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The lightfastness of early synthetic organic dyes

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Abstract

Synthetic organic colourants are extremely prominent in heritage collections, particularly throughout textiles. They are often generalized as highly light-sensitive; although, a broad distribution of lightfastness exists. This is evident in various fastness ratings published in late nineteenth century literature, the work of Schultz and Julius, and the Colour Index. In heritage conservation, much of the research related to light-sensitivity of dyed textiles has focused on natural colourants. This is likely due to a general interest in the dyes present on older objects, and the overwhelming selection of modern synthetic materials. To address this gap, a shortlist of targeted synthetic dyes was recently developed using census data for dye production and imports in the United States, and information gathered from the Colour Index. Our present work provides a follow up to the prior literature review, where a subset of samples from the published target list was used to evaluate lightfastness. To begin the study, a collection of dyed textiles from the last quarter of the nineteenth century was gathered from trade publications of the period, and those matching the target criteria were reserved for analysis. The lightfastness of more than 100 early synthetic dyes was then investigated using the historic materials. Test specimens were illuminated with a custom-built fadometer containing an LED light source that is characteristic of modern gallery lighting. Four batches of samples were exposed at 20 klx for approximately 6 months each, and diffuse reflectance was periodically measured with a portable spectrophotometer over white and black backgrounds. Measurements were taken at increasing light dose values to reach at least 85 Mlx·h per batch. Visible reflectance spectra were recorded in a dataset to document the colours as a function of light exposure, and foster future colorimetry research. Colour change was also calculated using the CIEDE2000 formula to assess lightfastness, and results were summarized as a resource to further develop risk analysis tools for exhibit lighting. In this paper, a detailed description of the test apparatus is presented with an overview of the lightfastness results and the resulting dataset. Comparisons are given with nineteenth century lightfastness data, and ISO values available in the Colour Index. It is hoped that the associated dataset will provide a foundation to be expanded over time with interest in further materials and test methods.

Introduction

Synthetic dyes invented in the nineteenth century are often categorized as highly fugitive when exposed to light. While this may be true for many of the earliest dyes, the rapid invention of new materials quickly presented options with higher fastness. Near the end of the 19th c. a large study was initiated by the British Association, and conducted by Thorpe et al. [1–6]. The aim was to clarify the lightfastness of synthetic dyes in relation to their natural counterparts since there was a negative perception toward the newer materials. In the concluding remarks of their final paper, the authors provide the following comment:

> *"... although the coal-tar dyestuffs include a very large number which yield fugitive colours, there are also many which yield fast colours. It is seen that both these classes are also represented among the natural or vegetable dyestuffs, and the preva-*

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lent idea that the latter are fast while the former are fugitive is merely a popular error. This opinion has, however, been so long fixed in the popular mind that it is to be hoped the conclusive proof of its fallacy afforded by these experiments will cause it to be finally abandoned. These tables, indeed, show that coal-tar furnishes the dyer with a larger number of colours fast to light than are derived from any other source."

This statement emphasizes the prevalent use of fugitive colourants as an ongoing issue despite the large number of options with higher fastness. In a review of the early synthetic dye industry, Barnett [7] notes a nearly identical comment by Hummel [8] in 1890. One likely issue was that dyers of the time were overwhelmed by the large number of available synthetic dyes, and selecting the lightfast options was a challenge with the available information. As time progressed, this data became commonly available in reference documents such as the work of Schultz and Julius [9] and the Colour Index (CI) [10]. It is important to note that several other contributing factors may have influenced the selection of materials: cost of dyes with higher fastness, marketing and availability, toxicity, or poor performance with respect to other properties [8].

The results of the British Association study are further reviewed here to provide context for the analysis in our current study. Figure 1a shows a final summary of the research by Thorpe et al. [6], where a large selection of natural and synthetic dye samples were categorized using a customized lightfastness scale and test method. The authors defined a 'standard fading period' as daylight exposure on vertically supported samples (behind glass) from May 24 to June 14, 1892 at a farm north of Leeds, UK. Samples were exposed to several fading periods that were adjusted in length to give consistent exposure for assessment intervals 1–3. The final exposure intervals (4–5) were 2-3 × greater and resulted in an overall exposure of one year. A visual assessment was used by the authors to rank light sensitivity in the following categories:

1. Very fugitive: faded so rapidly that at the end of the first period only a very faint colour remained, and at the end of the fifth period (one year) all traces of the original colour were gone.
2. Fugitive: significantly faded at the end of the second period, with complete fade or slight tint remaining after a full year.
3. Moderately fast: distinctly faded at the end of the second period, more pronounced at the end of the third, and a pale tint remained at the end of the fourth. Complete fade or slight tint remained after a full year.
4. Fast: faded relatively little during the first, second, and third periods. A pale shade remained at the end of the fourth period, and still a pale tint at the end of a year.
5. Very fast: very gradual fade during the different periods, and a moderately good colour after a full year.

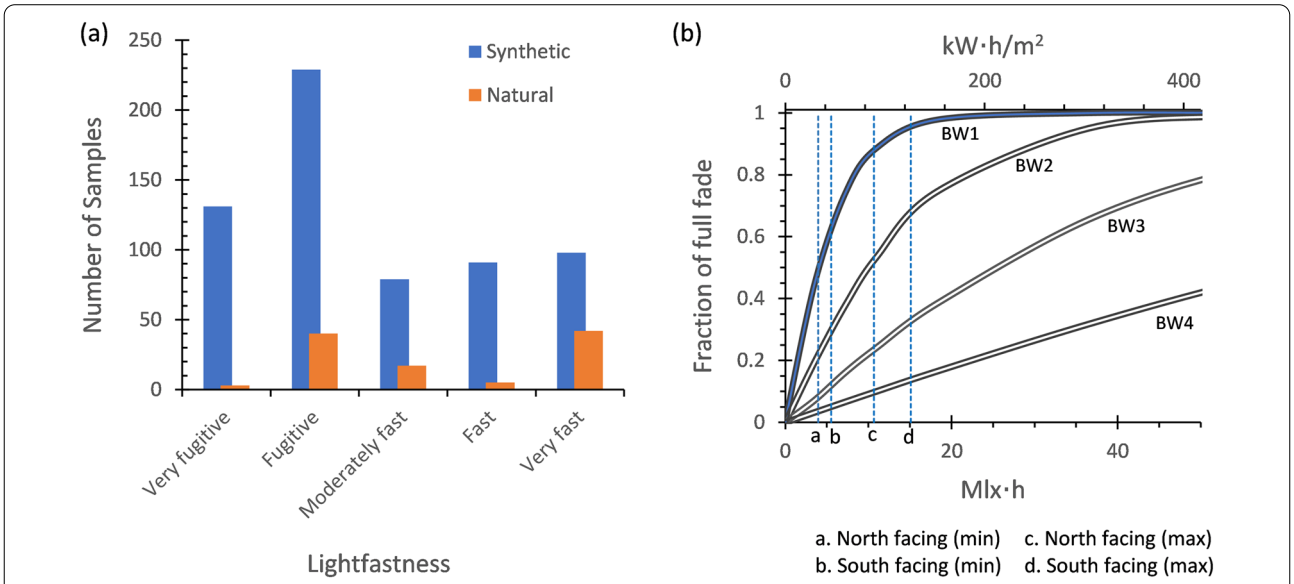

Fig. 1 **a** Summary of lightfastness results from Thorpe et al. for textiles dyed with synthetic and natural dyes in the late nineteenth century; **b** approximate fading of the ISO Blue Wool standards as a function of illuminance (daylight through glass) and irradiance hours. Vertical lines indicate possible scenarios for the standard fading period used by Thorpe et al.

An interpretation of the fastness rating system of Thorpe et al. is offered by Padfield and Landi [11], where the categories are given approximate Blue Wool (BW) equivalents: very fugitive (BW1); fugitive (BW1–2); moderately fast (BW3); fast (BW4–5); very fast (BW 5–7). For comparison with our present study, this ranking was further explored using estimates of Blue Wool fading from the CCI Light Damage Calculator [12], and an analysis of the possible irradiance that occurred in the 'standard fading period' of May 24–June 14, 1892. Daily NASA satellite weather data spanning 38 years (1984–2021) was imported into RETScreen [13], and used to calculate the irradiance-hours on vertical surfaces with different orientation. Irradiance-hours were calculated annually for each period of May 24–June 14 near Leeds, in order to asses the range of values that occur in the region at the specified time of year.

Figure 1b shows a summary of the approximate fractional fading of the Blue Wools with respect to light dose in Mega lux hours (Mlx·h) using the CCI Light Damage Calculator. The secondary x-axis gives a conversion of illuminance hours to daylight irradiance hours, $kW{\cdot}h/m^2$, using a generalized conversion factor of 1 $W/m^2 \approx 120$ lx [14]. Vertical lines, labeled 'a–d', indicate the minimum and maximum irradiance-hours that occurred during May 24–June 14 for the assessed years (1984–1921). Values are shown for north and south facing vertical surfaces since the authors did not specify the sample orientation; however, we assume that they were south-facing. The analysis indicates that the standard fading period likely resulted in a light dose in the range of 6 to 15 Mlx·h (south facing). A comparison of the qualitative fastness descriptions with the results of Fig. 1b show good agreement with the assessment of Padfield and Landi [11].

During the twentieth century, a wealth of reference lightfastness data was compiled by Schultz and Julius [9] and throughout three editions of the CI [10, 15, 16] for synthetic dyes. For some materials, lightfastness is given with respect to ISO/AATCC standards in the 3rd CI edition [16]; however, data for many other materials comes from a variety of earlier ranking systems or it is missing altogether. A summary of available ISO lightfastness data was recently compiled [17] for materials listed in the 1st edition of the CI. These values were used along with the reviewed work of Thorpe et al. [6] as comparative data for our present study.

The following sections describe the methodology for testing the lightfastness of more than 100 textiles dyed with early synthetic colourants in the period of 1874–1905. For brevity, a general overview of the results is presented, while detailed data regarding the samples and measurements is available in the accompanying dataset [18]. Supporting information for this study is given in a recent literature review [19], and of particular importance is the list of dyes that were targeted for analysis.

Methods

Sample materials

Samples were located in a collection of trade books and dyeing manuals published between 1874 and 1905 [20–27], and removed by softening the animal glue adhesive with a moist blotter. Multiple copies were obtained for many of the publications, and one of each was reserved specifically for analysis. From the thousands of available samples, the specific test materials were selected using a previously published list of target materials [19]. This list was created by focusing on the earliest dyes, colourants produced/imported in the US in large quantities, and those with a large number of manufacturers. Locating these materials within our complete collection involved significant effort in cross-referencing trade names and manufacturers with the first edition of the CI [10]. This was necessary to identify the CI numbers for comparison with the target list. Samples were not found for all materials of interest; however, many were located in some form of application. The dyed textiles are also currently being studied with gas chromatography-mass spectrometry (GC-MS) as another component of the research, and the ongoing work may lead to an adjustment of the chemical classification or possibly indicate the presence of dye mixtures. Characterization of some materials may require other techniques such as high performance liquid chromatography-mass spectrometry (HPLC-MS). All reference materials were saved for future research at the Canadian Conservation Institute, or other institutions with specialized instrumentation for dye analysis.

As a result of this effort, a total of 107 dyed textiles were catalogued and prepared for lightfastness testing—in addition to Blue Wools 1–4 as reference material. The list of test specimens may be expanded in future work pending sample availability. The characteristics of the dyed textiles (e.g., substrate and treatment) varied depending on the source, and how the products were promoted in the trade literature. A small number of samples were repeats of the same dye used in a different manner: e.g., primuline before and after being diazotized/developed with β-naphthol; Diamine Blue RW (Cassella) on wool, cotton, and cotton after-treated with $CuSO_4$. Where multiple shades were available, the lighter option was always selected for lightfastness tests. The range of dye classes was broad; however, the largest fractions were azo (48%) and triphenylmethane (20%). Further sample details are given in the dataset files with the corresponding colour measurements [18].

Light exposure

Lightfastness experiments were performed using a custom LED fadometer illustrated in the schematic of Fig. 2a. Samples were placed in a circular pattern at a distance of ~ 40.5 cm from the LED, and oriented toward the light source on angled supports. The lighting geometry provided a consistent illuminance of ~ 20 klx on all samples, and the same directionality of light exposure over the textured textile surfaces. Illuminance was similar to that used by Padfield and Landi [11] and other studies in heritage conservation. Two of the 30 sample supports were used to mount pairs of ISO Blue Wool standards (1–2 and 3–4), and another was reserved for a light sensor to monitor illuminance. Using this apparatus, Blue Wools 1–4 and 27 historic textile samples were tested in each of four batches. Figure 2c shows the arrangement in an image of the sample carousel loaded with the first group of specimens. Each experiment lasted more than six months to reach a final light dose exceeding 85 Mlx·h.

The LED illuminant provided several advantages over other light sources that were considered: lack of infrared and ultraviolet (UV) energy that requires filtering, negligible sample heating, high stability of light intensity over time, long life, and representativeness of modern electric gallery lighting. The apparatus was configured with a chip on board (COB) light-emitting diode (LED) with a colour temperature of 3200 K, colour rendering index (CRI) of 95+, and rated output of 5500–6500 lm. The relative spectral power distribution, normalized at 555 nm, is shown in Fig. 3 with comparison to a black body radiator at the same temperature. A variable current driver was trimmed to a value near the rated current of 3 A for the 100 W LED, to give consistent illuminance of 20 klx

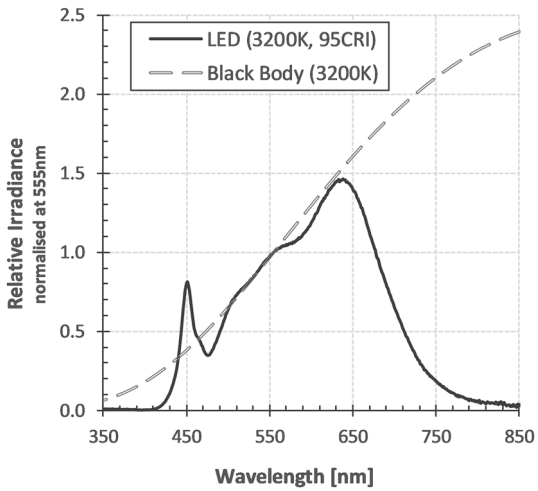

Fig. 3 Relative spectral power distribution of the LED light source compared to a black body radiator at the respective colour temperature

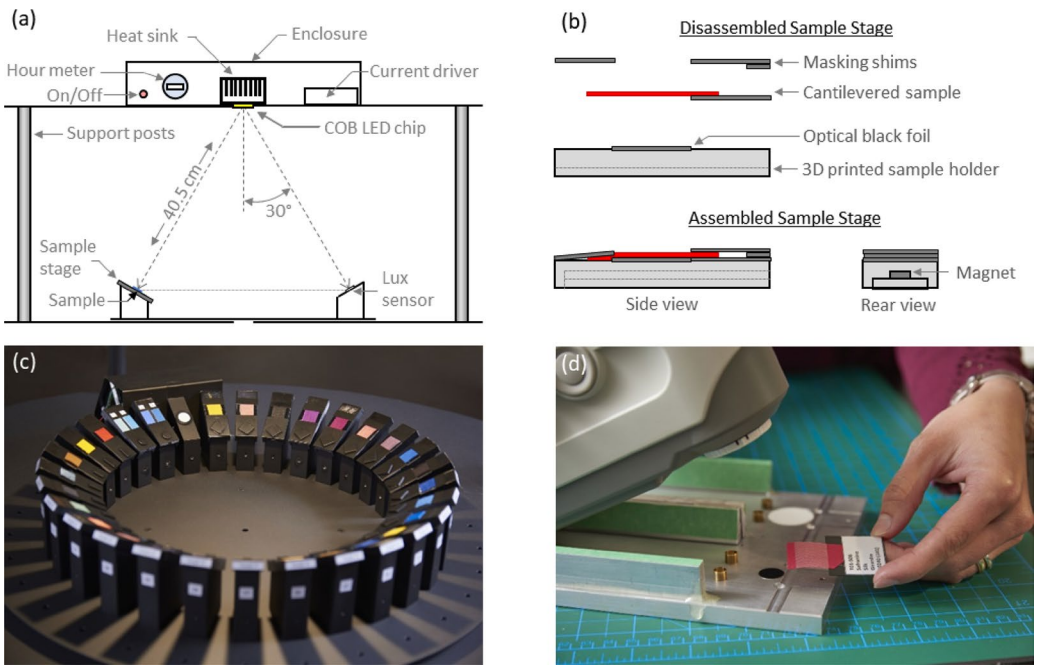

Fig. 2 Custom fadometer and sample measurement system for lightfastness testing of dyed textile samples: **a** diagram of the fadometer apparatus with samples oriented toward a single LED source; **b** schematic of the sample mounting stage; **c** image of the sample carousel and mounted lux sensor; **d** image of the colour measurement for cantilevered textile samples over black and white surfaces

at the sample surfaces. Sample heating was not an issue during the experiments due to the moderate illuminance and lack of infrared energy in the LED spectrum. Experiments were performed in a laboratory with environmental control typically in the range of 45–55% relative humidity, and 21 ± 2 °C.

Sample support and colour measurement

To reduce measurement error and labour required for data collection, special consideration was given to sample mounting and colour measurement. Samples were cantilevered from square sections of 0.25 mm thick steel shim-stock, and held on 3D-printed black plastic stages for light exposure. Black steel masking shims were placed over the end sections of each sample, and held in position by a rare earth magnet bonded to a groove in the underside of each support stage (see Fig. 2b). For colour measurement, a jig was constructed to rapidly position a Konica Minolta CM-2600d portable spectrophotometer at the same location for each sample. Measured area was set to medium area viewing (MAV) for large samples, and small area viewing (SAV) for smaller ones. The instrument was used to collect diffuse reflectance spectra from 360 to 740 nm (10 nm spacing) for the textiles over optical black and white backgrounds respectively. This assembly is shown in Fig. 2d. Measurements were collected frequently (~ 4 h spacing) at the beginning of exposure to capture the 'fast faders', and gradually adjusted to larger intervals of 1–2 weeks as light dose accumulated and colour change slowed.

The measured reflectance spectra at each light dose increment were used to calculate CIEXYZ colour values with D65 viewing illuminant, and 2° standard observer. These were converted to CIELAB colour space and subsequently used to evaluate colour change with the CIE ΔE2000 [28] formula, ΔE_{00}. Finally, the light dose causing a just-noticeable difference (JND) in colour was determined for each test sample. A JND was defined as a difference equal to ISO Grey Scale [29] contrast number 4 (GS4), which is a commonly used benchmark in heritage preservation [30, 31]. Note that the measured colour difference of samples includes changes in hue as well as lightness. Hoban [32] gives the CIELAB (ΔE_{76}) colour difference for GS4 as $\Delta E_{76} = 1.7 \pm 0.3$, and the full list of values for GS1-4 is shown in Table 1. In this study, $\Delta E_{00} = 1.7$ was defined as a JND in all reported values.

Figure 4a shows an approximate rendering of the ISO Grey Scale in full steps of GS 1–4. The upper left corner shows the definition of JND used to evaluate lightfastness of the test samples. Figure 4b gives an image of the BW 1–4 strips at the end of an experiment reaching 85 Mlx·h. The lower section of each sample is the original colour that was masked, and the upper section is the faded (exposed) region. At this light dose, the BW3 sample is showing a contrast approaching GS1 between the exposed and unexposed areas. This was the basis for selecting 85 Mlx·h as an approximate minimum target for the final dose with each test batch. For the development of risk assessment tools [12, 33], one aim of this work is to provide experimental data to visualize large colour changes of fugitive (BW1–3) materials with light exposure. Measurements to large dose values are useful for assessing the colour characteristics and sensitivity of materials in heritage collections that have significant prior light exposure [34].

Table 1 Comparison of ISO Grey Scale ratings with CIE colour difference values from Hoban

Grey Scale Rating	ΔE_{76}
5	0 ± 0.2
4–5 (4.5)	0.8 ± 0.2
4	1.7 ± 0.3
3–4 (3.5)	2.5 ± 0.3
3	3.4 ± 0.4
2–3 (2.5)	4.8 ± 0.5
2	6.8 ± 0.6
1–2 (1.5)	9.6 ± 0.7
1	13.6 ± 1.0

Results

ISO Blue Wools

Figure 5a presents a summary of test results for the Blue Wools included in this study. The dose causing each GS contrast is shown for BW1–4. The results indicate a similar slope for each colour difference evaluation. A similar plot in Fig. 5b, compares the dose response of the Blue Wools to GS4 using: 1. the LED illuminant in this study; 2. generalized values from CIE 157 [30] for an illuminant with and without UV respectively. The difference between the experimental data and the line for CIE (no UV) is pronounced for BW 3–4, where it takes a larger dose to reach a JND with the LED. This is likely because the warm-white LED emits less energy at shorter wavelengths near the UV region in comparison to a light source such daylight [35].

Dyed textile samples

A varied response to light exposure was evident in results for the historic textile samples. Several changed colour at a rate of BW1, while others were at a rate of BW5 or higher. For visual reference, the range of colour change at 85 Mlx·h is shown in Fig. 6 for the first test batch. A rendering of colour change (sRGB) versus light dose is

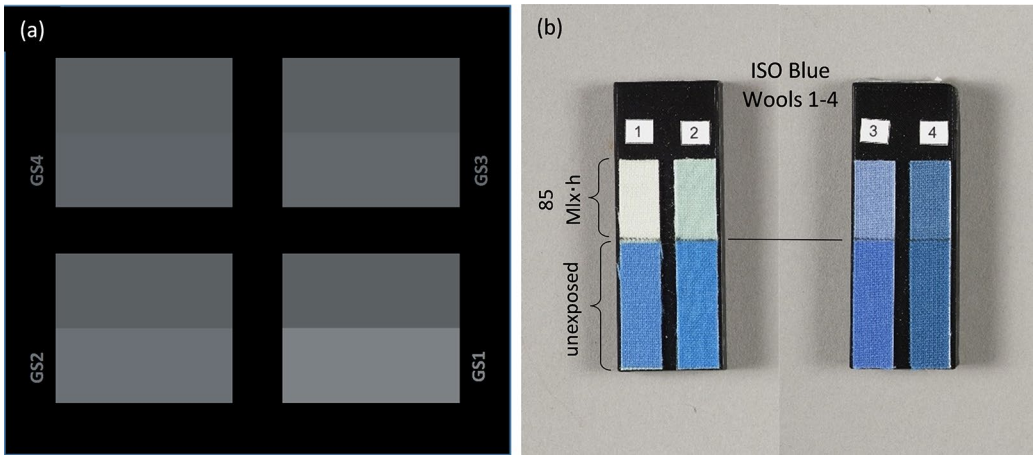

Fig. 4 **a** Approximate rendering of the ISO Grey Scale in full steps from 1 to 4; **b** image of the Blue Wool test samples at the end of an experiment to 85 Mlx·h

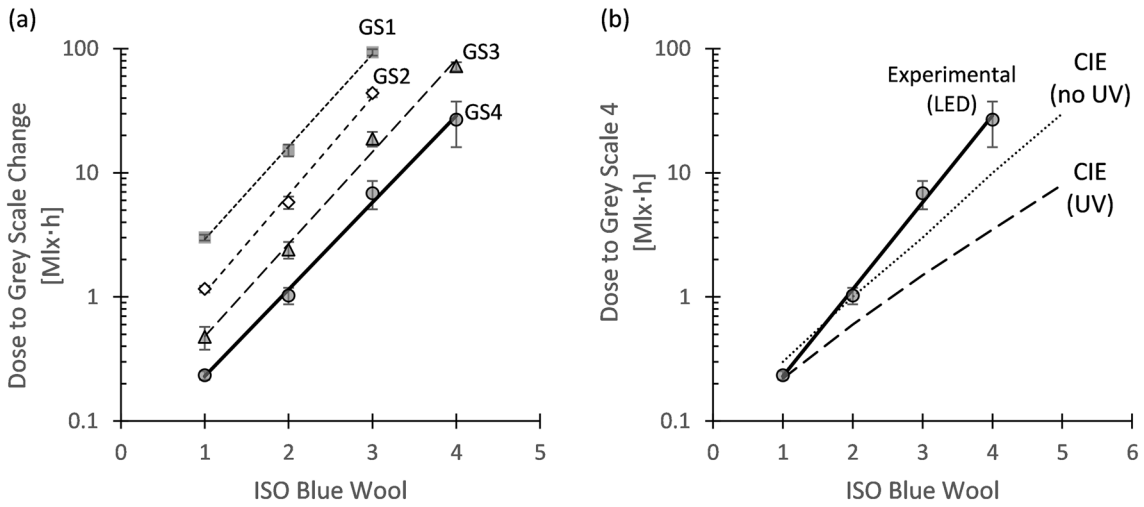

Fig. 5 **a** Light dose causing a colour change equal to ISO Grey Scale values 1–4 for ISO Blue Wools 1–4. Average values shown with 95% confidence intervals; **b** comparison of the dose causing a just-noticeable difference (GS4) for Blue Wools under the LED test illuminant, and values given in CIE 157 for BW response under a light source with and without UV

provided in Appendix Fig. 11 for these samples. Most samples exhibited significant fading, while picric acid [21] (upper left) and Orange No. 4 [23] (middle, 2nd from right) darkened. Fading was also evident on the reverse side for many of the swatches, indicating light penetration through the textile.

Measurements for each sample are available in the accompanying dataset [18]; however, the findings for a single dye are presented here as an overview of the content. Figure 7a shows vis-reflectance measurements for Hofmann's Violet RRR on wool [36] at the beginning/end of an experiment, over black/white backgrounds respectively. These measurements are documented for each dose increment to provide a resource for researchers interested in further colorimetric studies. Figure 7b shows the results of each measurement converted to CIEXYZ and subsequently CIELAB using D65/2° viewing conditions. The smooth curves highlight the effect of precisely positioning the sample within the jig for each measurement (see Fig. 2d). Figure 7c gives the calculated colour difference, ΔE_{00}, between the original and exposed sample as a function of light dose. This experiment progressed to 100 Mlx·h for a near full fade of Hofmann's Violet, while a JND was reached at a mere 0.12 Mlx·h. For visual reference, the faded sample at 85 Mlx·h is shown in Fig. 6 (middle right).

Fig. 6 Image of the first test batch of dyed textile samples showing masked (unexposed) ends with original colour, and central light-damaged areas at 85 Mlx·h

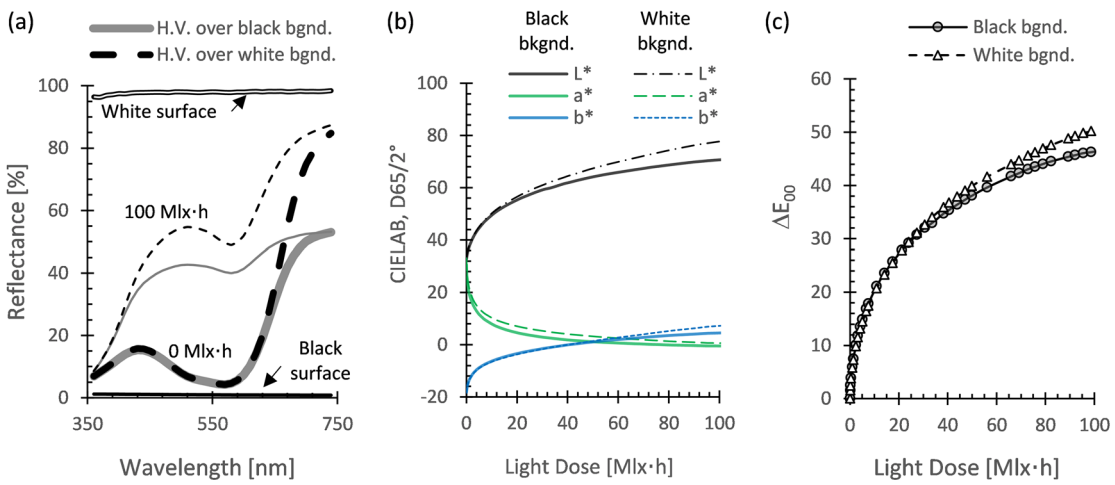

Fig. 7 Example data for Hofmann's Violet RRR on wool: **a** diffuse reflectance measured over white and black backgrounds. Thick lines are for 0 Mlx·h, and thin lines at 100 Mlx·h; **b** calculated CIELAB values versus light dose (D65/2°); **c** colour difference versus light dose

A summary of the lightfastness findings is presented in Fig. 8 using stacked histograms to show the number of samples with different rates of colour change, categorized by chemical class. In Fig. 8a, the samples are binned according to BW ratings using the CIE 157 [30] generalized values for ISO BW response under an illuminant with UV removed. Thresholds between each BW were determined as the mid-point between values on a semi-log plot (see Fig. 5b). The results show a large cluster of samples in the BW1 category, and another peak centered at BW3. It is important to keep in mind that the fastness of individual dyes can vary due to many factors [37]: substrate, dye concentration, aftertreatment, mordant etc. These factors may be explored further in future work, using other materials available in the sample collection.

The distribution of sensitivity is better shown in Fig. 8b using order of magnitude bin values for the dose to JND. The results indicate a normal distribution with a peak number of samples with dose to JND within the range of 1–10 Mlx·h. Azo dyes are the largest chemical class in the sample set, followed by the triphenylmethanes. Each group shows a wide distribution of lightfastness; however, the triphenylmethanes appear slightly more fugitive on average. At the tails, the plot shows a small cluster of anthraquinones with higher fastness values, and a group of xanthenes as highly fugitive. Note that the chemical classification is an estimate based on cross-referencing trade name and manufacturer with the 1st edition of the CI. Along with the chemical analysis, correlations between dye structure and lightfastness are being reviewed in greater detail. Previous research has shown the relationship as highly complex due to many factors [37–39].

A further interpretation of lightfastness data is presented in Fig. 9 using a calculation of the average fastness ratings for samples in different chemical classes, and the respective 90% confidence intervals from the Student's t-test. Values on each bar indicate the number of samples in the group. A second series on the graph illustrates the results from similar calculations using a dataset containing ISO lightfastness values from the CI [17]. With the exception of xanthene dyes, the experimental and CI results are in good agreement. A review of results for individual dyes showed 70% of the experimental

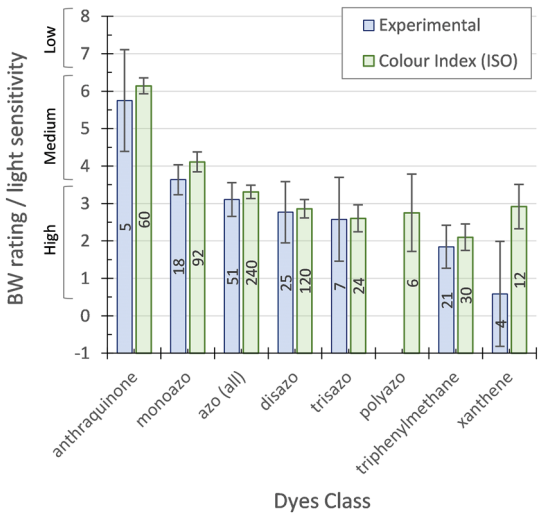

Fig. 9 Comparison of average lightfastness ratings by chemical class for experiments in this study and data available in the Colour Index. 90% confidence intervals are shown from the Student's t-test, and values on the bars indicate the sample size

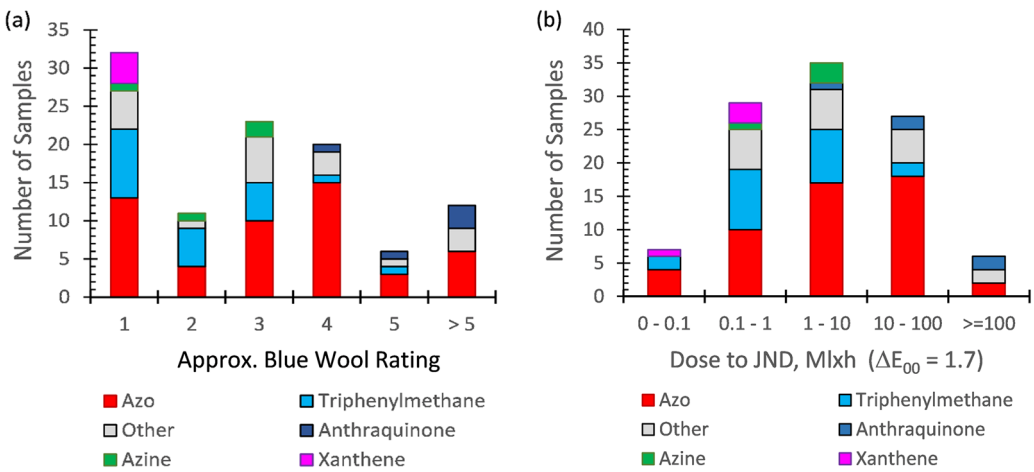

Fig. 8 Distribution of light sensitivity for the textile samples as a function of chemical class: **a** lightfastness binned relative to CIE approximate respose for ISO Blue Wools (no UV); **b** order of magnitude bin values for dose to JND

lightfastness ratings within one BW step of the CI values when comparative data were available. Overall, these results emphasize higher fastness for the anthraquinones (medium sensitivity: ~ BW6 on average), and they appear to show a slight decrease in fastness for the azo dyes with increasing azo groups. Average lightfastness for the monoazo dyes is at the lower bound of medium sensitivity, and it is approximately one BW step higher than the trisazo. Average fastness for the triphenylmethane dyes is at BW2, which is a step lower than that of the overall azo group. For the xanthene dyes, the low fastness from experimental results is quite pronounced, and some materials could be classified as 'ultrasensitive' if there was a rating below BW1. As a point of reference, the most fugitive of all test samples was erythrosine on cotton, with a dose to JND of 0.03 Mlx·h.

As a final comparison with published fastness ratings, the nineteenth century study of Thorpe et al. [6] (Fig. 1) was revisited. For these historical data, the approximately equivalent BW ranking system of Padfield and Landi [11] was used with minor adjustments for simplification: 'very fast' was defined as BW5 and higher; 'fast' was defined strictly as BW4; and 'very fugitive' and 'fugitive' were grouped together in a single category (BW1–2). The grouping of BW1 and BW2 was justified by the fact that the smallest exposure increment used by Thorpe et al. as a 'standard fade period' was so large that differentiation of the two groups would be difficult. The distributions in Fig. 10 show remarkable similarity despite the high degree of uncertainty when using historical data.

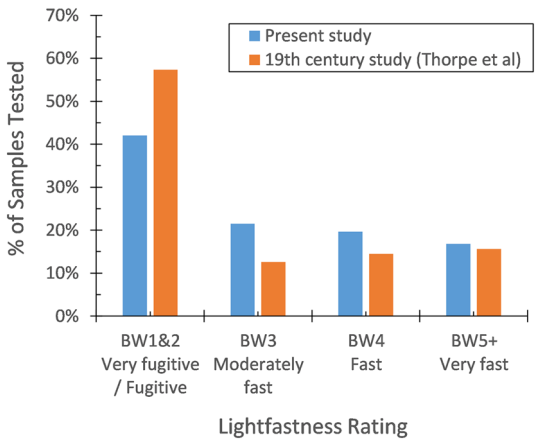

Fig. 10 Comparison of lightfastness distribution for samples tested in this study, and the nineteenth century study of Thorpe et al.

Conclusions

The light sensitivity of more than 100 historic textiles dyed with synthetic organic colourants in the period of 1874–1905 was evaluated by illumination with a warm-white LED that is characteristic of modern gallery lighting. Using a custom fadometer, portable spectrophotometer, and sample measurement jig, a dataset of vis-reflectance spectra was compiled to light dose values exceeding 85 Mlx·h. From these data, the colour values in CIEXYZ and CIELAB spaces were calculated and used to determine colour change with light exposure. A summary of the lightfastness results was presented, which highlighted a wide distribution of sensitivity with a peak number of samples exhibiting a JND after 1–10 Mlx·h. Results were further evaluated to show the average fastness for a selection of chemical classes: anthraquinone (BW6); azos (BW3); triphenylmethane (BW2); and xanthene (experimental: BW1–2; CI: BW3). Overall, comparisons with published lightfastness ratings from the CI and a nineteenth century study showed good agreement with the findings of this work. The raw measurements, calculated colour values, and associated metadata are provided in a supplemental dataset for researchers interested in dye analysis, lighting risk assessments, and colorimetry.

The results of this research provide the means for evaluating colour change of light-sensitive dyes in heritage collections beyond the JND used for modern fastness ratings. Data of this type will facilitate further development of tools such as the CCI Light Damage Calculator and HERIe. A forthcoming analysis will investigate lightfastness as a function of prior exposure, since most materials in collections have experienced light damage and are not in pristine condition. Colour change from past light exposure will change the reference colour (i.e., to what remains now), and the rate of colour change going forward. In addition to the lighting research, an analysis of the chemical markers for dye identification by GC-MS is underway, and it is hoped that other researchers will build upon this dataset with analyses using other techniques.

Appendix

Figure 11 provides a visual illustration of the results for the first test batch of dyed textiles. For each sample, the name is listed with the dose to JND beneath. Horizontal coloured bars show approximate colour in sRGB space for the unexposed (upper bar), and exposed (lower bar) material. Dose values are given at the top scale. Results are sorted in order of increasing lightfastness, and measurements for the Blue Wools (1–4) are provided for comparison. These results emphasize how the dataset may be used for further develop risk assessment tools such as the CCI Light Damage Calculator.

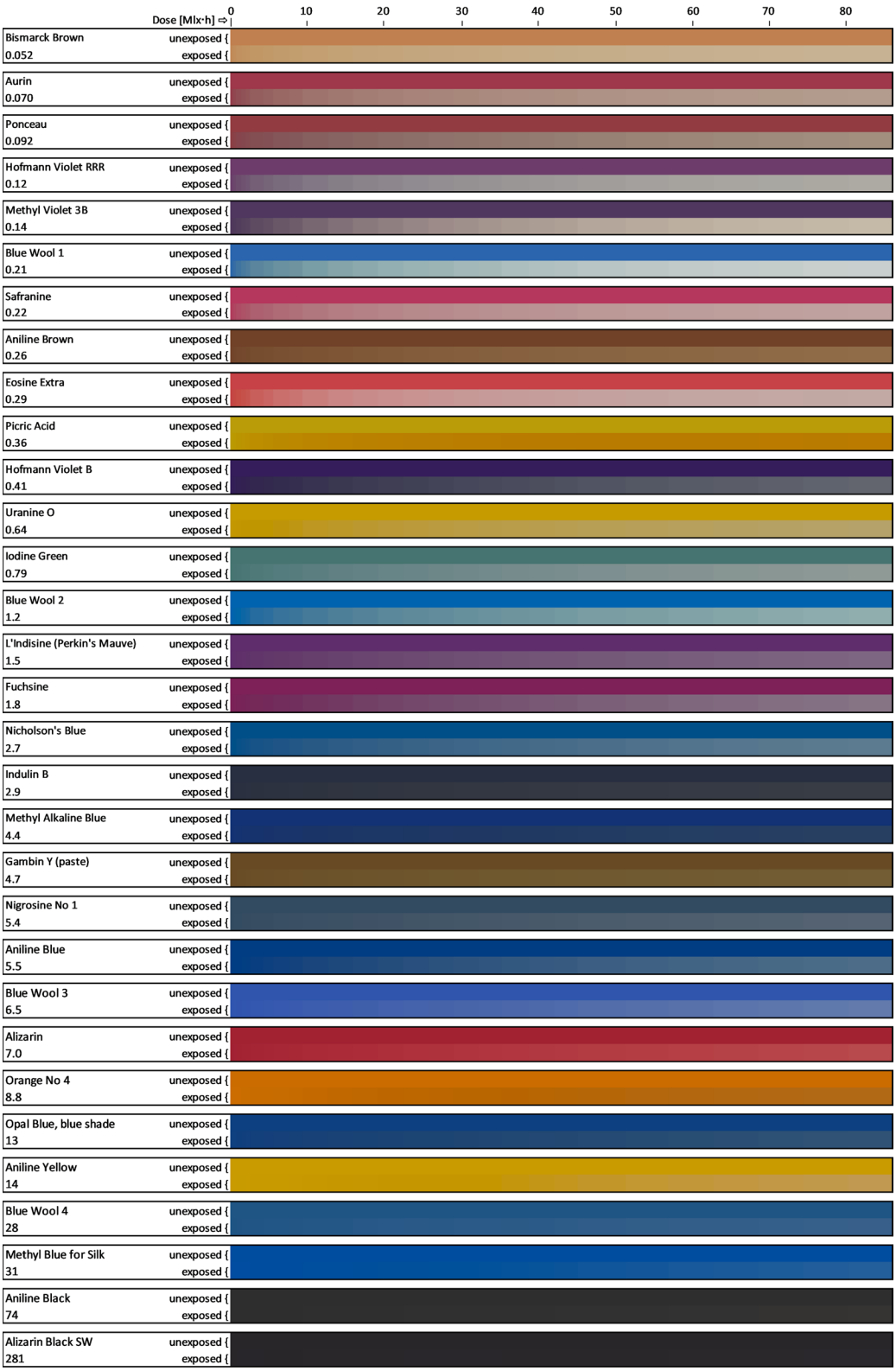

Fig. 11 Illustration of the effect of light exposure for the first test batch of dyed textile samples. Numbers beneath each trade name indicate the dose giving ΔE00 = 1.7 in Mlx·h. sRGB colours were calculated from diffuse reflectance measurements over a black surface using viewing conditions of D65/2°

Abbreviations
BW: Blue wool; CI: Colour Index; JND: Just-noticeable difference; GS: Grey scale.

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Authors' contributions
EH and JP documented and reviewed a collection of available materials, cross-referenced information with the Colour Index, and selected samples for analysis. EH constructed the test apparatus, developed the test method, and drafted the manuscript. IC-S and MB performed diffuse reflectance measurements and reviewed data quality during the progress of each test batch. All authors contributed to reviewing and editing the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
The dataset compiled during this study is available in the Harvard Dataverse repository, https://doi.org/10.7910/DVN/JQMYFM [18].

Declarations

Competing interests
The authors declare that they have no competing interests.

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References

1. Thorpe TE, et al. The action of light on dyed colours. In: Report of the sixty-third meeting of the British Association for the Advancement of Science. London: John Murray; 1893. p. 373–81.
2. Thorpe TE, et al. The action of light on dyed colours. In: Report of the sixty-fourth meeting of the British Association for the Advancement of Science. London: John Murray; 1894. p. 238–46.
3. Thorpe TE, et al. The action of light on dyed colours. In: Report of the sixty-fifth meeting of the British Association for the Advancement of Science. London: John Murray; 1895. p. 263–72.
4. Thorpe TE, et al. The action of light on dyed colours. In: Report of the sixty-sixth meeting of the British Association for the Advancement of Science. London: John Murray; 1896. p. 347–56.
5. Thorpe TE, et al. The action of light on dyed colours. In: Report of the sixty-eighth meeting of the British Association for the Advancement of Science. London: John Murray; 1898. p. 285–93.
6. Thorpe TE, et al. The action of light on dyed colours. In: Report of the sixty-ninth meeting of the British Association for the Advancement of Science. London: John Murray; 1899. p. 363–70.
7. Barnett JC. Synthetic organic dyes, 1856–1901: an introductory literature review of their use and related issues in textile conservation. Stud Conserv. 2007;52(sup1):67–77.
8. Hummel J. Fast and fugitive dyestuffs. J Soc Dye Colour. 1890;25:187–90.
9. Schultz G, Julius P. Farbstofftabellen. Berlin: Frankfurt; 1914.
10. Rowe F. Colour index. Bradford: Society of Dyers and Colourists; 1924.
11. Padfield T, Landi S. The light-fastness of the natural dyes. Stud Conserv. 1966;11(4):181–96.
12. Michalski S. CCI light damage calculator. Canadian Conservation Institute: Canada; 2012.
13. RETScreen. RETScreen expert software. Natural Resources Canada: Varennes; 2022.
14. Michael PR, Johnston DE, Moreno W. A conversion guide: solar irradiance and lux illuminance. J Meas Eng. 2020;8(4):153–66.
15. Rowe FM. Colour index. 2nd ed. Bradford: Society of Dyers and Colourists; 1956.
16. Rowe FM. Colour index. 3rd ed. Bradford: Society of Dyers and Colourists; 1971.
17. Hagan E, Poulin J. Statistics of the early synthetic dye industry: compiled data. Harvard: Harvard Dataverse; 2021.
18. Hagan E, et al. Replication data for: the lightfastness of early synthetic dyes. Harvard: Harvard Dataverse; 2022.
19. Hagan E, Poulin J. Statistics of the early synthetic dye industry. Herit Sci. 2021;9(1):1–14.
20. Woodbury CJ. The aniline colours of the Badische Anilin- & Soda-Fabrik, Ludwigshafen on Rhine and their application on wool, cotton, silk and other textile fibres. Badische Anilin- & Soda-Fabrik: Ludwigshafen o/Rhine; 1901.
21. Crace-Calvert F. Dyeing and Calico Printing: including an account of the most recent improvements in the manufacture and use of aniline colours; illustrated with wood-engravings and numerous specimens of printed and dyed fabrics. Manchester: Palmer & Howe; 1876.
22. Crookes W. A practical handbook of dyeing and calico-printing: with eleven page-plates, forty-seven specimens of dyed and printed fabrics, and thirty-eight woodcuts. London: Longmans, Green; 1874.
23. Beer JJ. The coal tar colours of the Farbwerke vorm. Meister Lucius & Brüning: A. General part. Fabwerke vorm Meister Lucius & Brüning: Höchst on the Main Germany; 1896.
24. Knecht E, Rawson C, Loewenthal R. A manual of dyeing: for the use of practical dyers, manufacturers, students, and all interested in the art of dyeing, vol. 3. London: C. Griffin, limited; 1893.
25. Cassella L. The dyeing of cotton and other vegetable fibres with the dyestuffs of Leopold Cassella & Co. Frankfort o. M.: Leopold Cassella & Co.; 1902.
26. Cassella L. The dyeing of wool including wool-printing: with the dyestuffs of Leopold Cassella & Co. New York: Leopold Cassella & Co.; 1905.
27. Girardin MJ. Leçons de chimie élémentaire appliquée aux arts industriels: Tome IV. Chimie organique. Matières textiles et matières tinctoriales. Paris: Libraire de l'Académie de Médecine; 1875.
28. Sharma G, Wu W, Dalal EN. The CIEDE2000 color-difference formula: implementation notes, supplementary test data, and mathematical observations. Color Res Appl. 2005;30(1):21–30.
29. ISO 105-A02. Textiles—tests for colour fastness—part a02: grey scale for assessing change in colour. Geneva: ISO; 1993.
30. CIE. Technical report 157: control of damage to museum objects by optical radiation. Vienna: Commission Internationale de l'Eclairage; 2004.
31. Michalski S. Damage to museum objects by visible radiation and ultraviolet radiation. In: Proceedings of the conference on lighting museums, galleries and historic houses. London: Museums Association; 1987.
32. Hoban RF. Color measurement in fastness evaluation. Text Chem Color. 1980;12(2):33.
33. Polish Academ of Sciences. HERIe. 2022. https://www.herie.pl/. Accessed 3 Feb 2022.
34. Kashiwagi M, Yamasaki S. The lightfastness properties of traditional vegetable dyes. Sci Pap Jpn Antiq Art Crafts. 1982;27:54–65.
35. McLaren K. The spectral regions of daylight which cause fading. J Soc Dyers Colour. 1956;72(3):86–99.
36. Crace-Calvert F. Dyeing and calico printing. Palmer & Howe: Manchester; 1876.
37. Giles CH, Duff DG, Sinclair RS. The relationship between dye structure and fastness properties. Rev Prog Color Relat Top. 1982;12(1):58–65.
38. Evans NA, Stapleton IW. Chapter VI—Structural factors affecting the lightfastness of dyed fibers. In: Venkataraman K, editor. The chemistry of synthetic dyes. Cambridge: Academic Press; 1978. p. 221–77.
39. Kienle RH, Stearns EI, Meulen PAVD. A correlation of structure with fastness to light of monoazo dyes. J Phys Chem. 1946;50(4):363–73.

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