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Enhancing Ultraviolet Protection of Bamboo Fabrics using Photochromic Vat Dyes

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ABSTRACT Historically, bamboo fabrics have been found to provide inadequate UVR protection, often falling into the poor or no category of Ultraviolet Protection Factor (UPF). To increase the UPF rating of bamboo fabrics, numerous kinds of ultraviolet absorbers have been utilized during the dyeing and finishing processes. Bamboo is a novel type of cellulosic fiber. This research has focused on evaluating the UV protection capabilities of bamboo fabrics, dyed using photochromic vat dyes. It is also important to note that no previous research has examined this topic, specifically the analysis of UV protection of bamboo cloth with photochromic colors. This research examines the UV protection capabilities of bamboo fabrics dyed with photochromic vat dyes. According to the results of the investigation, bamboo fibers can be colored utilizing the continuous dyeing process and light-sensitive/photochromic vat dyes. Furthermore, the findings demonstrate that the UPF values of bamboo fabrics significantly increase with the rise in dye concentration of vat dyes.

INDEX TERMS bamboo fabric, continuous dyeing, photochromic dyes, UV protection

I. INTRODUCTION

Skin cancer diagnoses have been gradually increasing over the past few decades [1], [2]. To prevent skin cancer, many countries such as the United States, Australia, and Europe, have initiated sun protection programs aimed at increasing public awareness of UVR's harmful effects on human skin [3]. The growing public understanding of the dangers associated with ultraviolet exposure has led to an increase in the demand for clothing that offers protection against UV rays. According to the World Health Organization (WHO), wearing protective is the most effective means of shielding exposed skin from the Sun, complementing the use of sunscreen [4]. However, the size of the UV-protective clothing market remains uncertain.

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Despite the recognized importance of UV protection, the market's exact dimensions remain elusive [5]. Typically, Ultraviolet radiation spectrum is categorized into three wavelength ranges: UV-A (320–400 nm), UV-B (290–320 nm), and UV-C (200–290 nm) [6]. The atmosphere completely absorbs UV-C, preventing it from ever reaching the Earth. While skin malignancies are mostly brought on by UV-B, UV-A only has a very slight apparent reaction [7].

The significance of UV protection in finished clothing depends on a variety of fabric characteristics, such as porosity, thickness, weight, color, and fabric type [8]. Bamboo fibers are inherently anti-bacterial, naturally breathable, and have outstanding qualities like water and moisture absorption. [9], [10]. They are also lighter and softer than cotton. Bamboo clothing, due to its very silky nature effectively prevents shrinkage and pilling issues [11], [12]. Poor UV protection is offered by bamboo fabrics without UV-protective treatments [13].

Textiles with photochromic properties are a type of functional fabric that serve dual purposes: providing dynamic visual appeal for fashion purposes and also functioning as intelligent textiles, like ultraviolet light detectors [14]. Photochromic dyes provide the added benefit of ultraviolet protection by changing color when they absorb UV rays, making them suitable for creating UV-protective clothing [15]. This study investigated the feasibility of dyeing bamboo materials with photochromic dyes. These dyes can easily change color when exposed to UV or sunlight since they are light-sensitive vat dyes. In this study, the bamboo fabrics were characterized in terms of their weight, thread count, thickness, and construction. A Cary 50 UV/Vis/NIR spectrophotometer (Varian produced in Australia) was used to calculate the UPF of bamboo fabrics.

II. METHODS

Two types of bamboo fabrics (woven and knitted) bleached and mercerized were selected for this study. ASTM test method D3776-96 was used to measure the weights of the fabrics [16]. By using the YG141N digital fabric thickness gauge the thickness of the fabrics was measured which complies with ISO5084 standard. According to the method ASTM D3775-98, thread counts were measured [16].

A. MATERIALS

Wujian Tangchao Co. Ltd. China and Wujiang City Shengze Lanxiang Textile Co. Ltd. China, provided 100% bamboo knitted fabric and woven bamboo fabrics to be used for this study. All of the fabrics did not go through any previous finishing treatments. Photochromic vat dyes with their commercial names such as INKO orange and INKO red were purchased from Lumi Co., USA.

B. FABRIC DYEING

The–fabric samples were dyed by continuous dyeing method with a concentration of the dyes ranging from 2% to 8% by using a laboratory padder (liquor ratio 1:10). After dyeing, the samples were placed under UV light for 10 minutes to fix the dye. After fixing the dye, the samples were dried at 60oC and then rinsed with soapy water. The ultraviolet protection factor is considered one of the scientific terms which are used to measure the amount of UVR protection by human skin. Table I presents the rating scheme of UPF from NS/NZ 4399 sun-shielding clothing (1996).

TABLE I
UPF RATING SCHEME FROM NS/NZ 4399 SUN-PROTECTIVE CLOTHING (1996)

Protection Category	UPF Range	Rating
Outstanding Protection	40–50, 50+	40, 45, 50, 50+
Very effective protection	25–39	25, 30, 35
Reliable protection	15–24	15, 20

Effective Dose (ED) represents an effective UVR dose for exposed skin. It is determined by adding values across the wavelength range of 290 to 400 nm after combining the relative spectral efficiency function with the incident solar spectral power distribution. The effective dose (EDm) for skin protection is calculated using the spectrum transmission of the fabric as an extra weighting component. The UPF is calculated using the following formula, which is determined by the ED/EDm ratio [17].

$$UPF = \frac{ED}{ED_m} = \frac{\sum_{290nm}^{400nm} E_\lambda S_\lambda \Delta\lambda}{\sum_{290nm}^{400nm} E_\lambda S_\lambda T_\lambda \Delta\lambda}$$

Where:

E_λ= erythemal spectral effectiveness

S_λ = solar spectral irradiance in Wm-2nm-1

T_λ= spectral transmittance of fabric

Δ_λ = the bandwidth in nm

λ = the wavelength in nm

UV Protection Factor was calculated using a Cary 50 UV/Vis/NIR spectrophotometer (Varian produced in Australia) [18]. A wavelength in the range of 320 to 400 nm is used to represent the UVA zone. Between UVC and UVA, the UVB region has a wavelength between 290 and 320 nm, whereas the UVC region refers to the area below 290 nm [19]. By using an X-Rite spectrophotometer to match the measured UPF values to the color intensity of the dyed materials, the equation of Kubelka and Munk was used to depict the results.

$$\frac{K}{S} = \frac{(1-R)^2}{2R}$$

The sorption coefficient, the scattering coefficient, and the reflectance of the colored fabric are K, S, and R, respectively. A specimen viewing aperture of 1 inch was calibrated for the spectrophotometer in reflectance specular-included mode. Using a CIE 10-degree observer and D65 illuminant, we assessed the K/S value of the colored fabrics.

IV. RESULTS AND DISCUSSION

TABLE II
UPF VALUE AND FABRIC CHARACTERIZATION OF FABRICS BEFORE DYEING

Fabric Type	Weight (g/m^2)	Thickness (mm)	Thread Count (per inch)	UPF	UPF protection class
Twill Weave	200	0.39	166	8.30	No class
Plan Weave	113	0.25	136	5.44	No class
Knitted	210	0.58	35 WPI 44 CPI	11.5	No class

Table II illustrates the UPF ratings for bamboo knit, twill, and plain weave fabrics prior to dyeing. Physical characteristics of the materials are crucial factors in UV protection, for example, larger weight and thickness of the fabric result in better UV protection levels. According to Table II, knitted bamboo fabrics have the highest UPF value when compared to twill weave and plain weave bamboo fabrics, which had weights of 200 g/m^2 and 113 g/m^2 and thicknesses of 0.39 mm and 0.25 mm, respectively [10]. UPF value and fabric characteristics of materials before dyeing are shown in Table II. [20].

The cloth cover factor, also known as fabric porosity, is thought to be a crucial component in the UV protection of clothes. Therefore, because of the tight weave or knitting patterns, materials with very low porosity transmit UV light less effectively. The intervals between the threads are often bigger in knit fabrics compared to woven fabrics, while plain-woven fabrics have less porosity than fabrics with different weaves, such as twill. Woven fabric is defined by the number of warp and weft strands per inch. Similarly, knitted materials is defined by the number of wales and courses per inch. The UPF value of 136 thread count plain weave bamboo cloth was 5.44, which is lower than the UPF value of 166 thread count twill fabric (8.30).

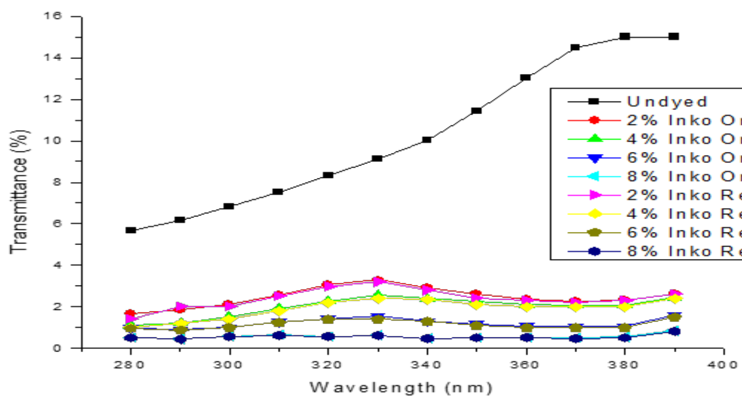

FIGURE 1. UV transmissions of knit bamboo cloth at various dye concentrations

Figure 1 displays the UV transmittance statistics for bamboo knit fabrics in both the presence and absence of photochromic pigments. The relative erythemal spectral effectiveness was found to be higher in the UV-B region as compared to the UV-A region. The UPF values are usually determined by UV-B transmission. Undyed knit fabrics had the highest UPF rating (11.5), indicating strong transmission as compared to twill and plain weave fabrics. Table III displays the UPF ratings and protective classifications for knitted fabric colored using vat dyes. Figures 2 and 3 display the UV transmittance statistics for plain and twill, respectively. As can be seen from the transmission data and UPF values, all bamboo materials effectively reduced UV transmission through the vat dyes employed in this investigation.

TABLE III

UPF, PROTECTION CLASS, AND K/S VALUES FOR KNIT BAMBOO FABRIC COLORED WITH PHOTOCHROMIC DYES IN VARYING AMOUNTS

Fabric	Colorant	UPF	UV Protection Class	KS Value
Kitted	2 % Inkodye orange	50+	Excellent	0.39
	4% Inkodye orange	50+	Excellent	0.95
	6% Inkodye orange	50+	Excellent	1.37
	8% Inkodye orange	50+	Excellent	1.44
	2% Inkodye red	50+	Excellent	1.39
	4% Inkodye red	50+	Excellent	2.145
	6% Inkodye red	50+	Excellent	4.67
	8% Inkodye red	50+	Excellent	4.79

Compared to orange dye, the UPF values in the presence of red dye are more significant. These findings concur with those of Reinert *et al.* [21] who showed that pale-colored fabrics showed less UV protection as compared to dark colors. The outcomes also demonstrated that an essential component of ultraviolet protection is dye concentration. The UPF value increases as dye concentration does. This study agrees with Gies *et al.* [17] who asserts that darker colors are more protective than lighter ones.

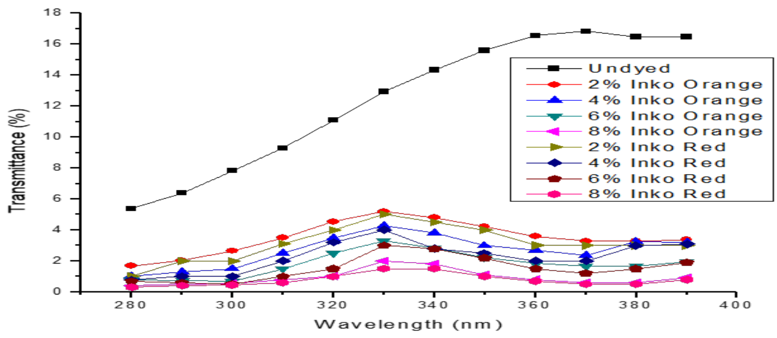

FIGURE 2. UV transmission of twill weave bamboo fabrics at different concentrations of dyes

For instance, the UPF value of plain bamboo fabrics at 2% of Inko dye red was tested at 25.0 and rapidly increased to 30 with the rise of dye concentration up to 8%. This investigation indicated that the K/S value of the colored materials was a significant factor. This is characterized as a measurement of the intensity of color in colored fabrics. In Table V, the K/S values of the dyes (orange and red) increased from 0.48 to 1.22 and 1.36 to 4.11 respectively, exhibiting an increase in UPF values from 15 to 20 and 25 to 30 respectively. It has been determined that the higher the K/S value, the higher the UPF value.

It has limited the correlation of UPF and K/S with the identical type of fabrics and the results cannot be simplified across fabrics with different weaving structures. This observation is just to acknowledge the UPF values which depend on the factors of fabric formation such as spaces in the fabrics, thickness, weight, and parameters of processing such as dyeing and finishing. The percentage of UV transmittance data and UPF classification for the twill weave fabrics (in the presence and absence of dyes) is shown in Figure 2. The UPF values and protection categories for the dyed twill weave bamboo fabric are listed in Table IV. Before dying, the twill weave fabrics showed UPF of 8.30 (no UPF class) which significantly moved to the excellent UV protection after the dyeing process.

TABLE IV

UPF, K/S, AND PROTECTION CLASS OF BAMBOO CLOTH DYED IN TWILL WEAVE USING VARIOUS CONCENTRATIONS OF PHOTOCHROMIC DYES

Fabric	Colorant	UPF	UV Protection Class	KS Value
Twill Weave	2 % Inkodye orange	50+	Excellent	0.50
	4% Inkodye orange	50+	Excellent	0.81
	6% Inkodye orange	50+	Excellent	1.03
	8% Inkodye orange	50+	Excellent	1.12
	2% Inkodye red	50+	Excellent	1.25
	4% Inkodye red	50+	Excellent	2.23
	6% Inkodye red	50+	Excellent	2.75
	8% Inkodye red	50+	Excellent	3.76

Table V displays information on bamboo plain weave fabrics with UPF ratings and protection levels, both before and after dyeing. Figure 3 displays the UV transmittance statistics for the plain weave fabric in both the absence and presence of dyes. Before dyeing, plain weave cloth (UPF 5.44) fell into no UV protection class category, but after dying using vat dyes, this protection class significantly improved to the class of very good UV protection.

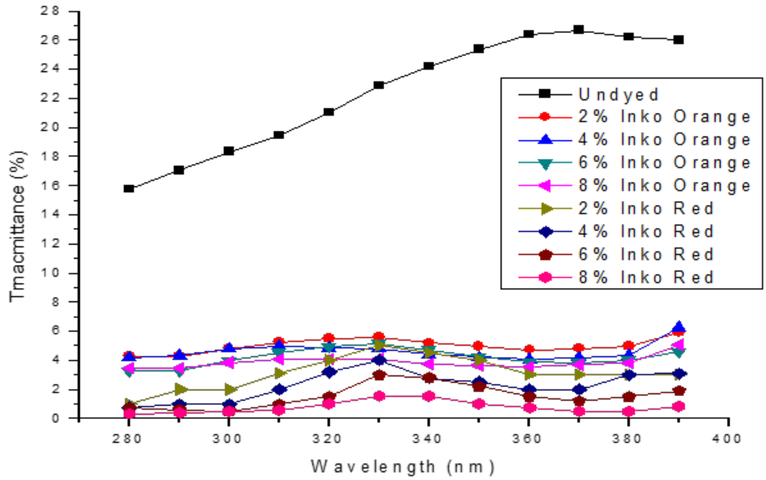

FIGURE 3. UV transmission of bamboo plain weave fabric in both the presence and absence of colors

TABLE V

UPF RATINGS FOR PLAIN-WEAVE BAMBOO FABRICS TREATED WITH PHOTOCHROMIC DYE IN A RANGE OF CONCENTRATIONS TOGETHER WITH THE PROTECTION CLASS AND K/S VALUES.

Fabric	Colorant	UPF	UV Protection Class	KS Value
	2 % Inkodye orange	15	Good	0.48
	4% Inkodye orange	17.5	Good	0.68
	6% Inkodye orange	19.3	Good	0.93
Plain	8% Inkodye orange	20	Good	1.22
Weave	2% Inkodye red	25	Very Good	1.36
	4% Inkodye red	27.7	Very Good	2.44
	6% Inkodye red	28	Very Good	3.40
	8% Inkodye red	30	Very Good	4.11

A. CONCLUSION

For undyed bamboo materials, construction characteristics like weight and thickness play a significant role in determining UPF levels. It has been observed that as weight and thickness increase, so does UPF. The application of photochromic vat dyes has been found to dramatically increase the UPF of undyed fabrics, particularly for materials like plain weave, twill, and single jersey knitted fabrics, which initially had no protective effect before dyeing. Darker colors, such as red dye, indicated better protection, which means higher UV absorption. The protection class after dyeing was a consequence of the concentration of the dye in the fabric. The findings of this study suggest that, plain, twill, and knitted bamboo fabrics colored with photochromic dyes are capable of providing adequate UV protection.

CONFLICT OF INTEREST

The authors of the manuscript have no financial or non-financial conflict of interest in the subject matter or materials discussed in this manuscript.

DATA AVALIABILITY STATEMENT

The data associated with this study will be provided by the corresponding author upon request.

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