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BREEDING, GENETICS, & GENOMICS

Correlation of Cotton Fiber Properties with Yarn Tenacity at Varying Levels of Fiber Length and Strength

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ABSTRACT

A data set containing High Volume Instrument (HVI) and Advanced Fiber Information System (AFIS) fiber properties and minispun 30 Ne ring-spun yarn properties was developed from a breeding program's archived data obtained between 2013 and 2018. All raw fibers were from hand-harvested samples across 282 genotypes and involved three years and two locations. All samples were ginned on a 10-saw laboratory gin and fiber and yarn parameters obtained. The 355 observations comprised five groups: total, high fiber bundle strength (FBS), low FBS, long upper-half mean length (UHML), and short UHML. Pearson's correlation analysis was performed to determine if the associations of HVI and AFIS fiber traits with yarn tenacity and yarn appearance change substantially when strength and length ranges were limited to the extremes. Correlation analysis indicated that all HVI traits for fiber length and strength and AFIS fiber fineness characteristics were highly correlated with yarn tenacity. Correlation values for these traits were robust regardless of subpopulation. Correlations for short fiber content (SFC) by weight and number with yarn tenacity were not as consistent across populations. Correlation of fiber traits with yarn appearance average imperfection index indicated that breeders should be cognizant of uniformity index and SFC during the selection process.

Fiber length and fiber bundle strength (FBS) of commercial cultivars have increased during the past decades and especially since the introduction of objective and affordable fiber property determination via High Volume Instrument (HVI) technology. Kuraparthy and Bowman (2013) reported that between 1980 and 2010 average U.S. FBS increased from approximately 235 kN m kg^{-1} to approximately 294 kN m kg^{-1}; upper-half mean length (UHML) increased from approximately 27.0 to 28.2 mm; and micronaire (MIC) increased from an average of 4.3 to 4.5. Central to the report of Kuraparthy and Bowman (2013) on improved fiber quality, was the assertion that upland cotton (*Gossypium hirsutum* L.) has a narrow genetic base (Brubaker et al., 1999), verified by both theoretical considerations of the polyploid nature of upland cotton and the molecular marker data available at the time of writing. They concluded that despite this presumed narrow genetic base, progress had been made in improving fiber quality.

Upland cotton fiber quality is impacted by the botanical growth of the cotton plant, availability of moisture, heat units, pest control, nutrient availability, and management (Ashley, 1972; Bednarz et al., 2006; Davidonis et al., 2004; Feng et al., 2011). Ramey et al. (1977) reported a positive correlation between ring-spun and open-end spun yarn tenacity and fiber tenacity and fiber length. They also concluded that, in general, comparative fiber quality across environments was stable and correlations of a cultivar's average fiber properties with yarn tenacity across those environments provided a good estimate of yarn properties. Meredith et al. (1991) stated that much of the fiber property variability in upland cotton was genetic in origin, and that breeders needed information on the impact of individual fiber traits on the commodity's final product, yarn. They evaluated the relationship between fiber properties and yarn tenacity across 19 cultivars that were grown concurrently in Mississippi and South Carolina in 1986. They used yarn sizes of 14 and 22 Ne open-end spun yarns and 20 and 50 Ne ring-spun yarns, both from miniature spinning frames, and correlated those values with Stelometer fiber length, Stelometer fiber strength, and fiber fineness as determined by Arealometer, Shirley fine maturity test, and Causticaire. They reported that Stelometer bundle strength,

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fiber length, and fiber fineness were significantly associated with yarn strength with R^2 values of 0.89, 0.52, and 0.50, respectively. Meredith et al. (1991) concluded that upland cotton breeding programs should concentrate on genetically improving FBS to improve cotton's portfolio of yarn products.

Measurement of cotton fiber properties were automated with several individual instruments engineered into a single HVI beginning in 1980 (Delhom et al., 2020). Delhom et al. (2020) and Latimer et al. (1996) verified the accuracy of HVI methodology, and HVI has become the standard for determining MIC (a measure of fiber fineness that is confounded by fiber maturity), fiber length as UHML, uniformity of fiber lengths as an index (UI), and fiber strength as FBS.

Many HVI and Advanced Fiber Information System (AFIS) measurements are significantly correlated, indicating the complexity and difficulty in improving both yield potential and fiber quality in upland cotton. Breeders are aware of the negative relationships between yield and such quality factors as FBS or UHML that limit the simultaneous selection for yield and fiber quality traits that are important in yarn production. Despite these known negative associations, UHML and FBS have been incrementally improved along with yield potential (Kuraparthy and Bowman, 2013). Previous reports on the correlations, or regression, of fiber and yarn properties generally ignore the extremes in a specific fiber property, for example, high or low FBS or UHML, in their data set development, analyses, and reports. The objective of this report was to examine if the level of association or correlation of selected HVI and AFIS characteristics with yarn tenacity and appearance varied when the population exhibited the extremes of FBS and UHML fiber characteristics.

MATERIALS AND METHODS

Hugie (2015) evaluated 155 $F_{2:4}$ lines that had been derived from five breeding populations within the Texas A&M AgriLife Research cotton breeding program at College Station, TX in 2013 as a part of a dissertation research program. These lines had been selected as part of a divergent selection program to establish populations with either relatively high or low UHML. Seventy-three $F_{2:5}$ lines were subsequentially selected and grown at College Station in 2014. Lint from each of these 2013 and 2014 progeny rows, a total of 228 observations, was subjected to HVI fiber testing, AFIS analysis, and mini-spun 30 Ne ring-spun yarn evaluation.

Schumann (2018) explored the possibility that obsolete upland cotton cultivars contained alleles for fiber quality that had been lost or did not exist in modern cultivars and breeding lines at Texas A&M AgriLife Research breeding program. Schumann grew 127 obsolete and near-modern commercial cultivars plus several program breeding lines at Weslaco, TX in 2016. These 127 genotypes consisted of 94 mostly obsolete cultivars and 33 program breeding lines. Seed cotton samples were hand harvested from each entry by Hugie and Schumann, ginned on a laboratory 10-saw gin, and HVI and AFIS fiber properties plus mini-spun 30 Ne ring-spun yarn properties determined by the Fiber and Biopolymer Research Institute at Texas Tech University. All plots were grown at the Weslaco Research and Extension Center in Weslaco, TX or at the Texas A&M Research Farm at College Station, TX. All production practices were normal for the region, including furrow irrigation as deemed appropriate.

These 355 observations of fiber properties correlated with yarn tenacity and yarn appearance were use to create five data sets: total group consisting of 355 observations; high-FBS group consisting of 102 observations with FBS of 346 to 394 kN m kg^{-1}; low-FBS group consisting of 104 observations with FBS ranging from 259 to 311 kN m kg^{-1}; long-UHML group consisting of 109 observations with UHML of 32.8 to 37.3 mm; and short-UHML group consisting of 104 observations with UHML of 25.7 to 29.0 mm. Pearson's correlation coefficient (r) and coefficient of determination (R^2) were determined within each of these five populations to determine if the associations, as defined by correlations, among HVI and AFIS fiber traits with yarn tenacity and yarn appearance are impacted by the level of fiber quality in the data set.

RESULTS AND DISCUSSION

The overall population consisted of 355 observations and should be considered the best general estimate of the correlations among HVI and AFIS fiber traits with yarn tenacity and yarn appearance. Correlations were determined across the entire data set, resulting in 780 comparisons (data not shown). Of those 780 possible pairs of components, approximately 12% were significantly different than zero, supporting the complex interactions in cotton fiber

and essential yarn properties. Because developing a regression model to predict tenacity would violate the independence assumption, breeders have depended heavily on correlation analyses of individual components to ascertain the importance of HVI and AFIS properties in cultivar development.

Descriptive statistics for the five groups are given in Tables 1 and 2. The FBS of the total group ranged from 258 to 394 kN m kg^{-1}. Among these 355 data points, 55 samples exhibited FBS from 258 to 293 kN m kg^{-1}, 106 samples were between 293 and 333 kN m kg^{-1}, 152 were from 333 to 362 kN m kg^{-1}, and 42 ranged from 362 to 394 kN m kg^{-1}. The UHML of the total group ranged from 25.7 to 37.3 mm with 35 genotype data points having UHML below 28 mm, 117 between 28 and 30 mm, 118 between 30 and 33 mm, 72 between 33 and 35 mm, and 13 between 35 and 37 mm. The remaining HVI and AFIS descriptive statistics for the high- and low-FBS groups, and long- and short-UHML groups, as well as the range of yarn tenacity values, were normal for upland cotton produced in Central and South Texas.

The r value for yarn tenacity with FBS within the total group was 0.85, similar to the findings of Meredith et al. (1991), suggesting that 75%, R^2, of the variation in yarn tenacity was positively associated with variation in FBS (Table 3). When the data set was divided into high- and low-FBS groups, R^2 values were 0.32 and 0.62, respectively, indicating that approximately 10% of FBS variation in the high-FBS group was associated with variation in yarn tenacity. This suggested that FBS above 346 kN m kg^{-1}, while ignoring all other fiber properties, could provide diminishing returns relative to improving yarn tenacity. At present there are not many genotypes, especially cultivars, of upland cotton exhibiting FBS above this value to further test that hypothesis. Correlations of FBS with yarn tenacity among the total group, long-UHML group, and short-UHML group were relatively constant and strong at 0.85, 0.71, and 0.72, respectively, suggesting that UHML remained highly associated with yarn tenacity regardless of FBS limits.

The r value for yarn tenacity with UHML within the total group was 0.87, again suggesting that 75% of the variation in UHML was associated with variation in tenacity (Table 3). The r values in the long-UHML group and short-UHML group were 0.63 and 0.38, respectively. These values suggest that as breeders increase UHML this relationship does not change, but if UHMLs are below 29 mm this HVI parameter has reduced predictive power

Table 1. Summary statistics for HVI[z] and AFIS[y] cotton fiber properties, yarn tenacity, and yarn appearance across 355 observations grouped by high and low FBS

	Total group (n=355)			High FBS group (n=102)			Low FBS group (n=104)		
Variable	Mean	min	max	Mean	min	max	Mean	min	max
MIC (units)	4.2	2.8	5.6	4.0	2.8	5.2	4.5	3.5	5.6
UHML (mm)	31.0	25.7	37.3	32.5	28.7	37.3	28.4	25.7	32.8
UI (%)	82	77	86	84	80	86	81	77	83
FBS (kNmkg^{-1})	327	258	394	362	346	394	292	259	311
Lw (mm)	27.0	21.8	32.0	28.5	22.9	32.0	25.0	21.8	29.7
Ln (mm)	21.8	17.3	27.7	23.1	18.0	27.2	20.0	17.3	24.1
SFCw (%)	7.0	2.5	14.2	6.2	2.5	12.8	8.2	2.5	14.2
SFCn (%)	22.7	8.3	37.0	20.8	9.6	31.9	25.0	8.3	37.0
Fine (mTex)	156	121	201	150	121	181	165	136	201
Hs (mTex)	173	144	207	166	146	191	184	163	207
Yarn tenacity (cNtex)	17.3	9.7	24.0	20.2	16.1	24.0	13.7	9.7	18.5
AvgIPI (#)	518	186	1488	462	186	878	583	196	1488

[z]High Volume Instrument (HVI) fiber properties: MIC, micronaire; UHML, upper-half mean length; UI, uniformity index; FBS, fiber bundle strength

[y]Advanced Fiber Information System (AFIS) fiber properties: Lw, length by weight; Ln, length by number; SFCw, short fiber (< 12.5 mm) content by weight; SFCn, short fiber content by number; Fine, fineness or diameter of fibers; Hs, standard fineness calculated as fineness/maturity ratio; and yarn tenacity defined as force required to break yarn; AvgIPI, average yarn imperfections index defined as the average of thin40, thin50, thick35, thick50, neps140, and neps280

Table 2. Summary statistics for HVI[z] and AFIS[y] cotton fiber properties, yarn tenacity, and yarn appearance across 355 observations grouped by long and short UHML

	Total group (n=355)			Long UHML group (n=109)			Short UHML group (n=104)		
Variable	Mean	min	max	Mean	min	max	Mean	min	max
MIC (units)	4.2	2.8	5.6	3.8	2.8	5.2	4.6	3.6	5.6
UHML (mm)	31.0	25.7	37.3	33.8	32.8	37.3	28.0	25.7	29.0
UI (%)	82	77	86	83	81	86	81	77	83
FBS ($kNmkg^{-1}$)	327	259	394	345	307	394	297	259	349
Lw (mm)**	27.0	21.8	32.0	29.2	22.9	32.0	24.7	21.8	29.7
Ln (mm)	21.8	17.3	27.7	23.4	18.0	27.7	20.0	17.3	24.4
SFCw (%)	7.0	2.5	14.2	6.3	2.6	12.8	7.9	2.5	14.2
SFCn (%)	22.7	8.3	37.0	21.8	10.5	31.9	24.2	8.3	35.1
Fine (mTex)	156	121	201	146	121	181	168	139	201
Hs (mTex)	173	144	207	162	144	182	187	164	207
Yarn tenacity (cNtex)	17.3	9.7	24.0	20.2	16.8	24.0	13.6	9.7	18.2
AvgIPI (#)	518	186	1488	489	255	680	564	274	1241

[z]High Volume Instrument (HVI) fiber properties: MIC, micronaire; UHML, upper-half mean length; UI, uniformity index; FBS, fiber bundle strength

[y]Advanced Fiber Information System (AFIS) fiber properties: Lw, length by weight; Ln, length by number; SFCw, short fiber (< 12.5 mm) content by weight; SFCn, short fiber content by number; Fine, fineness or diameter of fibers; Hs, standard fineness calculated as fineness/maturity ratio; and yarn tenacity defined as force required to break yarn; AvgIPI, average yarn imperfections index defined as the average of thin40, thin50, thick35, thick50, neps140, and neps280

Table 3. Pearson's correlation coefficients and coefficients of determination for HVI[z] and AFIS fiber properties with yarn tenacity within a set of 355 data points and grouped into high/low FBS and long/short UHML

	Total group (n=355)		High FBS group (n=102)		Low FBS group (n=104)		Long UHML group (n=109)		Short UHML group (n=104)	
	r	R^2	r	R^2	r	R^2	r	R^2	r	R^2
MIC	-0.64	0.40	-0.65	0.42	-0.36	0.13	-0.44	0.19	-0.20	0.04
UHML	0.87	0.75	0.73	0.53	0.64	0.41	0.63	0.39	0.38	0.14
UI	0.71	0.51	0.46	0.21	0.34	0.12	0.34	0.12	0.37	0.13
FBS	0.85	0.71	0.32	0.1	0.62	0.38	0.71	0.5	0.72	0.52
Lw	0.80	0.63	0.57	0.33	0.47	0.22	0.47	0.22	0.24	0.06
Ln	0.71	0.5	0.46	0.21	0.31	0.09	0.38	0.15	0.23	0.05
SFCw	-0.45	0.2	-0.22	0.05	-0.16	0.03	-0.21	0.04	-0.22	0.05
SFCn	-0.35	0.12	-0.11[y]	0.01	-0.06	<0.00	-0.20	0.04	-0.18	0.03
Fine	-0.69	0.47	-0.71	0.5	-0.41	0.18	-0.52	0.27	-0.28	0.08
Hs	-0.84	0.7	-0.79	0.63	-0.54	0.29	-0.68	0.46	-0.41	0.16

[z]Abbreviations: HVI, High volume instrument; FBS, fiber bundle strength; UHML, upper-half mean length; Mic, micronaire; UI, length uniformity index; Elong, elongation at break; AFIS, Advanced Fiber Instrument System; Lw, length by weight; Ln, length by number; SFCw, short fiber content by weight; SFCn, short fiber content by number; fine, indication of fiber diameter; Hs, fineness standardized to AFIS fiber maturity

[y]All r values are different that zero at $p < 0.05$ except those underlined

or associations with yarn tenacity. This lower level of association is not of value to breeders because it occurs in a UHML range below current desirability.

In the overall data set of 355 observations, UHML and FBS were correlated with a significant r value of 0.66, $R^2 = 0.43$. In observations categorized into either the long- or short-UHML groups (n = 213), the fiber length and FBS correlated significantly at r = 0.39, $R^2 = 0.15$ (data not shown). Similarly, among the 206 observations within the high- and low-FBS groups, length and strength were correlated at r = 0.21, $R^2 = 0.04$ (data not shown). To further evaluate the relationships within the length and strength groupings, of the 109 observations in the high-FBS group, 46 (42%) were also included in the long-UHML group. However, of the 104 observations with low FBS, 88 (85%) were in the short-UHML group. These numbers suggest a weaker association of UHML and FBS as one selects for or develops higher quality upland cotton germplasm and cultivars, and that stronger yarns are determined by fiber length and fiber bundle strength, as well as other fiber characteristics such as fineness and elongation before break, which were not examined in this report.

Other HVI fiber properties considered in this report were MIC and UI. MIC was negatively associated with yarn tenacity with 40% of the variation in yarn tenacity associated with variation in MIC in the total group (Table 3). When the population was divided into high and low FBS, this association was reduced in the low-FBS group. Breeders select MIC to be within a narrow range of 3.5 to 4.9 with 3.9 to 4.2 most desirable. Thus, it would not be unexpected to find low r values for MIC with many other properties in a small population of observation. In the short-UHML group, a r of -0.20 was found, indicating that within these short-UHML samples, 4% of the variation in MIC was associated with variation in yarn tenacity. Not an unexpected outcome given that MIC is neither maximized nor minimized by breeders.

Breeders are aware of the desirability of uniform fiber lengths but the industry and market system places little value on this parameter; plus there is little to no information on the value of incremental units. In this study, UI was strongly associated with tenacity but only moderately to lowly associated in the high- and low-FBS groups and the long- and short-UHML groups. This finding could reflect the narrowing of the variability ranges in one or both parameters being correlated or indicate a change in the associations with changes in the range of FBS or UHML.

The two AFIS length parameters, average fiber length by weight (Lw) and average fiber length by number (Ln), were positively correlated with yarn tenacity just as UHML (Table 3). These HVI and AFIS measurements are highly correlated so one would expect this result. As with UHML, the r value in the overall group of tenacity with Lw and Ln suggests a strong correlation. The associations were affected by the groupings, however, with the greatest impact in the low-FBS group and short-UHML group. This could be a result of the groupings but because the other subgroups were approximately the same size, such findings could indicate that the associations of any given two traits could become more or less powerful by changing the genetic associations within another parameter in this complex of measurements that attempt to define desirable fiber for making yarns. The association and influence of fiber length, for example, on yarn tenacity or appearance, could be reduced if elevated FBS results in stronger yarn such that an equal incremental increase in UHML would have a greater effect on yarn tenacity at low FBS than higher FBS.

Cotton fibers less than or equal to 12.5 mm are of increasing concern as a selectable parameter, probably with the advent of AFIS and the capability of breeders to objectively select on this parameter. HVI has been programed to measure short fiber content (SFC) as well but only in recent years. As one would expect, as SFC increases, yarn tenacity decreases. This occurred regardless of group but the association within the total group was low to moderate at -0.35 for SFC by number (SFCn) and -0.45 for SFC by weight (SFCw), explaining 12 to 20% of the tenacity variation (Table 3). This result could be expected because many of the short fibers in raw cotton can be removed in the carding process. However, when the population was sorted into high- and low-FBS groups and long- and short-UHML groups, the r values dropped and SFC explained < 0 to 5% of yarn tenacity variation. Again, additional populations need to be developed to ascertain the reliability of these results. However, results suggest that SFC, although correlated with yarn tenacity, is not as important as fiber length and strength as a selection criterion for developing new and improved cultivars.

Breeders also are cognizant of the impact of fiber fineness or diameter on yarn tenacity. The finer the

fibers, disregarding other fiber characteristics, then more fibers can be placed in the cross section of a given diameter yarn and, therefore, the stronger the yarn. The fineness (Fine) measurement in AFIS identifies the average diameter of fibers in the sample and dividing that number by the AFIS maturity ratio standardizes the value for comparison purposes. As expected, both parameters are negatively associated with yarn tenacity (Table 3). Recall that lower Fine and standard fineness (Hs), that is, fiber fineness standardized to the level of fiber maturity, values indicate finer fibers, and therefore, lower numbers were associated with higher yarn tenacity values. Correlation values in all groups were moderate to strong, ranging from -0.41 to -0.84 across all groups, except for short-UHML group where variation in yarn tenacity was associated with 8%, r = -0.28, of the variation in Fine. Hs was consistently the stronger correlation with yarn tenacity regardless of grouping, suggesting that breeders should select on this estimate of fiber fineness or diameter.

Standard yarn analyses provide several indicators of uniformity of yarn, such as the number of places in a kilometer of yarn that have diameters of a smaller or larger percent than the average diameter of the yarn and the number and size of neps, which are fiber entanglements that were not removed in the fiber carding process. These imperfections in yarn appearance can lead to loss of aesthetic appeal, yarn strength, comfort, and performance. Breeders usually have little or no access to yarn development and analyses, especially in early segregating and selection generations. Thus, as with yarn strength, breeders depend mostly on HVI fiber traits as predictors of yarn performance.

Breeders usually consider MIC, FBS, and UHML as the first fiber parameters, and maybe the only parameters, when deciding which genotypes to keep and which to discard relative to fiber quality. Desirable MIC values are determined by the industry and must be within the range of 3.5 to 4.9 to avoid reduced price received. These three parameters have the most impact on the farm value of the product, and the U.S. classing system rewards higher FBS and longer UHML. Potential yarn appearance has essentially no role in raw fiber value. However, the accumulation of the data reported herein over the course of several years provides the opportunity to look at the relationship of both HVI and AFIS fiber properties regularly obtainable by breeders and their correlation with yarn appearance.

Data in Table 4 indicate that UI and SFCw had the greatest correlations with average imperfection index (AvgIPI) in this study, regardless of the group-

Table 4. Pearson's correlation coefficients and coefficients of determination for HVI[z] and AFIS fiber properties with yarn appearance, average IPI[y], within a set of 355 data points and subdivided into high/low FBS and long/short-UHML groups.

	Total group (n=355)		High FBS group (n=102)		Low FBS group (n=104)		Long UHML group (n=109)		Short UHML group (n=104)	
	r	R^2	r	R^2	r	R^2	r	R^2	r	R^2
MIC	-0.02[x]	0.00	-0.12	0.01	-0.22	0.05	-0.15	0.02	-0.28	0.08
UHML	-0.18	0.03	0.12	0.01	-0.03	0.00	-0.11	0.01	-0.17	0.03
UI	-0.55	0.30	-0.53	0.28	-0.64	0.41	-0.44	0.19	-0.59	0.34
FBS	-0.37	0.14	-0.21	0.04	-0.45	0.20	-0.17	0.03	-0.36	0.13
Lw	-0.21	0.05	0.01	0.00	-0.02	0.00	-0.30	0.09	-0.11	0.01
Ln	-0.22	0.05	-0.16	0.02	0.03	0.00	-0.29	0.08	-0.13	0.02
SFCw	0.38	0.14	0.41	0.16	0.28	0.08	0.33	0.11	0.39	0.15
SFCn	0.22	0.05	0.38	0.14	0.04	0.00	0.24	0.06	0.20	0.04
Fine	0.03	0.00	-0.01	0.00	-0.18	0.03	-0.05	0.00	-0.23	0.05
Hs	0.18	0.03	0.17	0.03	-0.10	0.01	0.14	0.02	-0.07	0.01

[z]HVI, High volume instrument; FBS, fiber bundle strength; UHML, upper-half mean length; Mic, micronaire; UI, length uniformity index; Elong, elongation at break; AFIS, Advanced Fiber Instrument System; Lw, length by weight; Ln, length by number; SFCw, short fiber content by weight; SFCn, short fiber content by number; fine, indication of fiber diameter; Hs, fineness standardized to AFIS fiber maturity.

[y]average imperfection index as the average of the number of thin and thick places km^{-1} of yarn plus the number of neps of a given size. Average IPI for this report was the average of thin40, thin50, thick35, thick50, neps140, and neps280.

[x]All r values are different than zero at $p < 0.05$ except those underlined

ing by FBS or UHML. Both parameters are measurements of fiber length uniformity and logically, yarn appearance would be improved if every fiber was the same length. SFCn was essentially the same as SFCw except in the low-FBS group where r = 0.04 was not different ($p = 0.05$) than zero. Interestingly, none of the measurements of fiber diameter, that is, MIC, Fine, and Hs, were correlated uniformly across data groups with AvgIPI, and in those cases where a significant r occurred, for example, MIC in the low-FBS and short-UHML groups, explained only 3 to 8% of the variation in AvgIPI. These data generally agree with those of Chanselme et al. (1997) and indicate that the associations of HVI and AFIS fiber traits with yarn appearance are not impacted within populations of breeding material at the current extremes of FBS and UHML.

CONCLUSIONS

The correlations reported herein indicate that all HVI traits for fiber length and strength and AFIS Fine and Hs characteristics were highly correlated with yarn tenacity. Accepting that the total group of 355 observations represent the most accurate estimate, most r values for MIC, UHML, UI, and FBS were essentially as robust in the subgroups as in the total group, indicating that breeders should not expect a change in these associations as they improve an individual trait. However, the correlations of SFCw and SFCn with yarn tenacity were not as consistent and exhibit a different relationship with tenacity as other traits are maximized or minimized.

The correlation of most HVI and AFIS traits with yarn appearance reported herein were weak correlations and thus conclusions of any changes in the robustness of the r values across subpopulations are problematic. However, the correlations with yarn AvgIPI suggested that breeders should be aware of the importance of UI and SFC.

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