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TEXTILE TECHNOLOGY

The Ultraviolet Protection Factor of Naturally-pigmented Cotton

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ABSTRACT

The sun-blocking properties of a textile are enhanced when a dye, pigment, delustrant, or ultraviolet absorber finish is present that absorbs ultraviolet radiation and blocks its transmission through a fabric to the skin. For this reason, dyed fabrics provide better sun protection than bleached fabrics. Since naturally-colored cottons contain pigments that produce shades ranging from light green to tan and brown, it seemed reasonable to postulate that they would provide better sun protection than conventional bleached cotton, and that natural pigments might prove more durable to laundering and light exposure than dyes, but there is no published research on the ultraviolet transmission values for naturally-pigmented cottons. The purpose of this study was to determine the ultraviolet protection (UPF) values of naturally-pigmented cotton in three shades (green, tan, and brown), and the effect of light exposure and laundering on the sun-blocking properties of naturally-pigmented cotton. Naturally-pigmented cotton specimens were exposed to xenon light and accelerated laundering, ultraviolet transmission values measured, and UPF values calculated following light exposure and laundering. The naturally-pigmented cottons exhibited significantly higher UPF values than conventional cotton (bleached or unbleached). Although xenon light exposure and laundering caused some fading, the UPF values of naturally-pigmented cotton continue to be sufficiently high so that all three shades continue to provide good sun protection after the equivalent of 5 home launderings and 80 American Association of Textile Chemists and Colorists fading units (AFUs) of xenon light exposure.

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Prolonged and repeated exposure to ultraviolet radiation (UVR) from sunlight has been identified as the cause of an increase in the incidence of skin cancer in the U.S. population. Limiting the skin's exposure to sunlight, especially during the hours of maximum intensity, 1000 h to 1400 h (10 am to 2 pm), is the best way to reduce risk. For persons who must work outdoors this is not feasible, which is why well-designed clothing made from UVR-blocking textiles is their best option.

Many factors influence the UVR transmission properties of textiles. Among the most important factors are fiber type, dyes and finishes, and fabric porosity (Abidi et al., 2001; Capjack et al., 1994; Crews et al., 1999; Pailthorpe, 1993; Reinert et al., 1997; Zhou and Crews, 1998). Radiation absorbed by a dye, pigment, delustrant, or UV absorber cannot be passed through to the skin and in this way enhances sun protection provided by a textile. In general, dyed fabrics provide better sun protection than bleached fabrics. Pailthorpe (1993) observed that unbleached cotton has a higher UPF (ultraviolet protection factor) than bleached cotton and speculated that this was due to the pigments remaining in unbleached cotton. The UVR transmission of bleached conventional cotton is nearly twice as high as unbleached conventional cotton (Crews et al., 1999).

Pigments found in naturally-pigmented cotton produce shades ranging from tan to green and brown. Naturally-pigmented green cotton derives its color from caffeic-acid, a derivative of cinnamic acid, found in the suberin (wax) layer that is deposited in alternating layers with cellulose around the outside of the fiber (Schmutz et al., 1993; Schmutz et al., 1994). The isolated compound is fluorescent (Conrad, 1941; Schmutz et al., 1993) and it has been theorized that its purpose is to absorb UVR radiation in order to protect the seed (Ryser, 1999).

This led to speculation that naturally-pigmented green cotton might have superior UV blocking properties compared with conventional bleached cotton, but no published research has reported on the UPF or UVR transmission values for naturally-pigmented cottons.

Brown and tan cottons derive their color from tannin vacuoles in the lumen of the fiber cells (Halloin, 1982), rather than in the wax layer as in green cotton. Thin layer chromotography analysis revealed the pigment to be a tannin precursor, catechin, and tannin derivatives (Ryser, 1999). The brown color does not form until the fibers are exposed to oxygen and sunlight, which happens when the seed pod opens.

Another point of interest was the potential long-term stability of the UVR-blocking properties of naturally-pigmented cottons. Since the parts of the molecules that provide color in naturally-pigmented cotton are inherent to the fiber, it seemed reasonable to expect that the UVR transmission of naturally-pigmented cotton might remain stable even as it faded upon light exposure and laundering. Most previous research focused on the advantages of the inherent color (Kimmel and Day, 2001) or focused on the flame resistance of brown cotton (Williams, 1994) and color changes (darkening instead of fading) occurring with certain laundering methods (Őktem et al., 2003; Van Zandt, 1994).

The purpose of this study was to determine the UVR transmission and UPF values of naturally-pigmented green, tan, and brown cotton. Also of interest was whether naturally-pigmented cottons would retain their UVR blocking properties following laundering and light exposure.

MATERIALS AND METHODS

Treatment and experimental design. Bleached conventional cotton and three naturally-pigmented cottons (green, tan, and brown) were included in this study and analyzed separately. The experiment was conducted and analyzed as a split plot design with the main plot arranged in a random complete block design. The treatment design was a 3 x 3 factorial. The sub-plot treatment factor was type of laundering, which had three levels: none, laundered with detergent alone, and laundered with detergent plus non-chlorine bleach. The whole plot treatment factor was the amount of light exposure which also had 3 levels: none, 40 AFUs, and 80 AFUs. The four dependant variables analyzed included color change (ΔE), UPF, percentage UVA transmission, and percentage UVB transmission. The entire experiment was replicated three times.

Conventional and naturally-pigmented cotton. Conventional, bleached cotton print cloth (Style 400M) was secured from Testfabrics (West Pittston, PA). The naturally-pigmented green, tan, and brown cotton fabrics included in this study, all were donated by Peru Naturtex Partners (Lima, Peru). The cotton fabrics were characterized (Table 1) according to the following American Society for Testing and Materials (ASTM, 2004) test methods: ASTM D 3775, Standard Test Method for Fabric Count of Woven Fabric; ASTM D 3776, Standard Test Method for Mass per Unit Area (Weight) of Fabric, Option B, Full Width Sample; and ASTM D 1777, Measuring Thickness of Textile Materials. Thickness measurements were made using a C&R Thickness Tester # CS-55 produced by Custom Scientific Instruments, Inc. (Newark, NJ).

Light exposure. Specimens were exposed to light for 40 and 80 AFUs according to American Association of Textile Chemists and Colorists Test Method 16: Colorfastness to Light, Option E using an Atlas (Chicago, IL) Ci65A Xenon Weather-Ometer (AATCC, 2002). AATCC Blue Wool Lightfastness Standards L5 and L6 were used to control length of exposure.

Laundering. Specimens were laundered with and without non-chlorine bleach. One accelerated laundering was performed using an Atlas (Chicago, IL) Launder-Ometer, model LO-3837, according to AATCC Test Method 61: Colorfastness to Laundering, Home and Commercial: Accelerated (AATCC, 2002). Laundering conditions outlined in Test 2A were followed. The color loss resulting from five typical home launderings in warm water is "roughly

Table 1. Construction characteristics of cotton fabrics evaluated

Cotton type	Source	Weave	Thread count (w x f per cm)	Weight (g/sq. m.)	Thickness (mm)
400M	TestFabrics	Plain	33 x 29	112	0.25
Green	PeruNaturetex	Plain	24 x 22	156	0.4
Brown	PeruNaturetex	Plain	24 x 22	156	0.4
Tan	PeruNaturetex	Plain	24 x 22	156	0.35

approximated by one 45 minute test" conducted according to those conditions (AATCC, 2002). AATCC Standard Reference Detergent (without optical brighteners) WOB was selected in order to prevent the introduction of optical brightening agents (OBAs), which could confound results because they are known to decrease UVR transmission (Zhou and Crews, 1998). For the launderings with a non-chlorine bleach, sodium perborate was added to the wash liquor. The amount of sodium perborate added to each Launder-Ometer canister corresponded to the percentage of available oxygen found in Clorox 2 (Chlorox Co.; Oakland, CA), a popular, commercially-available non-chlorine bleach. The percentage of available oxygen was determined according to AATCC Test Method 172: Colorfastness to Non-Chlorine Bleach in Home Laundering (AATCC, 2002). Following laundering, specimens were conditioned overnight at 72±2°C and 65±2% relative humidity prior to instrumental evaluation of color change and measurement of UVR transmission and UPF values.

UPF and percentage transmission. Percentage UVA and UVB transmission were measured and the UPF calculated according to AATCC Test Method 183: Transmittance or Blocking of Erythemally Weighted Ultraviolet Radiation through Fabrics (AATCC, 2002). Measurements were performed using a Cary 50 UV/Visible spectrophotometer (Varian; Palo Alto, CA) with an integrating sphere attachment and a Schott glass UG-11 filter. Ultraviolet protection factor (UPF) was calculated using mean percentage transmission in the UVA region (320-400 nm) and mean percentage transmission in the UVB region (280-320 nm) according to the following equation:

$$UPF_i = \frac{\sum_{\lambda=280}^{400} E_\lambda \times S_\lambda \times \Delta\lambda}{\sum_{\lambda=280}^{400} E_\lambda \times S_\lambda \times T_\lambda \times \Delta\lambda}$$

where:
E_λ = relative erythemal spectral effectiveness
S_λ = solar spectral irradiance
T_λ = average spectral transmission of the specimen
Δ_λ = measured wavelength interval (nm)

The UPF equation weighs the UVB radiation more heavily than the UVA radiation because UVB radiation causes considerably more biological damage than UVA. Consequently, many scientists and consumer advocates prefer to use UPF values, rather than percentage UVR transmission, to convey a fabric's sun protection properties (Hatch, 2001).

Color change. Measurement of color change was performed according to AATCC Evaluation Procedure 7: Instrumental Assessment of the Change in Color of a Test Specimen (AATCC, 2002). Measurements were made using a HunterLab Ultrascan XE diffuse/8 spectrophotometer (Hunter Associates; Reston, VA), with specular reflection excluded, illuminant D65 and 10 observer, and a 2.54 cm area of view. Total color change (ΔE) was calculated using the CIE 1976 L*a*b* equation (AATCC, 2002).

Statistical analysis. All dependent variables were statistically analyzed using a general linear model analysis of variance (ANOVA) procedure (SAS Institute Inc.; Cary, NC). ANOVAs were performed for each type of cotton to determine the influence of level of light exposure and level of laundering on UPF and color change. The level of significance was $P \leq 0.05$ for these tests. When the main effects were significant, Tukey's post hoc mean comparison tests were performed to determine differences among means.

RESULTS AND DISCUSSION

Results of the effects of light exposure and laundering on mean UVA and UVB transmission, UPF, and ΔE values for four types of cotton are shown in Tables 2, 3, 6, and 9. The statistical analysis of the UPF and ΔE data for each type of cotton is presented and discussed in subsequent sections, but the UVR transmission data will not be discussed. Percentage UVA and UVB transmission values are used to calculate UPF values and are sometimes useful in better understanding the sun protective properties of fibers. An in-depth examination of the UVR transmission data afforded little additional insight into the sun blocking properties of these cotton fibers; therefore, the UVR transmission data is presented but not discussed separately.

Conventional, bleached cotton. Results of the effect of light exposure and laundering on conventional, bleached cotton are shown in Table 2. Conventional, bleached cotton exhibited UPF values ≤4, which means that it offers little sun protection. A UPF rating of 15 or above is required before a fabric may be labeled sun protective according to the voluntary ASTM D6603 Standard Guide for Labeling of UV-Protective Textiles (ASTM, 2004). Analysis

Table 2. Effect of light exposure and laundering on ultraviolet protection factor (UPF) values, percentage ultraviolet (UV) radiation transmission, and color difference (ΔE) for conventional, bleached cotton

Light exposure (AFUs) [y]	Laundering [z]	UPF	UVA transmission (%)	UVB transmission (%)	ΔE
0	N	4.0	27.2	21.1	0.1
0	WBL	3.8	27.9	22.7	0.5
0	WOBL	3.8	27.8	22.3	0.6
40	N	3.8	27.6	22.3	0.4
40	WBL	3.7	28.2	23.3	0.7
40	WOBL	4.0	23.6	21.7	0.6
80	N	3.8	27.8	22.6	0.6
80	WBL	3.7	28.2	23.6	0.6
80	WOBL	3.6	28.3	24.1	0.7
Std. Error		0.2	1.5	0.8	0.1

[y] AATCC fading units.

[z] N = no laundering, WOBL = laundered without bleach, WBL = laundered with bleach.

of UPF values of the conventional, bleached cotton shows that neither light exposure nor laundering significantly affected its mean UPF value. Despite some shrinkage, bleached cotton is so transparent to UVR radiation that its UPF remains virtually unchanged by the shrinkage associated with laundering.

Analysis of the mean ΔE of the conventional cotton showed that both light exposure (df = 2; F = 18.40; P = 0.0096) and laundering (df = 2; F = 30.60; P < 0.0001) were significant independent variables. Even though the instrumentally-detected color change proved statistically significant, it was so small that it was not visually perceptible either as yellowing or whitening. Ordinarily, ΔE would not be measured on undyed fabrics, but for the sake of consistency and comparison to the naturally-pigmented cottons, it was performed on the conventional bleached cotton in this study.

Naturally-pigmented green cotton. Results of the effect of light exposure and laundering on UPF and ΔE of the naturally-pigmented green cotton are shown in Table 3. Naturally-pigmented green cotton had a mean UPF of 64 initially, whereas the conventional, bleached cotton print cloth had a mean

Table 3. Effect of light exposure and laundering on ultraviolet protection factor (UPF) values, percentage ultraviolet (UV) radiation transmission, and color difference (ΔE) for naturally-pigmented green cotton

Light exposure (AFUs) [y]	Laundering [z]	UPF	UVA transmission (%)	UVB transmission (%)	ΔE
0	N	64	2.4	0.8	0.2
0	WOBL	216	1.5	0.3	0.8
0	WBL	140	1.7	0.4	5.4
40	N	47	3.8	1.3	7.4
40	WOBL	101	2.6	0.6	7.0
40	WBL	77	3.1	0.9	6.8
80	N	32	4.8	2.1	9.9
80	WOBL	46	3.7	1.2	9.5
80	WBL	43	3.9	1.4	9.6
Std. Error		21	0.2	0.3	1.5

[y] AATCC fading units.

[z] N = no laundering, WOBL = laundered without bleach, WBL = laundered with bleach.

UPF of only 4. Furthermore, naturally-pigmented green cotton retained a much higher UPF value than conventional, bleached cotton throughout both laundering treatments (with and without bleach) and following 40 and 80 AFUs of light exposure.

Analysis of UPF values showed that both light exposure (df = 2; F = 13.99; P = 0.0156) and laundering (df = 2; F = 10.54; P = 0.0023) significantly affected the mean UPF values of naturally-pigmented green cotton. A significant interaction between light exposure and laundering (df = 4; F = 3.29; P = 0.0487) indicated that the influence of light on UPF depended on whether specimens remained unlaundered or were laundered with or without bleach. Tukey's post hoc mean comparison tests, performed to determine where significant differences existed, showed that laundering resulted in significant increases in the UPF values for all of the naturally-pigmented cottons. The increase in UPF and decrease in the percentage of UVA and UVB transmission values following laundering can be attributed to shrinkage, which reduced fabric porosity and was visibly noticeable. On the other hand, light exposure reduced the mean UPF of green cotton across all levels of laundering, but the reduction proved statistically significant only for specimens laundered without bleach (Table 4). Nevertheless, even after 80 AFUs of light exposure, the UPF of unlaundered, naturally-pigmented green cotton remained above 30, which is high enough for an ASTM sun protective label rating of "very good" (UPF = 25 to 39). Furthermore, the UPF of the laundered green cotton remained above 40, which is sufficient for a rating in the ASTM sun protection category of "excellent" (UPF $\geq$ 40).

Table 4. Results of mean comparison tests on mean ultraviolet protection factor (UPF) values of naturally-pigmented green cotton following light exposure

Laundering	UPF values [z]		
	0 AFUs	40 AFUs	80 AFUs
None	64 Aa	47 Aa	32 Aa
Without bleach	216 Ba	101 Ab	46 Ab
With bleach	140 ABa	77 Aa	43 Aa

[z] **Means followed by the same lower case letter across a row or by the same upper case letter down a column are not significantly different according to Tukey's post hoc mean comparison test at P = 0.10. AFUs are AATCC fading units.**

It must be acknowledged that the specimens included in this study were not subjected to 100 AFUs of light exposure or to 40 home launderings as outlined in ASTM D6544 Standard Practice for Preparation of Textiles Prior to Ultraviolet (UV) Transmission Testing for "prepared-for-testing" specimens (ASTM, 2004). The ASTM Standard Practice states that manufacturers may either report UPF values for "unprepared" (unlaundered and unexposed) specimens or "prepared" specimens, whichever value is lower, because the UPF value placed on a garment label "needs to be the lowest protection value expected during consumer use over a two-year period" (ASTM, 2004). The results of this study show that the majority of the color loss in the naturally-pigmented cottons occurred during the first 40 AFUs of light exposure. In fact, there was no significant difference in ΔE between 40 and 80 AFUs for any of the naturally-pigmented cottons. Therefore, extrapolation of the data indicates that the green cotton could still be labeled as sun protective after 100 AFUs of light exposure. It may not be eligible for a rating of excellent (UPF $\geq$ 40), but the data indicate that the green cotton would be eligible for a rating of at least "good" (UPF = 15 to 24).

It also must be acknowledged that these data represent the UPF values of naturally-pigmented cottons following 5 home launderings, rather than 40 home launderings. On the other hand, if the naturally-pigmented cotton fabrics were subjected to typical home laundering, they would be laundered in a detergent containing an OBA, because it is almost impossible to buy a home laundry detergent without an OBA. Because OBAs accumulate with repeated laundering, the UPF values of cotton fabrics laundered at home by the average consumer typically increase significantly over time, rather than decrease (Zhou and Crews, 1998). Zhou and Crews (1998) found that some conventional cottons with a UPF of $\leq$4 before laundering, exhibited UPFs as high as 50 after only 20 home launderings. Since a detergent without an OBA was used in this study, these naturally-pigmented specimens actually exhibited lower UPF values following the combination of laundering and light exposure than would be the case if a typical home laundry detergent were used and 40 launderings conducted.

Consequently, it could be argued that the UPF values of the "unprepared" naturally-pigmented specimens included in this study are actually the lowest UPF values likely to be encountered by the average consumer and, therefore, the values that the ASTM guidelines would require to be used for determining the protection category for a garment label. In fact, it has been the experience of our laboratory, which has conducted UPF testing for a number of manufacturers, that the UPF value of the so-called "unprepared" specimen is always the lowest UPF value. For these reasons, it seemed valid to compare these data (both before and after light exposure and laundering) with the UPF values required for the various UV-protection categories given in ASTM D6603 Standard Guide for Labeling of UV-Protective Textiles (ASTM, 2004).

ANOVA performed on ΔE values showed that light (df = 2; F = 20.59; P = 0.0078) significantly affected the mean ΔE of naturally-pigmented green cotton, but laundering did not. Tukey's post hoc mean comparison test showed that exposure to 40 and 80 AFUs resulted in significant amounts of color change (ΔE) in the green cotton (Table 5). Following 80 AFUs of light exposure, the green cotton exhibited 9.7 units of color change. This was the largest amount of color change of all of the naturally-pigmented cottons. The color loss (fading) due to 80 AFUs of xenon light exposure was visually perceptible and equivalent to a step 2 on the AATCC Gray Scale for Color Change (AATCC, 2002). The fading suggests that the pigments or the cinnamic acid derivatives found in the wax content of green cotton were damaged by UVR so that they could no longer absorb the radiation, which allowed it to pass through the fibers. Nevertheless, if laundered so that shrinkage reduced the porosity of the fabric, the naturally-pigmented green cotton specimens exhibited a UPF greater than 40 even after significant color loss due to 80 AFUs of light exposure, which gives it an ASTM sun protection label rating of "excellent" (UPF = 40 or greater).

Table 5. Results of mean comparison tests on mean color difference (ΔE) of naturally-pigmented green cotton following laundering

Light exposure (AFUs) [y]	Mean ΔE [z]
0	2.1 a
40	7.1 b
80	9.7 b

[y] AATCC fading units.

[z] Means followed by the same letter are not significantly different according to Tukey's post hoc mean comparison at the P = 0.10.

Naturally-pigmented brown cotton. Results showing the effect of light exposure and laundering on ΔE and UPF of the naturally-pigmented brown cotton are shown in Table 6. Unlaundered, naturally-pigmented brown cotton had a mean UPF of 47, whereas conventional bleached cotton print cloth had a mean UPF of only 4. Furthermore, naturally-pigmented brown cotton retained a higher UPF value throughout all laundering treatments and levels of light exposure than conventional cotton (Tables 7 and 8).

Table 6. Effect of light exposure and laundering on ultraviolet protection factor (UPF) values, percentage ultraviolet (UV) transmission, and color difference (ΔE) for naturally-pigmented brown cotton

Light exposure (AFUs) [x]	Laundering [y]	UPF	UVA transmission (%)	UVB transmission (%)	ΔE
0	N	47	2.9	1.4	0.2
0	WOBL	222	1.4	0.2	0.5
0	WBL	170	1.6	0.4	0.9
40	N	60	3.2	1.1	4.5
40	WOBL	132	2.2	0.6	4.6
40	WBL	100	2.6	0.8	4.3
80	N	43	3.7	1.7	5.2
80	WOBL	89	2.6	0.8	5.3
80	WBL	60	3.0	1.1	5.7
Std. Error		26 [z]	0.2	0.2	0.4

[x] AATCC fading units.

[y] N = no laundering, WOBL = laundered without bleach, WBL = laundered with bleach.

[z] A large standard error is common for specimens with UPF values > 50 according to Gies et al. (2003).

Analysis of ΔE values showed that light (df = 2; F = 117.48; P = 0.0003) significantly affected the color of naturally-pigmented brown cotton, but laundering did not. Tukey's post hoc mean comparison test (see Table 7) showed that exposure to both 40 and 80 AFUs of light resulted in significant amounts of color change (ΔE). The color loss or fading due to 80 AFUs of light exposure was large enough to be visually perceptible and was equivalent to a rating of 3.0 on the AATCC Gray Scale for Color Change (AATCC, 2002). The color loss indicates that some damage occurred to the chromophores, such as the tannins and catechin, a tannin precursor. The color difference after 40 AFUs was smaller and was equivalent to a rating of step 4, which would give this variety of brown cotton a lightfastness rating of L5, which is consistent with previously published data (Őkem et al., 2003).

Table 7. Results of mean comparison tests on mean difference (ΔE) of naturally-pigmented brown cotton following light exposure

Light exposure (AFUs) [y]	Mean ΔE [z]
0	0.5 a
40	4.5 b
80	5.4 b

[y] AATCC fading units.

[z] Means followed by the same letter are not significantly different according to Tukey's post hoc mean comparison test at P = 0.10.

Analysis of the mean UPF of naturally-pigmented brown cotton showed that laundering (df = 2; F = 13.86; P = 0.0008) significantly increased UPF (Table 8), but light exposure, although it caused significant and visually perceptible fading, did not significantly reduce UPF. In fact, the laundered brown cotton, which exhibited no significant decrease in UPF following 80 AFUs of light exposure, maintained a sun protection rating of "excellent" under ASTM 6603 labeling guidelines (UPF = 40 or greater), even after significant fading (ASTM, 2004).

Table 8. Results of mean comparison tests on mean ultraviolet protection factor (UPF) values of naturally-pigmented brown cotton following laundering

Laundering	Mean UPF [z]
None	50 a
Without bleach	147 b
With bleach	110 b

z Means followed by the same letter are not significantly different according to Tukey's post hoc mean comparison test at P = 0.10.

Naturally-pigmented tan cotton. Results showing the effect of light exposure and laundering on ΔE and UPF of the naturally-pigmented tan cotton are shown in Table 9. Naturally-pigmented tan cotton, like the other naturally-pigmented cottons, had a much higher mean UPF of 47 than conventional bleached cotton with a UPF of 4. In fact, although

Table 9. Effect of light exposure and laundering on ultraviolet protection factor (UPF) values, percentage ultraviolet (UV) transmission, and color difference (ΔE) for naturally-pigmented tan cotton

Light exposure (AFUs) [y]	Laundering [z]	UPF	UVA transmission (%)	UVB transmission (%)	ΔE
0	N	47	3.4	1.4	0.1
0	WOBL	73	2.6	0.6	1.0
0	WBL	82	2.6	0.6	0.7
40	N	29	5.5	2.6	5.3
40	WOBL	33	5.2	2.0	5.9
40	WBL	32	5.2	1.9	5.8
80	N	21	6.9	3.5	5.9
80	WOBL	26	5.8	2.4	7.2
80	WBL	27	5.9	2.6	7.2
Std. Error		4.4	0.3	0.3	0.5

[y] AATCC fading units.

[z] N = no laundering, WOBL = laundered without bleach, WBL = laundered with bleach.

it was similar in shade to unbleached conventional cotton, the naturally-pigmented tan cotton had a much higher UFP value (6x higher) than unbleached conventional cotton, which has been found to have a UPF ≤8 (Crews et al., 1999). Furthermore, naturally-pigmented tan cotton retained a higher UPF value than conventional cotton despite significant color loss following laundering treatments and levels of light exposure.

Analysis of ΔE values showed that both light exposure (df = 2; F = 92.55; P = 0.0004) and laundering (df = 2; F = 4.70; P = 0.0310) significantly affected the mean ΔE of naturally-pigmented tan cotton. Tukey's post hoc mean comparison test showed that exposure to both 40 and 80 AFUs of light resulted in significant amounts of color change (ΔE), as did laundering with and without bleach (Table 10). Although significant, the color change in the laundered specimens was not visually perceptible and was equivalent to a rating of Step 4.5 on the AATCC Gray Scale for Color Change (AATCC, 2002). On the other hand, the color loss (fading) due to 40 and 80 AFUs of light exposure was visually perceptible and equivalent to a rating of step 2 on the AATCC Gray Scale for Color Change (AATCC, 2002). Color loss indicates damage to the chromophores, such as tannins and tannin precursors, by UVR.

Table 10. Results of mean comparison tests on mean color difference (ΔE) of naturally-pigmented tan cotton following light exposure and laundering

Light exposure (AFUs) [y]	Mean ΔE [z]	Laundering	Mean ΔE [z]
0	0.6 a	None	3.8 a
40	5.7 b	Without bleach	4.7 b
80	6.8 b	With bleach	4.6 b

[y] AATCC fading units.

[z] Means within the same column followed by the same letter are not significantly different according to Tukey's post hoc mean comparison test at P = 0.10.

Analysis of UPF values showed that there was a significant interaction between light exposure and laundering (df = 4; F = 7.32; P = 0.0032), which indicates that the influence of light on UPF depended on whether specimens were unlaundered with or without bleach. Tukey's post hoc mean comparison test showed there were significant differences between unlaundered specimens and specimens laundered with and without bleach at 0 AFUs of light exposure, but not after 40 or 80 AFUs of light exposure (Table 11). Laundering significantly increased the mean UPF of the unexposed specimens due to reduction in fabric porosity associated with shrinkage. After light exposure, however, the tan cotton experienced fading that negated the positive gains in UPF associated with shrinkage from laundering. Consequently, UPF of the naturally-pigmented tan cotton decreased significantly following light exposure. Nevertheless, the sun-blocking properties of the laundered and light exposed tan cotton samples remained sufficiently high to be labeled as having "very good" (UPF = 25 to 39) sun protection according to ASTM 6603 guidelines, even after 80 AFUs of light exposure (ASTM, 2004).

Table 11. Results of mean comparison tests on mean ultraviolet protection factor (UPF) values of naturally-pigmented tan cotton following light exposure and laundering

Laundering	UPF values [z]		
	0 AFUs	40 AFUs	80 AFUs
None	47 Aa	29 Aab	21 Ab
Without bleach	73 Ba	33 Ab	26 Ab
With bleach	82 Ba	32 Ab	26 Ab

[z] Means followed by the same lower case letter across a row or by the same upper case letter down a column are not significantly different according to Tukey's post hoc mean comparison test at P = 0.10. AFUs are AATTCC fading units.

SUMMARY AND CONCLUSIONS

The results of this study demonstrate that naturally-pigmented cottons have excellent sun protection properties (high UPF values), which are far superior to conventional, bleached or unbleached cotton (green UPF = 30 to 50+; tan UPF = 20 to 45; brown UPF = 40 to 50+; bleached conventional UPF = 4; unbleached conventional UPF = 8). It is clear that the pigments in naturally-pigmented cotton fibers not only provide protection from ultraviolet radiation for the embryonic cotton seeds, they also provide protection from the sun's harmful rays for consumers who wear garments manufactured from these naturally-pigmented fibers. The UPF values of the naturally-pigmented cottons remained high enough, even after 80 AFUs light exposure, so that the fabrics merited sun protection ratings of "good" to "very good" according to ASTM 6603 voluntary labeling guidelines for UV-protective textiles.

Since the results of this study demonstrate that naturally-pigmented cottons offer better UV protection than conventional bleached or unbleached cotton, this should encourage producers to further develop and more vigorously market naturally-pigmented cottons to new, health conscious consumers.

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