	368	431	500	391	464	526
Length by no. (cm)	1.93	1.96	2.01	1.88	1.95	2.01
No. length CV (%)	52.4	53.5	54.4	57.8	59.9	62.5
UQL[a](cm)	3.07	3.12	3.18	3.07	3.11	3.15
SFC_w[b](%)	9.3	10.0	10.7	9.3	10.3	11.3
Total count[c](cnt/g)	224	331	402	243	384	484
Trash size (μm)	286	315	343	308	319	346
Dust (cnt/g)	190	282	352	207	325	406
Trash (cnt/g)	32	49	70	36	60	78
VFM[d](%)	0.60	1.06	1.49	0.78	1.29	1.49
SCN size[d](μm)	779	881	952	806	865	964
SCN[e](cnt/g)	10	13	17	14	19	22
IFC[f](%)	8.3	8.7	9.2	8.3	8.9	9.8
Maturity ratio	0.80	0.81	0.82	0.80	0.82	0.82
Standard fineness	185	187	189	184	187	189

[a] UQL = upper quartile length.
[b] SFC_w = short fiber content by weight.
[c] Total count = Dust + Trash count per gram.
[d] VFM = visible foreign matter.
[e] SCN = seed coat nep.
[f] IFC = immature fiber content.
HVI: High Volume Instrument, AFIS: Advanced Fiber Information System, CV: coefficient of variation.

TN) (10 bobbins per sample and 400 m per bobbin) as specified by American Society for Testing and Materials (ASTM) Standard D1425/D1425M.[16]

A standardized principal component analysis (PCA) was performed on all fiber and yarn quality data to give insight to causes of deviation between samples and to identify outlying samples. Harvest method, cultivar and location were treated as categorical variables. All other data were standardized by centering the mean on zero and scaling such that the standard deviation of all data within each variable was equal to one. This standardization process was performed to give equal opportunity for all variables to influence the model regardless of their original variance (e.g. a standardized analysis gives equal weight to fiber length and dust size even through the variance of dust size data (in μm) is two orders of magnitude larger than that of fiber length data (in cm); an unstandardized analysis would give greater weight to variations in dust size than in fiber length). Results of the PCA include a number of principal components (PCs), which are linear combinations of variables (fiber properties, harvest method and cultivar) that account for the maximum variance within a dataset by describing mutually orthogonal vectors that most closely fit the n observations in p-dimensional space, where p is the number of variables measured on each object. Each successive PC explains the maximum possible amount of residual variance in the dataset. The PCA reveals the effective dimensionality of a dataset and eliminates redundancy caused by collinear variables, such as those expected in the type of fiber analyses conducted.

Following PCAs, partial least squares (PLS) regression analyses were performed to relate variations in fiber properties and harvest method to relevant yarn quality parameters. A PLS analysis is well suited for relating the host of fiber quality parameters from HVI and AFIS to yarn quality parameters because, unlike standard regression methods that fail under conditions of collinearity among independent variables, PLS regression handles collinearity well.[17] PLS regression is akin to the PCA in that linear combinations of variables (fiber properties, harvest method and cultivar) are constructed that account for the maximum variance within the response variables (yarn quality parameters). Given the limited number of samples, full cross validation was used to test model predicitivity after each successive PC was added. Because full cross validation does not utilize a truly independent dataset, it tends to lead to over-estimation of the predictive ability of a model, but it is the best option when sample size is limited relative to the model dimensionality.[17] Loadings and regression coefficients from PLS analyses were used to identify those fiber properties that most influenced yarn quality. PCA and PLS analyses were conducted using The Unscrambler (v. 9.8; CAMO Software AS; Oslo, Norway) software. Analyses of variance investigations into select differences in fiber and yarn properties were conducted using the General Linear Model function in SPSS (ver. 14.0; SPSS, Inc.; Chicago, Ill.).

Results and discussion

Fiber quality PCA

The PCA was performed using all data from HVI and AFIS analyses. The first two PCs explained 70% of the variance in the fiber quality dataset. The score plot of PC1 and PC2 shows clear grouping by cultivar, with all FiberMax cultivars clustered together and distinct groupings for PHY 485 and ST 4554 (Figure 5). PC1 explained 40% of the variance in the fiber property data and primarily differentiated between samples based on micronaire, length and length variation. PC2 explained 30% of the variance in fiber quality dataset and primarily differentiated samples based on reflectance (Rd) and foreign matter content.

The loading plot of PC1 and PC2 (Figure 6) shows that length parameters were highly correlated, as were length uniformity and foreign matter parameters. Correlations between all fiber length parameters were significant, with AFIS fiber length by weight (Lw) being most highly correlated to all other parameters (Figure 7). Correlations between trash count, dust count and visible foreign matter were also significant,

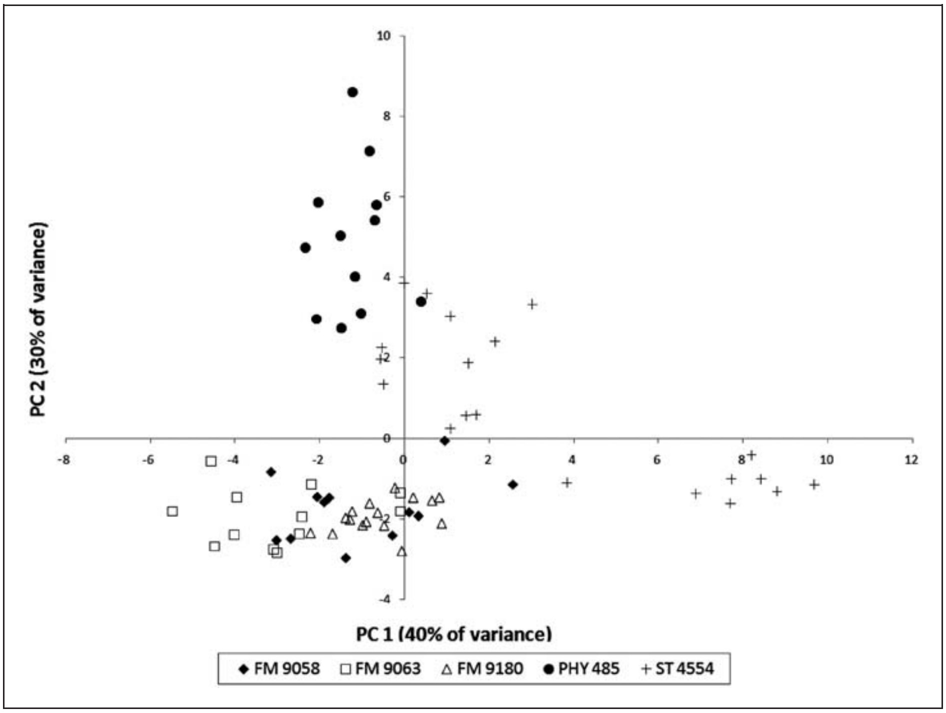

Figure 5. Score plot for first two fiber quality principle components.

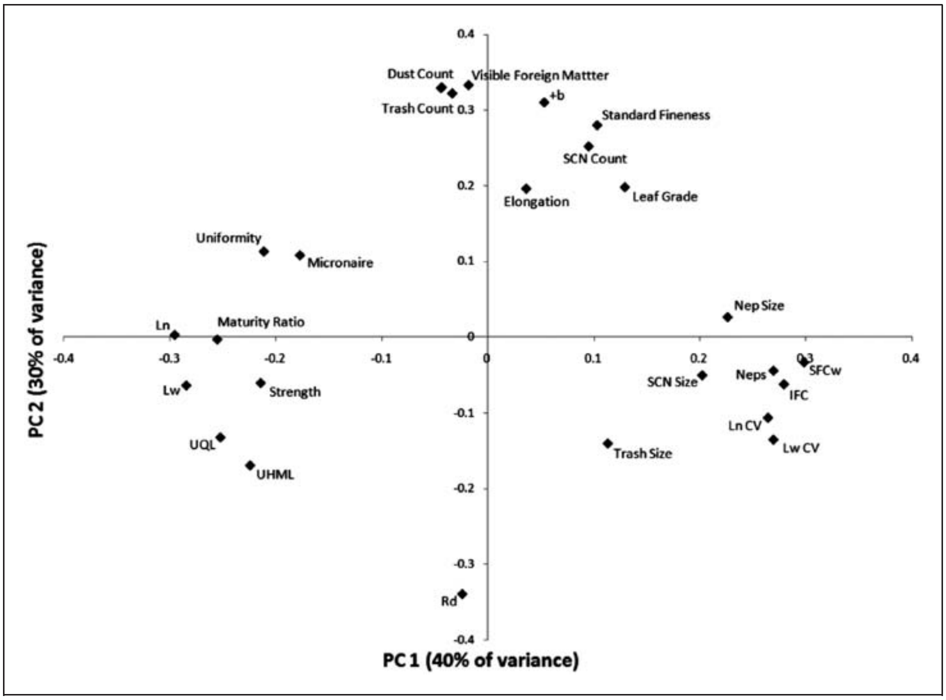

Figure 6. Loading plot for fiber quality principal component analysis.

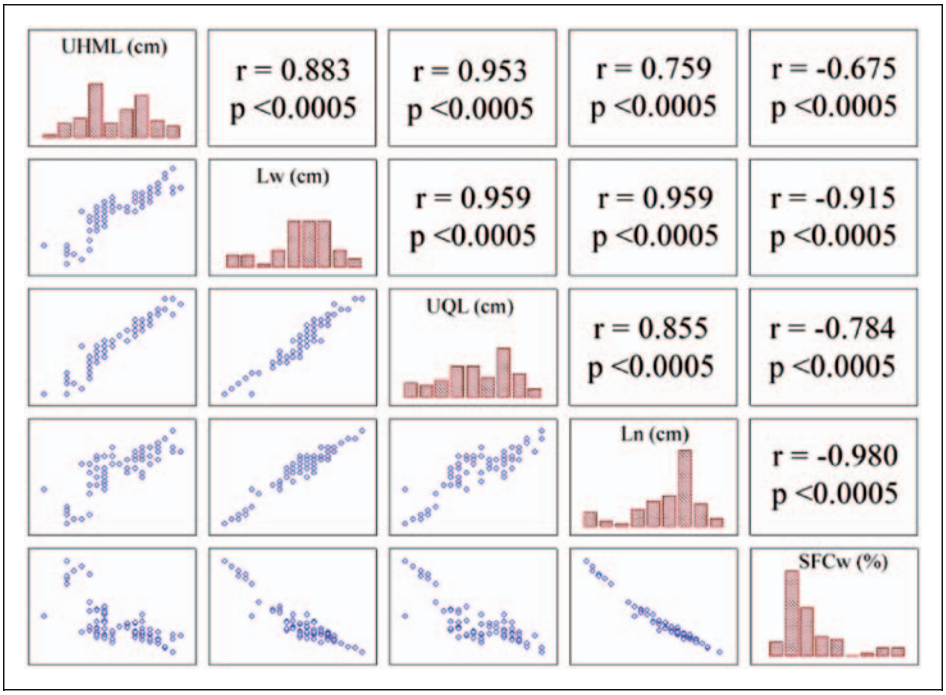

Figure 7. Correlation matricies for length parameters.

with all correlation coefficients greater than 0.94. While AFIS length uniformity parameters (LnCV and LwCV) were highly correlated ($r = 0.969$), correlation coefficients between AFIS uniformity parameters and HVI uniformity were less than 0.8. This reduced correlation between HVI and AFIS length uniformity parameters is likely the result of AFIS characterizing the entire distribution of measured fiber lengths, whereas HVI length parameters focus on the longest half of the fiber distribution.

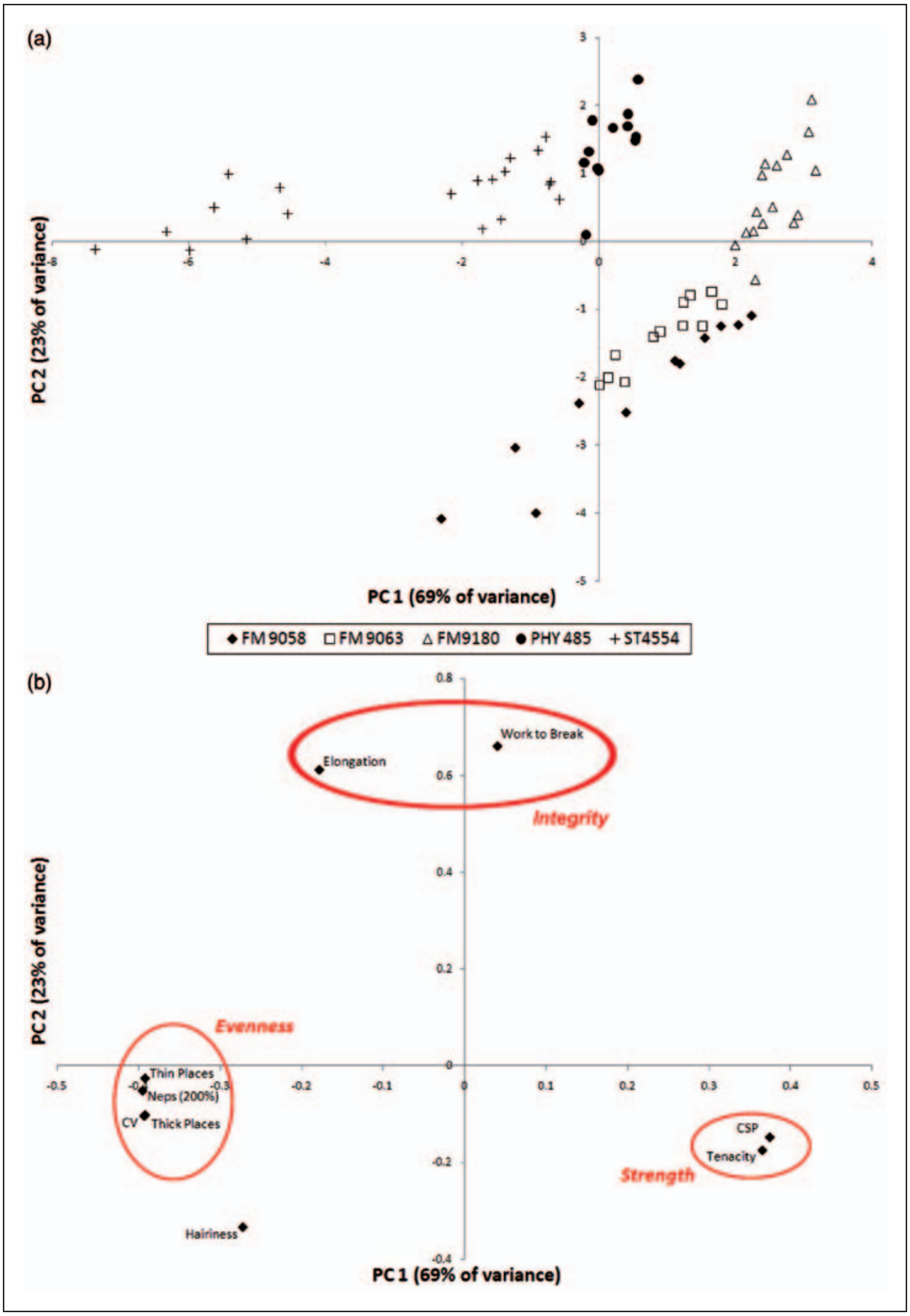

Figure 8. Score plot (a) and loading plot (b) for yarn quality principal component analysis.

Yarn quality PCA

The PCA was performed on all carded yarn quality parameters. The first two PCs explained 92% of the variance in the yarn quality data. The score plot of PC1 and PC2 also showed clear groupings by cultivar (Figure 8). The loading plot (Figure 8) showed that:

- variation in yarn evenness parameters (thin places, thick places, coefficient of variation (CV) and neps greater than 200% of the yarn cross-sectional area) explain most of the variations in the sampled yarns followed by variations in yarn strength parameters (tenacity and count-strength-product (CSP));
- yarn strength parameters (CSP and tenacity) were highly correlated to each other and negatively correlated to yarn evenness parameters (Figure 9);
- yarn elongation and work-to-break were correlated ($r = 0.838$; $p < 0.0005$); and

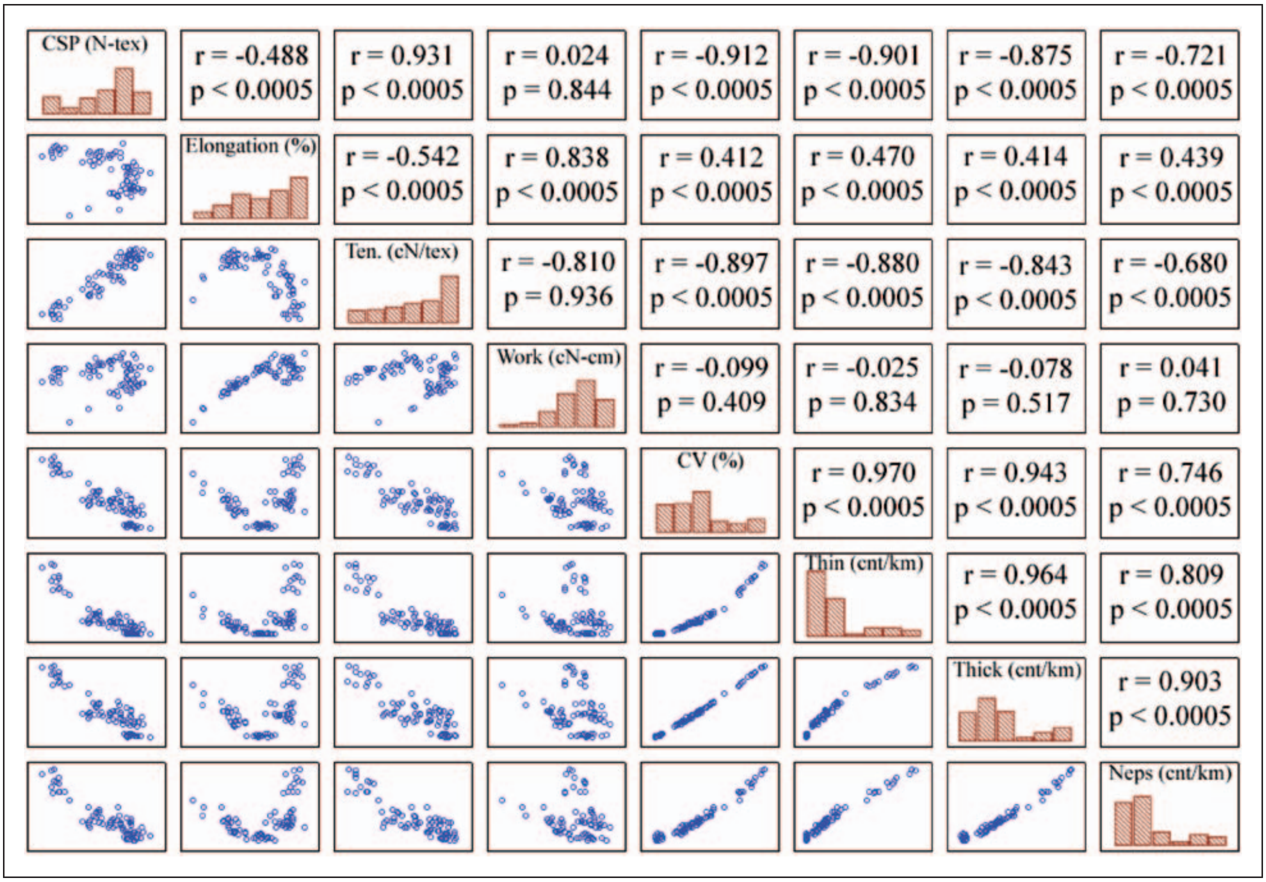

Figure 9. Correlation matrix for yarn strength and evenness parameters.

- yarn hairiness was not correlated with any of these parameters (maximum $|r| = 0.578$).

Yarn evenness regression

Because all yarn evenness parameters were well correlated to the number of neps (+200%) per km of yarn, a PLS1 regression was performed in which the number of yarn neps was regressed against HVI, AFIS, harvest method and cultivar data. Seven outliers having low maturity (maturity ratio ≤ 0.78) were removed from this and all subsequent regression. These seven samples formed an outlying group of weak yarns with exceptionally high numbers of thick places. Redundant fiber quality variables (related variables with $|r| > 0.9$) were also removed from this and all subsequent regressions (e.g. Lw was used to indicate fiber length and all other AFIS length measurements were removed) along with variables having regression coefficients with confidence intervals encompassing zero (including harvest treatment).

Table 6. Average yarn evenness parameters

Parameter	FiberMax samples	Non-FiberMax samples	*p*-value
CV (%)	14.5	14.7	<0.0005
Thin places[a] (cnt/km)	9	28	<0.0005
Thick places[b] (cnt/km)	90	170	<0.0005
Neps (+200%) (cnt/km)	65	104	0.001

[a] Thin places = points in the yarn less than 50% of the average thickness.
[b] Thick places = points in the yarn greater that 150% of the average thickness.
CV: coefficient of variation.

After these modifications to the dataset, variations in fiber length accounted for most of the variation in PC1, which explained 74% of the yarn evenness variance. FiberMax cultivars, which produced more even yarns (Table 6), were significantly longer ($p < 0.0005$) than other samples and had lower values of standard fineness (H_s; $p < 0.0005$). FM 9180 samples, which were characterized by lower values of micronaire, H_s and low foreign matter contents, formed a cluster of highly uniform yarns.

Yarn strength regression

Yarn tenacity was used to indicate yarn strength as it correlated well with CSP ($r = 0.931$). A PLS1 regression was performed in which yarn tenacity was regressed against HVI, AFIS, harvest method and cultivar data. After removing insignificant variables from the regression, including harvest treatment, grouping by cultivar was prevalent in the score plots. PC1 explained 74% of the tenacity variance and largely differentiated between FiberMax and non-FiberMax cultivars. PC2 explained only 3% of the remaning yarn tenacity variance. ST4554 and PHY 485 samples were less tenacious than most of the FiberMax samples.

Fiber length, fineness and reflectance were the most influential variables in PC1. Longer, more uniform fibers produce more tenacious yarns because the slipping resistance of fibers increases due to greater fiber-to-fiber friction.[18–20] Similar to the results of this study, El Mogahzy[21] reported that skein break factor (or CSP) increased with increasing fiber length, length uniformity and fiber strength but decreased with increasing Rd and fiber fineness. El Mogahzy et al.[22] found similar results for a different set of cottons but did not find significant correlations between Rd and CSP. Ramey et al.[18] found that fiber tenacity measured at 3.2 mm gage length explained more than 70% of the variation in observed yarn tenacity. Variances in fiber strength contributed to variances in yarn tenacity, but fiber length was more prevalent for the samples in this study.

Yarn work-to-break regression

Yarn work-to-break was correlated with yarn elongation ($r = 0.838$). A PLS1 regression was performed in which yarn work-to-break was regressed against HVI, AFIS, harvest method and cultivar data. In addition to the seven immature samples removed in previous analyses, three samples with low work-to-break values (< 300 cN-cm) were excluded from the analysis because they lay outside the body of most data points and exerted high levereage on the regression analysis.

After removal of insignificant variables from the regression, including harvest treatment, the first two PCs explained 84% of the variance in yarn work-to-break. Distinct clusters, grouped by cultivar, were obvious in the regression plots and can be seen in boxplots of the work-to-break data (Figure 10). Although the FM 9058 and FM 9063 samples produced stronger yarns, the yarns required less total energy to break than yarns produced by the PHY 485 and ST 4554 samples. An analysis of variance of fiber strength and elongation by cultivar revealed no significant differences between cultivars with regards to fiber strength, but PHY 485 and ST 4554 samples demonstrated significantly better elongation than the FM 9058 and FM 9063 samples (Figure 11; $p < 0.0005$).

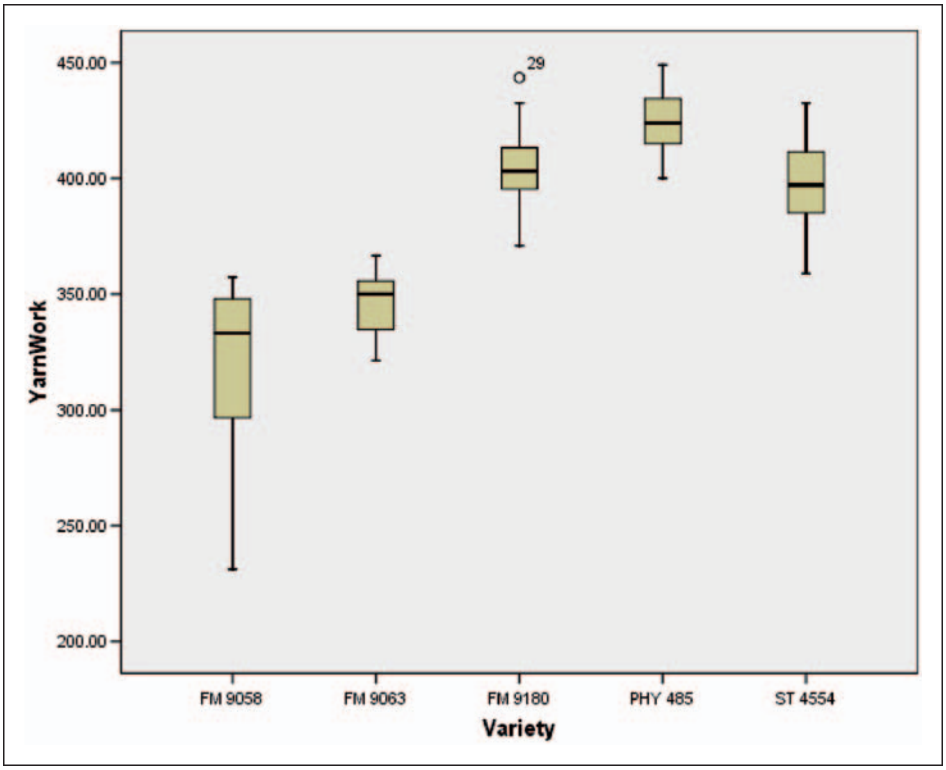

Figure 10. Yarn work-to-break by cultivar.

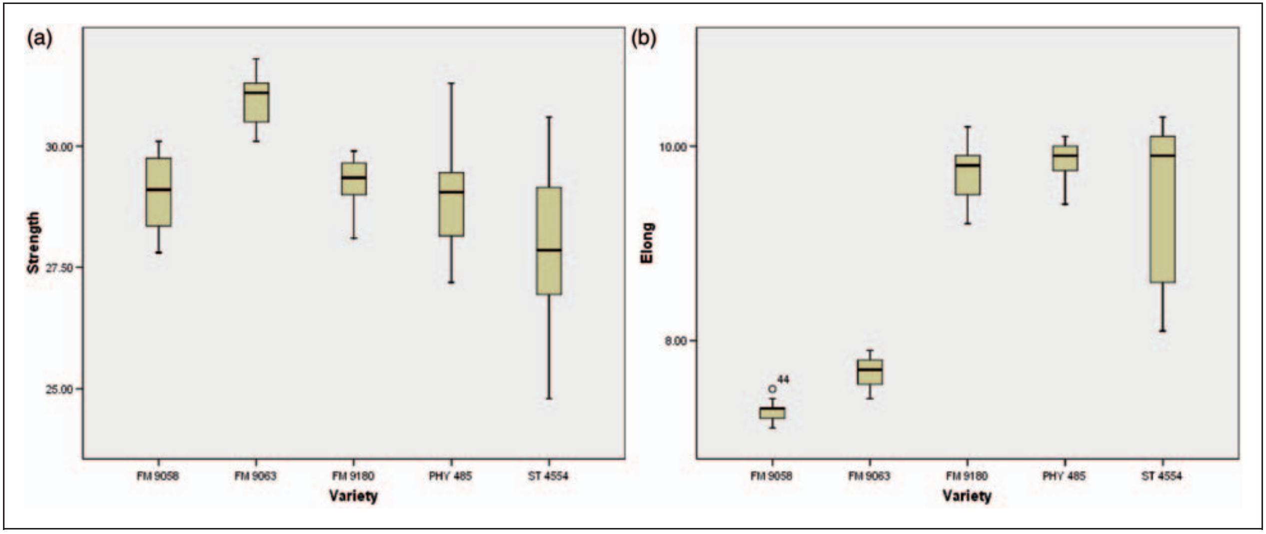

Figure 11. Fiber strength (a) and elongation (b) by cultivar.

Work-to-break is determined by integrating the area under the displacement-force to break the curve up to the point of rupture. For cotton this curve is mostly linear and can be approximated by the product of tenacity and elongation. Therefore, it is not surprising that work-to-break was positively correlated to fiber elongation ($r = 0.841$). Previous research has demonstrated that the elongation of ring-spun yarns is most influenced by the elongation of the fibers comprising that yarn.[23–27] Yarn elongation and work-to-break are important properties because they correlate well with weaving efficiency.[28] Modern air-jet looms require yarns to elongate more than 4% without breaking during typical opening and closing cycles, which typically occur 3000 times per minute.[29] Although yarn tenacity is often used to judge weaving performance, work-to-break (or work of rupture) is a more appropriate indicator of yarn performance because it describes the total energy required to break a yarn.

As cotton fibers mature, the secondary wall thickens as highly crystalline cellulose is deposited inside the primary cell wall.[30] The increasing thickness leads to greater fiber strength, but the crystalline structure of the secondary wall makes the fibers more brittle, thus decreasing fiber elongation. This tradeoff between fiber strength and elongation explains why yarn work-to-break was positively correlated to fiber elongation but negatively correlated to fiber maturity.

Although yarn work-to-break is approximated by the product of tenacity and elongation, variations in yarn work-to-break were more highly correlated to variations in yarn elongation than to variations in yarn strength parameters (Figure 8). Within the analyzed samples, the CV for HVI strength was 3.9%, while the CV for fiber elongation was 13%. Because there is little variation in fiber strength between samples, regardless of the cultivar, most of the variation in work-to-break resulted from varations in fiber and yarn elongation.

The results of yarn work-to-break analyses reveal the importance of fiber elongation in producing yarns that can withstand the forces placed on them during weaving. However, fiber elongation is not currently included in cotton classing reports due to difficulties in calibrating this measurement between HVI machines. Although it has been recognized that fiber elongation affects yarn quality and weaving performance,[29] presently, there is no method by which customers can evaluate fiber elongation prior to purchase.

Bargeron[31] attempted to predict the bundle elongation of cotton fibers using HVI measurements accounting for the flex in the columns connecting the stepper motors and fiber clamps in HVI systems in order to develop a standard measurement protocol for fiber elongation unaffected by fiber bundle strength. Benzina et al.[29] reported that elongation results from a single HVI were repeatable, but values could not be reliably compared between HVI systems. The authors proposed developing calibration standards for fiber elongation to allow for inter-system comparison. Results of the present research point to the need for continuing efforts to reliably characterize the breaking elongation of fibers as an additional cotton classing paramter.

Yarn hairiness regression

A PLS1 regression was performed in which yarn hairiness was regressed against HVI, AFIS, harvest method and cultivar data. After removal of insignificant variables from the regression, including harvest treatment, the regression explained a maximum of 59% of the variation in yarn hairiness with two PCs. PC1 and PC2 explained 56% and 3% of the variation in yarn hairiness, respectively. Variations in fiber length by weight (Lw; $r = -0.399$; $p = 0.001$) and length uniformity ($r = -0.563$; $p < 0.0005$) explained most of the accounted-for variation in yarn hairiness. The current results support those of previous researchers that increasing fiber length reduces yarn hairiness.[32–34] Viswanathan et al.[33] found that fiber fineness had the greatest effect on yarn hairiness, followed by fiber length, but Zhu and Ethridge[34] found no correlation between fiber fineness and yarn hairiness.

Some hairiness is desirable as it leads to comfort and coverage in fabrics and it increases the velocity and insertion rate of wefts during weaving due to higher friction between yarns and the air surface.[35,36] However, excessive hairiness affects the appearance of yarns in a fabric and increases the tension placed on yarns during the weaving process, which in turn affects both ends down and fabric properties. Adanur and Jing[37] reported that the maximum filling tension placed on a warp yarn increased between 53% (for an average of 35 picks) and 145% (for a single pick) as hairiness increased from 1750 to 2500 cnt/1000 m during 3/1 twill weaving. This increase in filling tension led to increased fabric air permeability, which led to greater fabric shrink after laundering and a decrease in fabric tear strength.[36] While the observed changes in filling tension resulted from a complex interaction of yarn twist, count and hairiness, it suggests that excessive increases in yarn hairiness lead to reductions in yarn performance and fabric quality, and that variations in yarn hairiness were not predicted well by variations in measured fiber characteristics for the analyzed samples.

Conclusions

Although differences in yarn quality were evident between yarns formed from picker- and stripper-harvested cottons,[15] based on the 76 cotton samples analyzed in this study, differences in yarn quality resulting from harvest method were sufficiently captured by differences in fiber quality parameters measured by the HVI and AFIS such that harvest method was not a significant factor in any of the final yarn quality models analyzed. Variations in yarn evenness were largely explained by variations in fiber length such that FiberMax cultivars, which in general had longer fibers, formed more even yarns than non-FiberMax samples. Yarn strength was most influenced by variations in fiber length, fineness and reflectance. Yarn work-to-break was substantially affected by fiber bundle elongation, which is not currently included in cotton classing reports. Those samples demonstrating the greatest bundle elongation-produced yarns, requiring more total energy to rupture. Fiber bundle elongation can be measured by HVI systems, but, due to a lack of calibration standards, the results are not comparable between systems.[29] The present research points to the need for a calibrated method for efficiently measuring fiber elongation for both breeding selection and for predicting a cotton's performance during spinning and textile production.

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Disclaimer

Mention of trade names or commercial products in this manuscript is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the US Department of Agriculture.

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Conflict of interest statement

None declared.

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