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Wavelength sensitivity of AATCC Blue wool lightfastness standards under light radiation

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ABSTRACT

The fading characteristics of the AATCC Blue Wool L2 and L4 lightfastness standards were examined from the standpoint of wavelength sensitivity. Experiments were carried out by exposing a specimen to a narrow monochromatic band isolated from the dispersed polychromatic light emitted by a Xe lamp source. The wavelength sensitivity characteristics of Blue wool L2 and L4 lightfastness were determined on a radiant energy basis. Both Blue Wool Standards displayed peak maxima at 245 and 294 nm. The results indicated that UVA and UVB had a significant fading effect, whereas visible light caused fading to a small extent. Specific wavelengths caused Blue wool to significantly fade, suggesting that the total irradiated UV energy may not be an appropriate index. In addition, their spectral reflectances did not directly explain these characteristics of the standards.

1. Introduction

Light irradiation is one of the most influential factors in the fading of dyestuffs in addition to temperature, humidity, and air pollutants. Many approaches have been reported to investigate lightfastness [1–8]. Most lightfastness experiments were carried out under accelerated conditions using artificial light sources like carbon and xenon arc lamps instead of direct solar radiation. In these experiments, lightfastness standards such as the AATCC Blue Wool lightfastness standards [9], the Japan Industrial Standard Blue Scales [10] and the British dyed-wool lightfastness standards [11] were used to measure the accumulated light intensity.

The performance of these blue standards has been examined since the 1950s, and some extensive discussions related to the measurement of solar radiation intensity in langleys have been carried out [12–17]. A question arose concerning whether a UV narrow band in the sunlight spectral regions may cause greater fading than the visible light region despite its negligible intensity compared to the total solar energy recorded. It was pointed out that measurement of the active wavelengths was necessary to better understand lightfastness testing results [15]. However, information given about the wavelength dependence of fading has been insufficient for blue standards.

The use of blue wool standards is not limited to dyed fabrics. The standards have also been applied as fading references to evaluate various material deteriorations such as wool yellowing [18], fading of water colors [19], photodamage of human hair [20] and to perform instrumental solar radiation measurements [21,22]. As mentioned above, sets of blue wool standards have been widely used in light dosimetry to qualitatively evaluate light induced damage. However, they have occasionally failed to give a proper prediction of fading characteristics. For instance, Zhang et al. [18] concluded that blue wool standards may not be effective in showing the impact of irradiated light on spectrum-sensitive fabrics. Crews [23] also found the inadequacy of blue wool standards on their sensitivity in the visible light. Some failures of the standards are considered to be due to the lack of knowledge regarding the wavelength sensitivity of blue wool standards.

Ideally, the correlation between fading characteristics generated using artificial and natural sunlight would be expected to be consistent. In certain cases, however, total energies emitted by the lamp and by the sun are not well correlated. This may lead to contradictory data because materials adsorb at their defined wavelengths. Measuring the fading or deterioration resulting from different radiant wavelengths is necessary to better understand photodamage.

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As noted above, most fading experiments were performed under accelerated conditions using polychromatic light sources. However, it is important to understand the photosensitivity of a material to a specific wavelength, because photoreactions generally depend on specific wavelengths that relate to the bonding energy of molecules. Identifying these specific wavelengths is useful when investigating processes that promote material degradation. Therefore, knowing spectral sensitivities is crucial in photodegradation control.

Investigations on the wavelength dependence of a given reaction or a process have been applied to biological systems [24,25], erythema in human skin [26], and polymer materials [27,28]. However, studies related to the fading of dyestuffs and fabrics have been scarce [29–33]. This may be partly due to limitations of instrumental availability and recognition of serious necessity on their fading evaluation.

In this study, the fading characteristics of AATCC Blue Wool lightfastness standards were investigated in terms of radiant energy on exposure to monochromatic light. The sensitivity of the standards to radiant wavelengths with respect to fading was determined. We herein provide some clues and insightful discussion on some contradicting questions pertinent to the assessment of materials that exhibit sensitivity to both visible and ultraviolet radiations such as wool yellowing and bleaching [18], some colorants [19], and natural dyes [23,34,35].

2. Experimental

2.1. Materials

AATCC Blue Wool L2 and L4 lightfastness standards [9] were used in this experiment. As described in the AATCC technical manual [9], these standards were prepared by blending different proportions of wool dyed with the very fugitive Erio Chrome Azurole BA dyestuff (C.I. 43 830) (Fig. 1) and wool dyed with the fast Indigosol Blue AGG dyestuff (C.I. 73 801) (Fig. 2).

These specimens were stored in a refrigerator to prevent pre-ageing of the dye before the usage.

2.2. Exposure to light sources

Samples were irradiated with monochromatic light using a JASCO CRM-FD spectroirradiator (Fig. 3). The spectroirradiator was equipped with a 300 W xenon arc lamp with an ellipse half sphere mirror to collect light emission. Radiation from this source was converted into monochromatic light using a diffraction lattice grating with 1200 lines/mm. The wavelength dispersion was about 2 nm mm^{-1} and the slit was set to 2 mm, resulting in an accuracy of about 4 nm for each irradiation wavelength. The specimens were placed in an appropriate position in a sample holder and exposed to monochromatic radiations interspaced by about 16 nm within the 220–700 nm wavelength range. The light intensity in W m^{-2} nm^{-1} was periodically measured for each wavelength using a photometer. The photometer was an advanced device which consisted of a thermopile detector attached to the spectroirradiator, unlike the previous model used by Katsuda et al. [29,30]. Light exposures were carried out at temperatures and relative humidities ranging from 20 to 25 °C and from 50% to 70%, respectively.

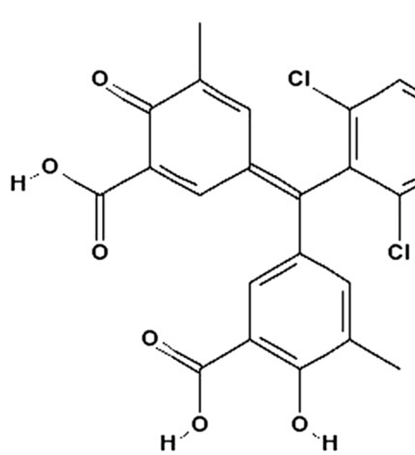

Fig. 1. Chemical structure of Erio Chrome Azurole BA.

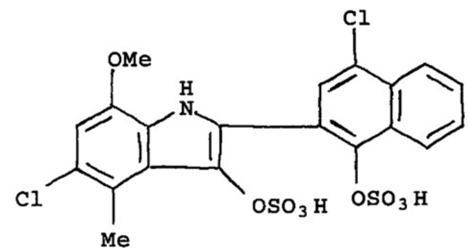

Fig. 2. Chemical structure of Indigosol Blue AGG.

2.3. Evaluation of fading

The specimen color change was measured using a Minolta Model CM-3700d color analyzer with a 4 × 7 mm^2 viewing aperture. The amount of fading was evaluated in terms of color difference and calculated using the following formula proposed by the CIE Committee in 1976 (Equation (1)):

$$\Delta E = \left[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2\right]^{1/2} \tag{1}$$

where ΔL^* is the lightness–darkness difference, Δa^* is the redness–greenness difference, and Δb^* is the yellowness–blueness difference.

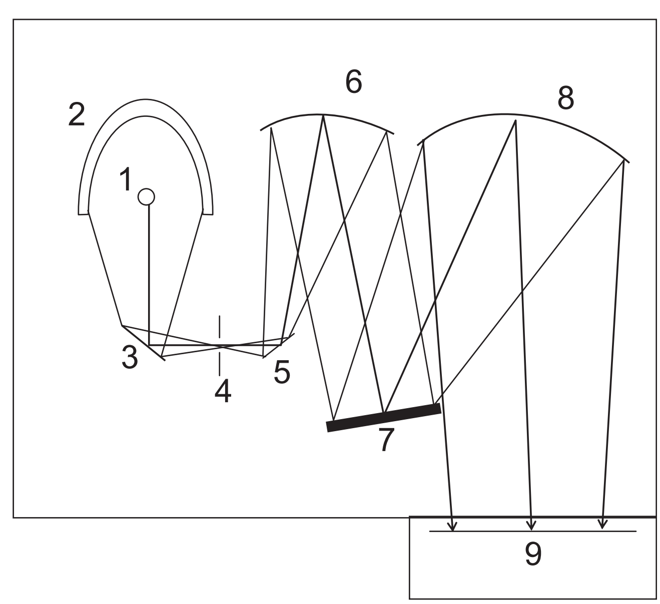

Fig. 3. Schematic diagram of the spectroirradiator: (1) Xenon arc lamp; (2) elliptical sphere mirror; (4) slit; (7) diffraction grating; (9) sample holder. (3), (5), (6), and (8) are mirrors.

The formula in Equation (1) has long-been used to give instrumentally measured color differences as standard means of calculating and communicating color differences although some defects have been discussed [36,37]. In this study, we used Equation (1) to maintain the consistency with previous research results [4–8,18,21].

2.4. Compilation of radiant wavelength sensitivity

The accumulated energy (J m^{-2} nm^{-1}) was calculated in light intensity (W m^{-2} nm^{-1}) by exposure time for each exposure wavelength, because the light source did not radiate at the same intensity at each wavelength. For a specimen, the relationship between accumulated radiant energy and color difference was examined in a time sequential experiment at each exposure wavelength. Then, a smooth curve was drawn to give a representative fading characteristic. Color difference data under a specified radiant energy was read out from the curve to obtain wavelength sensitivity characteristics at each exposure wavelength.

3. Results and discussion

3.1. Color features of Blue wool L2 and L4

Fig. 4 shows the reflectance of the Blue wool L2 specimen. With a peak of 27.5% at 450 nm, the reflectance was higher in the 400–500 nm wavelength range compared to other visible light regions, which is a typical feature of blue color. The lowest reflectance was observed to be 3.5% at 615 nm, where the specimen significantly absorbed most radiated light. The difference between the maximum and minimum reflectances is large, resulting in a bright blue specimen.

Fig. 5 shows the reflectance of the Blue wool L4 specimen which displayed a blue color characteristic. However, the maximum and minimum reflectances in the visible light region were found to be 16.0% at 450 nm and 3.5% at 615 nm, respectively.

3.2. Fading characteristics of Blue wool L2 and L4 standards under a 294 nm monochromatic light

As described in the experimental section, the results shown in Figs. 6 and 7 were obtained upon specimen exposure to a narrow radiation band isolated from dispersed polychromatic light emitted from a source. In this case, the irradiance depends on the wavelength because the source does not emit wavelengths of equal intensities. Therefore, varying the exposure time at each wavelength accordingly will render the irradiance to be constant.

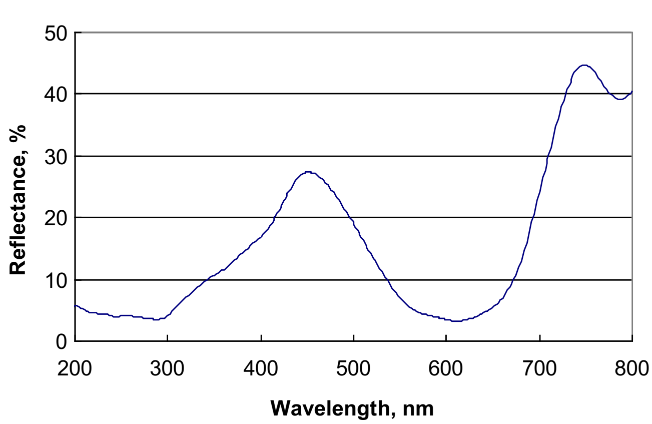

Fig. 4. Reflectance spectra of the AATCC Blue Wool L2 lightfastness standard.

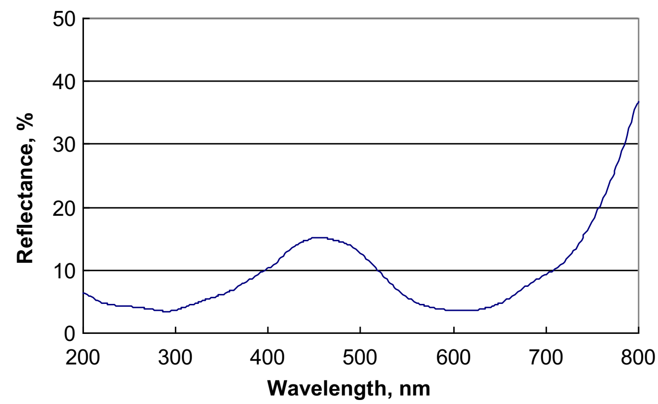

Fig. 5. Reflectance spectra of the AATCC Blue Wool L4 lightfastness standard.

Fig. 6 shows the fading curve for Blue wool L2 under a continuous monochromatic radiation at 294 nm. Fading increased with increasing accumulated radiant energy. Instead of a linear fading rate, the resulting fading rate was found to be curved. Fig. 7 shows the fading curve for Blue wool L4 under a continuous monochromatic radiation at 294 nm. Blue wool L4 displays the same characteristic curve as Blue wool L2 with respect to continuous radiation.

Fig. 8 shows the comparison between Blue wool L2 and L4 fading characteristics. According to the AATCC technical manual [9], standards with a sequentially high number are expected to be twice as colorfast as standards bearing the preceding number [9]. Blue wool L4 is expected to be more colorfast than Blue wool L2 by a factor of 4. The radiant energy was shown to be reduced by a factor of 4 for Blue wool L4 compared to Blue wool L2 (Fig. 8). Indeed, the two characteristic curves appear almost coincidental. It is confirmed that these characteristics may be identical on the monochromatically radiant energy basis.

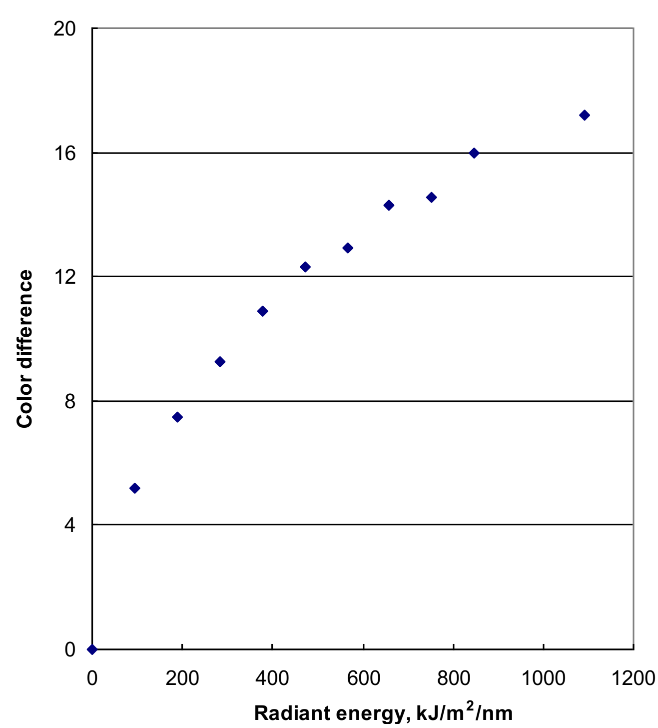

Fig. 6. Fading characteristics of the AATCC Blue Wool L2 lightfastness standard under monochromatic irradiation at 294 nm.

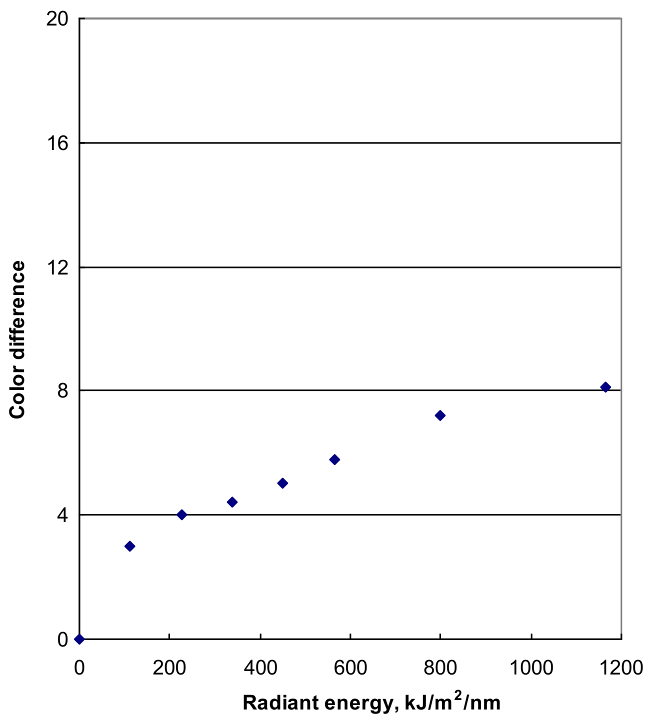

Fig. 7. Fading characteristics of the AATCC Blue Wool L4 lightfastness standard under monochromatic light irradiation at 294 nm.

3.3. Wavelength sensitivity characteristics

The wavelength sensitivity characteristic, also known as an action spectrum [25–27], is shown in Fig. 9 for Blue wool L2 lightfastness.

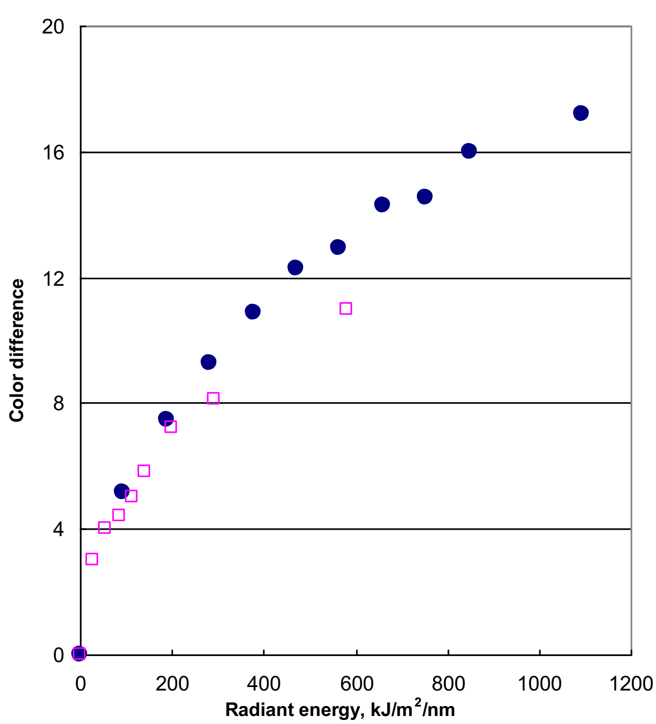

Fig. 8. Comparison between the fading characteristics of AATCC Blue Wool L2 (●) and L4 (□) lightfastness standards under monochromatic irradiation at 294 nm as a function of radiation energy. The radiant energy has been scaled down by a factor of ¼ for L4.

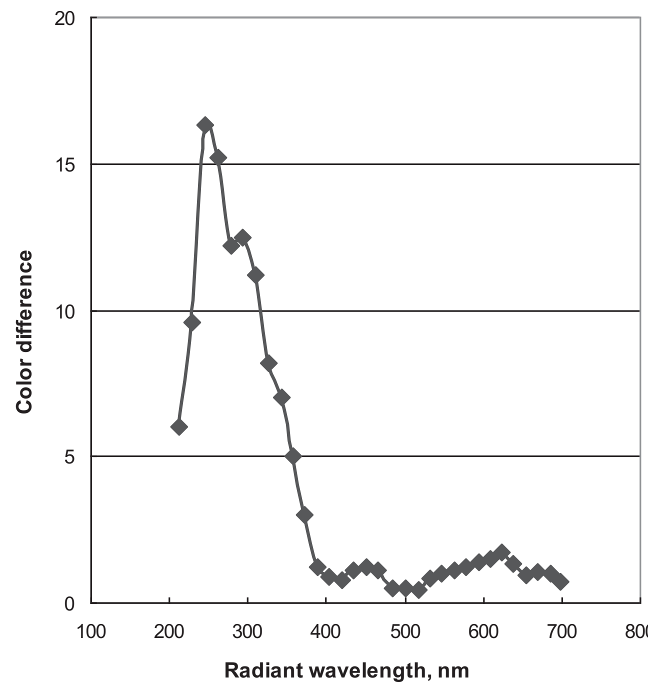

Fig. 9. Wavelength sensitivity characteristics for the fading of the AATCC Blue Wool L2 lightfastness standard under a radiant energy of 500 kJ m^{-2} nm^{-1} at each wavelength.

In this study, the fading characteristics of the dyed fabrics were compiled when the accumulated radiant energy reached 500 kJ m^{-2} nm^{-1} for each wavelength in a way as shown in Fig. 6. Two intense peaks were observed at 245 and 295 nm in the UVB–UVC range for Blue wool L2 (Fig. 9). This suggests that UVA radiation will have significant fading effects, whereas visible light will cause fading to a small extent.

This characteristic is consistent with previous results by Crews [23,34], who reported that Blue wool L2 was not sensitive to visible light when studying the effectiveness of UV filtering materials. In addition, Yoshizumi et al. [35] suggested that most Blue wool L2 fading under sunlight radiation might be caused by UVA and UVB rays, and that the effect of visible light on fading might be very small. The results obtained in this study provide direct evidence to these previous reports.

Fig. 10 shows the lightfastness characteristic of Blue wool L4. As expected, Blue wool L4 behaved with better lightfastness than Blue wool L2. Like for Blue wool L2, two dominant peaks, which are characteristics of fading, appeared at 245 and 295 nm. This lightfastness characteristic is considered to be acceptable because Blue wool L4 was shown to have a consistent wavelength sensitivity with Blue wool L2.

Ultraviolet radiation is known to strongly influence the fading of dyestuffs in general. Quantum chemistry also suggests that the absorbed photoenergy causes dye molecules to undergo photodecomposition. Here, two specified wavelengths were found to distinctly cause Blue wool L2 and L4 to fade. Ultraviolet radiation did not exhibit fading effects on Blue wool as a whole, but fading was highly wavelength dependent. Moreover, the absorption of these specimens around 600 nm would slightly affect fading as suggested by the presence of a small peak around 600 nm in Figs. 9 and 10.

Discussing the photomolecular aspect of these results in detail is not easy, but experimentally important facts were shown in this study. Blue wool L2 and L4 have been widely used as references to monitor accumulated light exposure. According to these results, the AATCC blue wool lightfastness standards are clearly very sensitive

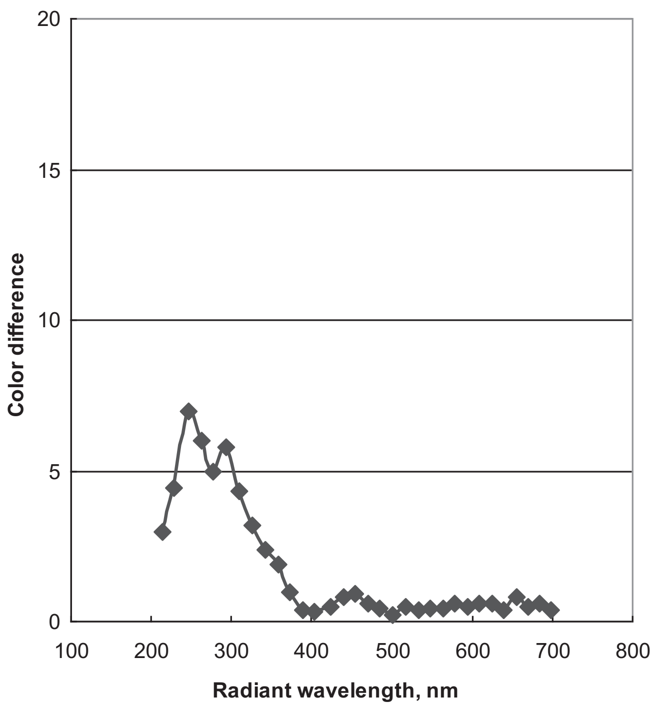

Fig. 10. Wavelength sensitivity characteristics for the fading of the AATCC Blue Wool L4 lightfastness standard under a radiant energy of 500 kJ m^{-2} nm^{-1} at each wavelength.

to ultraviolet radiation but insensitive to visible radiation. As noted previously, these standards would not be appropriate for assessing materials that exhibit sensitivity to both visible and ultraviolet radiation such as wool yellowing and bleaching [18], some colorants [19], and natural dyes [23,34,35].

Our results may explain why it is virtually impossible to obtain identical degrees of yellowing from two wool fabric specimens irradiated using two different lamps, regardless of the identical extent of Blue wool fading [18]. Moreover, these results support Zhang et al., who suggested that Blue wool was not effective in identifying small spectral differences between two lamp types and revealed the impact of these differences on spectrum-sensitive fabrics [18].

On the other hand, as opposed to natural dyes, the lightfastness of commercial synthetic dyes mostly depends on their lightfastness in the ultraviolet region. Therefore, Blue wool standards are considered useful in the evaluation of dyed fabrics.

4. Conclusions

The fading of Blue wool L2 and L4 under monochromatic light irradiation was determined in terms of wavelength sensitivity characteristics to discuss the effects of wavelength on fading. The characteristics were examined as a function of radiant energy.

The wavelength sensitivity characteristics exhibited peak maxima at 245 and 294 nm for both Blue wool L2 and L4. Therefore, UVA will significantly affect fading, whereas visible light will cause little fading. The photodegradation process was not discussed in detail. The wavelength sensitivity characteristics did not seem to directly relate to their spectral reflectances. We found that irradiation at specific wavelengths caused Blue wool to fade significantly. This result suggests that total irradiated UV energy may not be an effective index.

Further research work is necessary to completely understand nature of the Blue wool standards. However, our results present new aspects relative to the fading characteristics of Blue wool, which may provide explanations to controversial fading results.

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