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Correlation Between the Ultraviolet Protection Factor and the Weight and Thickness of Undyed Cellulosic Woven Fabrics

Abstract
The protection that a fabric offers against ultraviolet radiation can be quantified by the determination of the in vitro Ultraviolet Protection Factor (UPF). According to the literature, the factor that has a higher influence on the UPF of a fabric is its structure; it determines the aperture of a fabric, and thus the physical barrier that will oppose the passing of ultraviolet radiation. In the present paper, the UPF is correlated with the structural parameters of fabrics which are widely used in their technical description such as weight per surface unit and thickness. Models were defined for fabrics made with three different cellulosic fibres, cotton, Modal and Modal Sun.

Key words: *cellulosic fabric, fabric structure, weight, thickness, Ultraviolet Protection Factor (UPF).*

■ Introduction

Exposure to minimal doses of the sun is beneficial for the organism since it contributes to the development of bones and the assimilation of vitamins. However, overexposure to the sun increases the risk of permanent damage to the skin caused by ultraviolet radiation. Experts in dermatology suggest protecting the body from excessive exposure to ultraviolet radiation [1 - 4].

Recently, there has been public awareness of this topic and, as a result, an increase in the use of sunscreens on the parts of the body that are exposed to the sun. In general, it is considered that clothing provides enough protection against sun radiation. However, this is not always true, particularly when using light garments [5].

The protection that a fabric offers against ultraviolet radiation can be quantified by the determination of the in vitrolet Protection Factor (UPF). According to the literature, the factor that has a higher influence on the UPF of a fabric is its structure. It determines the aperture of a fabric, and thus the physical barrier that will oppose the passing of ultraviolet radiation [6 - 12].

Several manufacturing parameters are related to the structure of fabrics. The first of these factors is the weaving system, woven or knitted fabrics. For each system there are many different knitted or woven structures. Other factors influencing the structure of fabrics are the thread count, or number of threads per centimetre of fabric, in the warp as well as in the weft direction, and the yarn number. The combination of all these factors determines the weight per surface unit, the thickness and porosity of textile structures [13].

Cotton, Modal and Modal Sun woven fabrics with plain weave were studied in the present research. Three warp yarn numbers, three weft yarn numbers and three weft thread counts were combined to obtain sets of fabrics with a wide range of compactness, with theoretical weights of between 100 and 200 g/m2, approximately. With these weights the fabrics are light or light-medium and hence appropriate for use in spring/summer garments (14).

These non-compacted and light fabrics contribute to the high comfort of summer garments. But the more open the structure the lower protection it provides, at a time of year in which elevated protection is needed, as the levels of ultraviolet radiation that reach the Earth's surface are extreme. For this reason study of the correlation between fabric structure and the UPF helps the establishment of the minimum structural conditions to obtain the desired UPF, with maximum possible comfort.

In previous research authors studied and modelled the UPF in regard to the following parameters warp yarn number, weft yarn number and weft thread count [15, 16]. In the present paper, the authors wanted to correlate the UPF with other structural parameters of fabrics widely used in their technical description, such as their weight per surface unit and thickness.

■ Experimental

Material

Three sets of woven fabrics, whose composition and structure were appropriate for summer garments, were manufactured and studied. Each set was made using yarns manufactured with different cellulosic fibres: cotton, Modal and Modal Sun (a Modal fibre that incorporates a UV absorber in the spinning bath). The cotton used was American cotton, with an average length of 28 mm and linear density of 1.8 dtex. The Modal and Modal Sun were staple fibres, with a length of 38 mm and 1.3 dtex.

Among the main manufacturing variables of the woven fabrics that influence the outcome of different structures, the weave (plain) and warp thread count (40 yarns/cm) remained constant, as it eases the manufacturing process of the samples.

To obtain a wide range of weights and thicknesses, the following parameters were cchanged: warp yarn number ($X1$), weft yarn number ($X2$) and weft thread count ($X3$). For each variable three different levels were chosen, as shown in Table 1.

Table 1. *Variables and their levels in the experimental plan.*

Level	COTTON - MODAL			MODAL SUN		
	X1, tex	X2, tex	X3, yarns/cm	X1, tex	X2, tex	X3, yarns/cm
Low	14.3	14.3	23	14.3	14.3	23
Medium	20	20	25	20	20	25
High	25	25	27	29.4	29.4	27

Table 2. *Experimental design.*

Sample	COTTON			MODAL			MODAL SUN		
	X1	X2	X3	X1	X2	X3	X1	X2	X3
1	14.3	14.3	23	14.3	14.3	23	14.3	14.3	23
2	20	14.3	23	20	14.3	23	20	14.3	23
3	25	14.3	23	25	14.3	23	29.4	14.3	23
4	14.3	20	23	14.3	20	23	14.3	20	23
5	20	20	23	20	20	23	20	20	23
6	25	20	23	25	20	23	29.4	20	23
7	14.3	25	23	14.3	25	23	14.3	29.4	23
8	20	25	23	20	25	23	20	29.4	23
9	25	25	23	25	25	23	29.4	29.4	23
10	14.3	14.3	25	14.3	14.3	25	14.3	14.3	25
11	20	14.3	25	20	14.3	25	20	14.3	25
12	25	14.3	25	25	14.3	25	29.4	14.3	25
13	14.3	20	25	14.3	20	25	14.3	20	25
14	20	20	25	20	20	25	20	20	25
15	25	20	25	25	20	25	29.4	20	25
16	14.3	25	25	14.3	25	25	14.3	29.4	25
17	20	25	25	20	25	25	20	29.4	25
18	25	25	25	25	25	25	29.4	29.4	25
19	14.3	14.3	27	14.3	14.3	27	14.3	14.3	27
20	20	14.3	27	20	14.3	27	20	14.3	27
21	25	14.3	27	25	14.3	27	29.4	14.3	27
22	14.3	20	27	14.3	20	27	14.3	20	27
23	20	20	27	20	20	27	20	20	27
24	25	20	27	25	20	27	29.4	20	27
25	14.3	25	27	14.3	25	27	14.3	29.4	27
26	20	25	27	20	25	27	20	29.4	27
27	25	25	27	25	25	27	29.4	29.4	27

Table 3. *UPF classification system of sun protective clothing, for the purposes of labelling (Standard AS/NZ 4399: 1996).*

UPF Range	UVR protection category	UVR transmission, %	UPF Rating
15 to 24	Good protection	6.7 to 4.2	15, 20
25 to 39	Very good protection	4.1 to 2.6	25, 30, 35
40 to 50, 50+	Excellent protection	≤ 2.5	40, 45, 50, 50+

The combination of the three variables and their three levels generates 27 fabrics in each set, as shown in Table 2 [17]. Each experiment corresponds to a fabric with a different structure, covering a wide range of weights and thicknesses.

After the weaving process, the fabrics were enzymatic at desized in order to eliminate the sizing products added to the to carry out weaving process. Furthermore, the cotton fabrics were also scoured and bleached in order to eliminate the particles and pigments usually found in this natural fibre.

Determined parameters and methods

Weight per surface unit, g/m²
The weight per surface unit of the fabrics was determined according to ASTM D3776 [18].

Thickness, mm
Fabric thickness was determined according to Standard UNE 40-224:1973 [19].

Ultraviolet Protection Factor UPF
The Ultraviolet Protection Factor (UPF) of the fabrics was determined by the in vitro method using an Ultraviolet Transmittance Analyser UV1000F (Labsphere) and according to Standard AS/NZ 4399: 1996 [20].

The UPF of each specimen is calculated as follows:

$$UPF_i = \frac{\sum_{\lambda=290}^{400} E_\lambda \times S_\lambda \times \Delta\lambda}{\sum_{\lambda=290}^{400} E_\lambda \times S_\lambda \times T_\lambda \times \Delta\lambda}$$

where:
E_λ - CIE relative erythemal spectral effectiveness,
S_λ - solar spectral irradiance,
T_λ - spectral transmittance of the fabric,
$\Delta\lambda$ - wavelength step in nm,
λ - wavelength in nm.

The rated *UPF* of the sample is calculated by introducing a statistical correction. Starting from the standard deviation of the mean *UPF*, the standard error in the mean *UPF* is calculated for a 99% confidence level. The rated *UPF* will be the mean *UPF* minus the standard error, rounded down to the nearest multiple of five.

$$UPF = \overline{UPF} - t_{\alpha/2,\, N-1} \cdot \frac{SD}{\sqrt{N}}$$

where $\overline{UPF}$ - mean *UPF*, $t_{\alpha/2,\, N-1}$ - *t* variance for the confidence level $\alpha = 0.005$, *SD* - standard deviation of the mean *UPF*.

If the rated *UPF* determined using the above formula is less than the lowest individual *UPF* measurement for that sample, then the rated *UPF* shall be the lowest *UPF* measured for the specimens, rounded down to the nearest multiple of five. The rated *UPF* is always a multiple of five. For *UPF* ratings of 51 or greater, the term 50+ shall be used.

The Australian / New Zealand Standard establishes, in addition, a classification system for fabrics according to their sun protective properties. For the purpose of labelling, sun protective clothing shall be categorised according to its rated *UPF*, as shown in Table 3.

■ **Results**

Weight, thickness and *UPF* of the fabrics

Table 4 shows the results obtained for the determination of the weight per surface unit and thickness, as well as the *UPF*, of the cotton, Modal and Modal Sun fabrics.

Figure 1 shows a graphic representation of the *UPF* of the fabrics against each of the structural parameters studied: weight and thickness.

The figure shows that for all the fibres studied, the ultraviolet protection factor *UPF* increases when the weight per surface unit and the thickness of the fabrics increase.

The *UPF* is strongly correlated with the weight and thickness of the Cotton fabrics studied, following a lineal regression. A higher correlation is found regarding the parameter weight, with a correlation coefficient r = 0.9872, and is lower for the parameter thickness, r = 0.8972, for which a higher dispersion of points with respect to the regression line is observed.

In Modal fabrics the *UPF* presents a strong lineal correlation (r = 0.9834) with the weight, while the lineal correlation diminishes (r = 0.8660) with the thickness. As regards thickness, a higher dispersion of the points is also observed.

In Modal Sun fabrics a high lineal correlation (r = 0.9235) between the *UPF* and the weight also exists, while the lineal correlation decreases considerably (r = 0.8264) with the thickness. In all cases the relation between the *UPF* and the parameters is not lineal, as shown by the figure.

Therefore, a higher correlation is always found between the *UPF* and the weight of the fabrics in question, and hence this parameter is the most appropriate to predict the *UPF*. In the following section, the results are statically analysed and a prediction model that quantifies the *UPF* in respect to the weight of the fabric is proposed.

Statistical analysis of the results

To relate the weight per surface unit to the ultraviolet protection factor *UPF*, a model of simple regression, which correlates the response with a single variable, is used. The model of simple regression was applied separately to each set of fabrics made with cotton, Modal and Modal Sun.

$$UPF = a + b \cdot X$$

where *X* - weight per surface unit of the fabrics in g/m^2.

When a lack of linearity is observed with this model, transformations are proposed to promote/produce linearity.

Estimation of the significant coefficients of the model and their R^2 value was done by means of Statgraphics 7.0. software.

Table 4. *Weight per surface unit, thickness and UPF of cotton, Modal and Modal Sun fabrics.*

Sample No	Cotton			Modal			Modal Sun		
	Weight, g/m^2	Thickness, mm	UPF	Weight, g/m^2	Thickness, mm	UPF	Weight, g/m^2	Thickness, mm	UPF
1	91.12	0.320	3.80	99.98	0.285	4.72	101.03	0.281	11.48
2	114.38	0.357	4.75	129.29	0.330	7.15	130.27	0.326	24.88
3	138.43	0.390	5.33	164.74	0.392	10.06	177.72	0.370	93.47
4	109.58	0.338	4.36	119.54	0.327	5.28	121.04	0.309	16.63
5	134.93	0.377	5.43	156.20	0.378	8.91	149.46	0.332	31.89
6	160.41	0.407	6.13	189.47	0.418	12.34	197.95	0.390	98.96
7	125.44	0.359	4.89	142.05	0.366	6.65	149.53	0.348	24.09
8	152.34	0.390	5.98	173.50	0.385	10.20	183.49	0.361	47.48
9	177.99	0.418	6.57	202.50	0.404	13.44	232.09	0.406	155.6
10	94.93	0.318	4.06	106.63	0.292	5.12	102.43	0.273	12.66
11	118.94	0.355	4.86	136.76	0.328	7.72	132.79	0.305	26.72
12	142.99	0.380	5.74	175.20	0.384	10.73	185.74	0.368	99.08
13	113.79	0.344	4.54	129.72	0.336	6.34	122.85	0.300	18.01
14	137.36	0.372	5.43	159.94	0.355	9.73	155.99	0.334	43.11
15	162.70	0.392	6.35	194.77	0.391	13.21	208.04	0.379	113.3
16	129.05	0.369	4.96	148.77	0.341	7.38	156.24	0.346	27.54
17	153.83	0.393	5.74	178.79	0.369	11.03	191.62	0.367	57.06
18	178.11	0.410	6.66	216.09	0.402	15.53	232.87	0.387	153.1
19	99.44	0.297	4.16	113.42	0.300	5.28	105.71	0.273	12.38
20	123.10	0.337	5.03	149.84	0.341	8.34	135.66	0.305	28.22
21	149.03	0.361	6.15	179.69	0.374	10.95	188.42	0.355	107.8
22	122.09	0.339	4.78	134.62	0.326	6.52	129.02	0.290	17.61
23	148.95	0.372	5.67	166.49	0.349	10.03	165.50	0.323	42.16
24	172.53	0.387	6.32	203.58	0.383	14.06	212.49	0.362	133.4
25	128.97	0.360	5.12	157.45	0.335	7.86	165.00	0.313	32.16
26	154.57	0.385	6.00	192.75	0.367	11.39	194.16	0.344	64.04
27	180.04	0.400	6.92	225.03	0.390	15.76	242.65	0.372	179.8
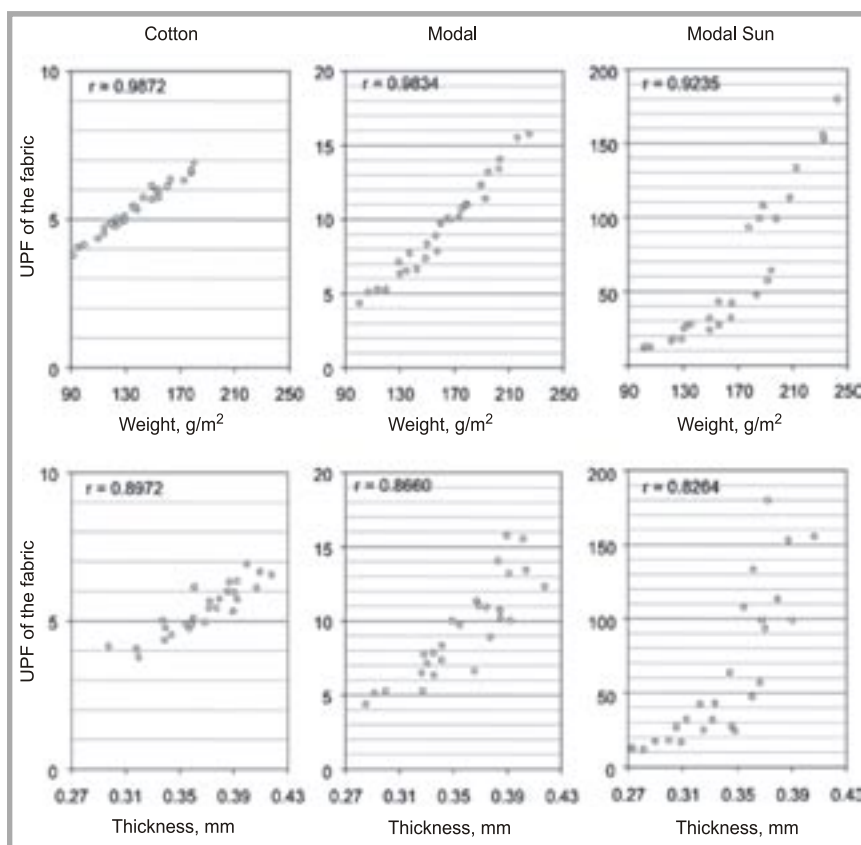
Figure 1. *Correlation UPF - weight per surface unit and UPF - thickness.*

The models that correlate the UPF response in regard to the weight per surface unit are the following:

- Cotton: $UPF = 0.9131 + 0.0326 \cdot X$
  with $R^2 = 97.28\%$
- Modal: $UPF = -5.6679 + 0.0939 \cdot X$
  with $R^2 = 96.69\%$
- Modal Sun: $UPF = 89.7940 + -1.5881 \cdot X + 0.0081 \cdot X^2$
  with $R^2 = 92.40\%$.

The first difference that can be appreciated when analysing the models is the fact that the model for Modal Sun fabrics includes a quadratic term. The significance of this term, with its positive effect, is indicative of an acceleration of the increase in the response when the value of the weight variable increases. Also, the independent term and the single effect have a notably higher value. To conclude, for the same level of the weight variable, the estimated values of the UPF are notably higher in Modal Sun fabrics than in cotton or Modal fabrics. The coefficients of the model for Modal fabrics are slightly higher than those obtained for Cotton fabrics. The better protection properties of Modal fabrics compared with cotton fabrics must be due to differences in the fibres themselves. The results expected would have to be, in theory, very similar for both Modal and cotton fabrics as both fibres are of cellulose and have the same chemical constitution. The differences can be caused by the different fine structure of the fibres (proportion of crystalline/amorphous zones) or by the presence of some kind of chemical product added during the spinning process of Modal fibre (as an anti-lustre or other finishing additive), but these aspects still need be investigated and proved.

The models obtained allow the estimation of the UPF according to the parameter weight, despite always being within the experimental range, that is, of values of the variable between the minimum and maximum levels that are used to estimate the model.

They also allow the adjustment of the variable to obtain a pre-defined UPF. In this case, the models are essential to estimate the minimum weight of the fabric needed to obtain a UPF of 15, 25 and 40, which will allow to label fabric as "good protection", "very good protection" and "excellent protection" respectively, according to Standard AS/NZ 4399:1996. For any of these estimations, the lower prediction interval is considered, which takes into account the experimental variance and guarantee of 95% security/certainty that the estimated value of UPF is higher than the pre-defined UPF.

Figures 2, show the representation of the estimated models, together with their confidence and prediction interval, for the sets of cotton, Modal and Modal Sun fabrics.

A summary of the minimum weights needed to obtain the protection levels proposed by Standard AS/NZ 4399:1996, for the three sets of fabrics studied, are presented in Table 5.

In the set of cotton fabrics, a UPF equal or higher than 15 is not reached, indicating that a fabric that could be labelled as protective cannot be obtained inside the experimental range studied. The model demonstrates that with a weight lower than 180 g/m², which corresponds to the maximum value of this variable in the experimental range, sufficient protection is not reached in untreated fabrics.

For the Modal fabrics, some values of the variable weight that could provide an estimated UPF higher than 15 are found, approximately, for weights higher that
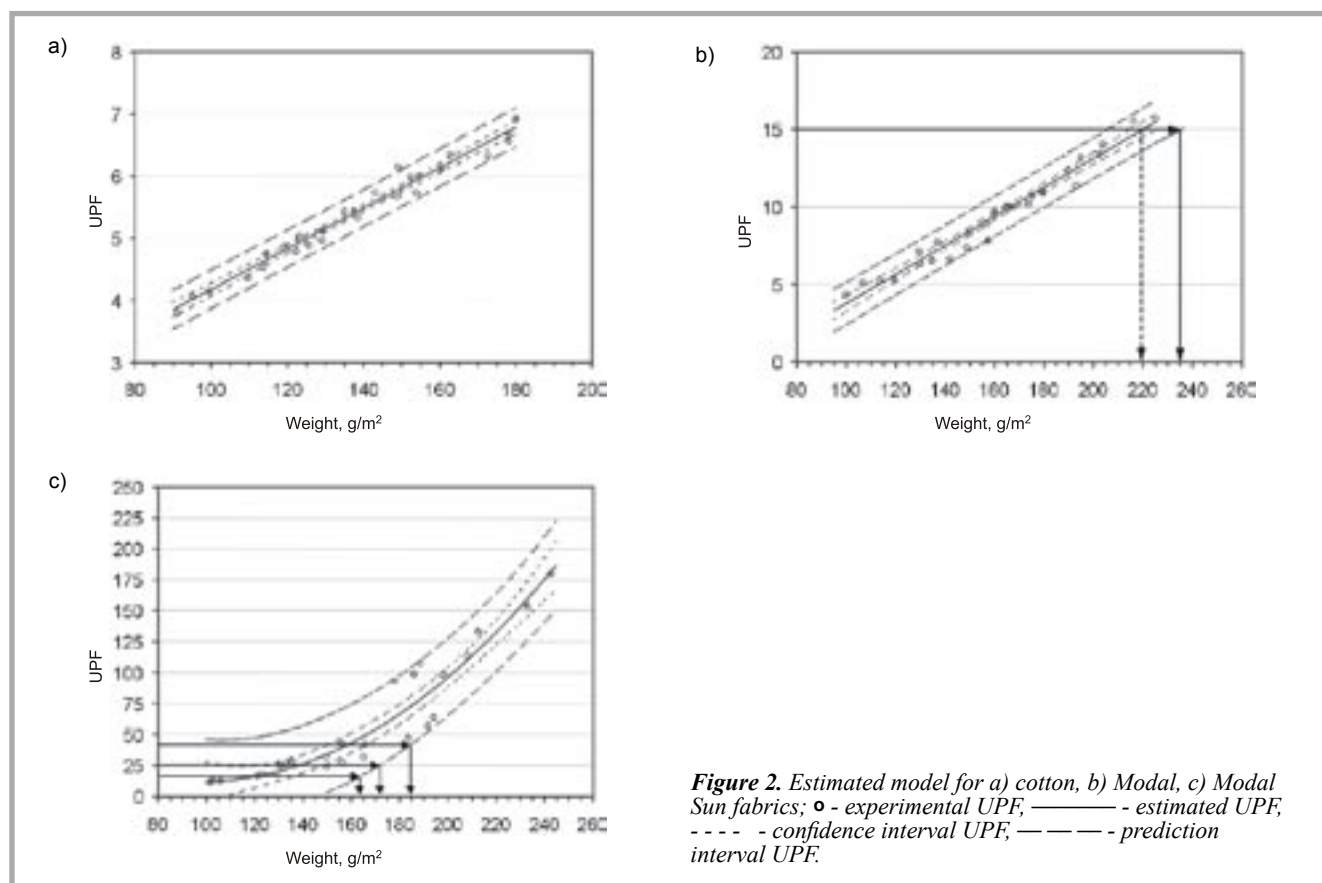
Figure 2. *Estimated model for a) cotton, b) Modal, c) Modal Sun fabrics; o - experimental UPF, ———— - estimated UPF, - - - - - confidence interval UPF, — — — - prediction interval UPF.*

Table 5. *Minimum estimated weight to reach the different protection categories.*

Category of protection	Minimum UPF	Minimum weight, g/m²		
		Cotton	Modal	Modal Sun
Good protection	15	Not reachable	(235)	163
Very good protection	25	Not reachable	Not reachable	172
Excellent protection	40	Not reachable	Not reachable	184

220 g/m². However, within the experimental range, none of the values of the lower prediction interval is equal or higher than 15. However, a value very near is reached (UPF = 14.5 for a weight of 225 g/m²). The minimum weight to have a quarantee, for the fabric to be protective, is considered to be around 235 g/m².

For Modal Sun fabrics it was possible to estimate the minimum weights needed to obtain fabrics with all levels of protection. With a minimum weight of 163 g/m², there is almost total security, and as a result the fabric will at least offer good protection (a *UPF* higher than 15). With a minimum weight of 172 g/m² the fabric will at least offer very good protection (*UPF* higher than 25). If the weight is higher than 184 g/m² ,the fabric will provide excellent protection (a *UPF* higher than 40).

■ Conclusions

- The type of fibre and the structure of the fabrics in question have a noticeable influence on the protection against ultraviolet radiation provided by textile articles.
- The *UPF* is strongly correlated with the structural parameters weight per surface unit and thickness of the fabrics. The *UPF* increases when any of these parameters increase.
- A higher correlation is found for the parameter weight. Therefore, from a statistical point of view, this parameter is the best and can be used to predict the *UPF*. It is also interesting from apractical point of view, as it is widely used in industry.
- Models that allow the estimation of the *UPF* with respect to the weight of the fabrics have being formulated, by means of statistical data analysis. The estimated models have R² sufficiently elevated, at around 97%, to consider the variable weight as a good estimator of the *UPF* of the fabrics.
- The increase in the protection factor caused by an increase in the weight is

not equal for all the fibres. The differences, due to the type of fibre, are very remarkable.

- Within the experimental range, and in spite of the high weight of some of the samples, it was not possible to obtain cotton fabrics with enough protection. To obtain good protection from Modal fibre, fabrics with quite high weights are needed (from 235 g/m²). Having said this, Modal Sun fibre can provide good protection when used in relatively very light-weight fabrics, and excellent protection can even be gained from quite light fabrics made with this fibre. This fact makes Modal Sun fibre very comfortable and appealing for it to be used in protective summer garments.

- To reach the minimum level of protection ("good protection") in cotton fabrics or levels of "very good protection" and "excellent protection" in cotton or Modal fabrics, an increase in their respective weight is needed. But this would cause excessive heaviness and make the fabrics inappropriate for their use in summer garments. Another possibility is the application of chemicals (dyestuffs, optical brightening agents or finishing products) that could provide the protection needed without increasing the weight of the fabric and reducing its comfort. The authors are also studying the action of these chemicals on the *UPF*.

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